Computer Simulation of Sintering 316L Stainless Steel Binder Jetting Sample

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ABSTRACT

Although the binder jetting process is the most cost-effective additive manufacturing technology, sintering is key to improving the sample density and mechanical strength. Like the sintering of conventionally processed green body parts (i.e. press and sinter), the sintering process brings many challenges also for metal binder jetting, affecting the final part size and final dimensional accuracy. To achieve the best result and desired material properties, precise sintering temperature and atmosphere control are vital.

In this work, 3D full-scale computational fluid dynamics (CFD) simulations of the sintering process for a 316L stainless steel specimen manufactured with the binder jetting technology are conducted, with the aim to be combined with experimental work to verify the simulations. In the simulation, the sintering process follows an about 15 hours full sintering cycle with all the heating, holding and cooling stages. A full-scale 3D CFD simulation method is presented with all the important processes including gas flow, thermal radiation, convection, and conjugate heat transfer in solids and fluids being simulated during the sintering. The simulation results are compared with the experiment.

Keywords: Metal binder jetting, Sintering, Full-scale 3D CFD simulation, Gas flow, Conjugate heat transfer, Thermal radiation, Experiment verification.

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Laser Powder Bed Fusion of TNTZO β-Ti Alloy: Microstructure, Mechanical Properties and Biocompatibility

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ABSTRACT

β Ti-alloys have been studied for the last two decades for their interesting mechanical properties. The TiNbTaZrO (TNTZ) alloy system shows an exceptional combination of high strength, low elastic modulus and high strain recovery percentage, creating a potential for their use in medical implants due to their excellent biocompatibility or shock absorption due to their high toughness.

In this study, pre-alloyed Ti-34Nb-13Ta-5Zr-0.3O powder was processed using Laser Powder Bed Fusion (LPBF) to assess the impact of the process on the microstructural and mechanical properties development. The influence of the process parameters on the build density, microstructural evolution, and texture were assessed using optical microscopy, XRD SEM-EBSD, and TEM. Post-LPBF heat treatment strategies were also developed. Tensile loading-unloading cycles were performed to assess the strain recovery limits for the various conditions.

Upon optimising LPBF process parameters, highly dense builds (> 99.9%) were achieved (Fig. A), which is among the highest in the literature for TNTZ LPBF [1]. The microstructure was optimised to be composed of equiaxed grains and the least textured microstructure (Fig. B). The as-built samples showed a tensile strength of 756 MPa, while keeping a low elastic modulus of 56.5 GPa and elongation-to-failure of 20% (Fig. C). The alloy also showed a high strain recovery of 1.3%. TEM and XRD investigations showed no evidence of the typical $\beta \leftrightarrow \alpha''$ stress-induced phase transformation following load. The stress-strain curves also showed a single-yielding curve, compared with the double yielding curve that is associated with the deformation induced phase transformation. Previous work suggests that the increase in the oxygen content of the alloy suppressed the deformation induced transformation [2].

While the heat treatments improved the build homogeneity, it led to the formation of fine needle-like α-precipitates (Fig. D). α-precipitation increased the strength and elastic modulus, and reduced the ductility, compared to the as-built and solution treated conditions. Precipitated α needles over 3 days of ageing increased the material hardness and ultimate strength by 20~25 %, while keeping the superelastic properties with 1.5% recoverable strain. The superelastic behaviour was found to be slip-dominated, with no sign of twinning or phase transformation by microscopic observations, aligned with similar findings for other oxygen-rich TNTZ alloys. Surface treatment of TNTZ showed significant effect on MC3T3 osteoblast cell viability. Surface polishing of the TNTZ flat surfaces to less than 3 μm surface roughness had a drastic effect on increasing cell adhesion and the metabolic rate compared to the etched and as-built surfaces. Moreover, high TNTZ acceptance by bone cells was demonstrated by the amount of deposited calcium on polished surfaces after 3 weeks

of testing (Fig. E). These mechanical and biomedical key results represent a promising milestone in the quest for new medical implants that fits the best as replacement for bone and other body tissues.

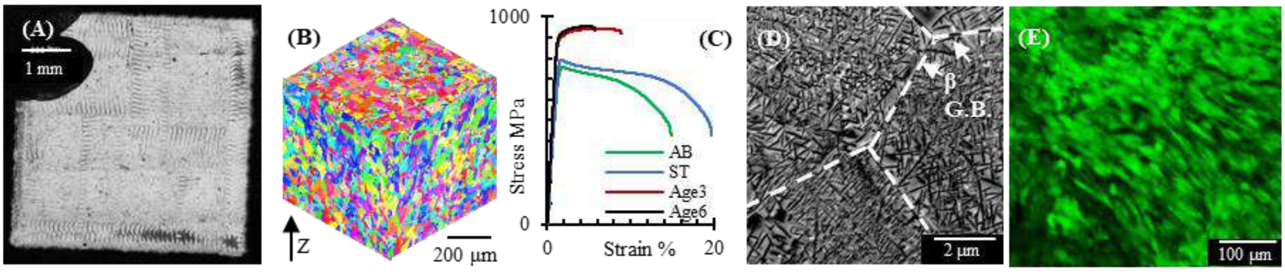

Fig (A) optimum LPBF build density, (B) near equiaxed as-built microstructure, (C) mechanical properties evolution , (D) precipitation of α-needles, (E) calcium deposition on polished TNTZ surface.

KEY WORDS: additive manufacturing, LPBF, titanium metallurgy, superelasticity, medical devices, biocompatibility.

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Microstructure and Mechanical Properties of L-DED Processed Fe-36Mn-9Al-7Ni (wt%) Superelastic Shape Memory Alloy

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ABSTRACT

Laser Direct Energy Deposition (L-DED) process is a metal additive manufacturing process that produces 3D components that involves the use of a high-power laser to melt and fuse metal powder directly onto a substrate. This process has gained popularity in recent years due to its ability to create complex, high-quality metal components with good dimensional accuracy. Furthermore, in comparison to the powder bed fusion process, L-DED process is generally able to produce components more rapidly due to the absence of the powder recoating time of the powder bed. On the other hand, superelastic shape memory alloy (SMA) is an alloy that can recover large deformation to its original shape when the applied load is removed. Due to this superelastic properties, SMAs can absorb vibration energy efficiently by converting the vibration into the heat. Superelasticity allows the SMA to withstand cyclic deformations without undergoing permanent deformation, making it an ideal candidate for various applications, including biomedical devices and aerospace components. Among several ally systems, Fe-Al-Mn-Ni SMA is a promising one due to its low raw material cost and excellent superelastic properties. However, it has been known that to produce sound components of the Fe-Al-Mn-Ni SMA using laser-based additive manufacturing process is challenging due to the cracking problems. In this study, Fe-36Mn-9Al-7Ni (wt.%) superelastic SMAs were produced by the L-DED process. Thin-walled structures with various wall thicknesses were produced. The results show that crack-free Fe-Al-Mn-Ni SMAs can be successfully produced when the wall thickness is thin enough, due to the heat accumulation effect. Microstructure and mechanical properties of the L-DED processed Fe-Al-Mn-Ni SMAs were investigated in terms of different L-DED process parameters and the wall thickness.

KEY WORDS: L-DED, Shape memory alloys, Superelasticity

Control of Interfacial Defects in Fe-Ni Multi-Material Structures Fabricated by Laser Direct Energy Deposition through Interface Geometry

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ABSTRACT

Among various additive manufacturing methods, laser direct energy deposition (LDED) has reached a milestone that it no longer fully focused on single material fabrication but additionally being focused on multi-material additive manufacturing (MMAM)[1]. As a primitive approach of the MMAM, in this study, a LDED deposition strategy to control the interfacial defect was developed. In LDED, the powder jetting angle is fixed in about 50 degrees, and it makes pores and cracks when depositing materials near a sharp corner due to the blocking of the powder jet. When producing the multi-material structure by the LDED, once the first material is deposited with a proper height in mm scale, interfacial defects can occur while depositing the second material due to the blocking effect. In this study, to control such interface defects, different interface shapes were designed with V-shaped and anchor-like interfaces, in a way to avoid the blocking effect. MMAM by LDED was performed using the developed interface shapes for a Fe-Ni multi-material structure. Interfacial microstructure was also investigated in order to figure out the interfacial reaction and the bonding behaviour of these two materials.

KEY WORDS: Additive manufacturing(AM), Laser direct energy deposition(LDED), Multi-material additive manufacturing(MMAM), Digital image correlation(DIC), Finite element model(FEM)

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NEGATIVE THERMAL EXPANSION BEHAVIOUR OF METALLIC METAMATERIALS PRODUCED VIA MULTI-MATERIAL L-PBF

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ABSTRACT

Most of the materials found in nature present a positive coefficient of thermal expansion (CTE), meaning they expand as the temperature rises. However, components that are subjected to high temperature variations and still require high dimensional accuracy, such as earth observation satellites, would benefit from the use of materials with extremely low or even negative CTE. Some metamaterials proposed in the literature should be able to achieve negative values of thermal expansion by combining two materials with high CTE difference in a specific lattice structure. Due to their complex geometry, AM is the most suitable process to fabricate such metamaterials. Negative-CTE metamaterials have been simulated in the literature and works on polymer AM have corroborated the simulation results. [1,2,3] However, AM of these complex structures using two different metallic materials, which would present higher stiffness than polymers, and broaden the applications for these metamaterials, hasn't been widely investigated. [4] Due to recent advances in the AM field, there are now technologies that allow a 3D metal multi-material Laser-Powder Bed Fusion process, which was used in this research. [5]

In this work, additively manufactured negative-CTE metamaterials made out of two different material combinations were studied: (1) Invar + 316L stainless steel and (2) Invar + Inconel 718. The specimens were printed in an L-PBF machine equipped with a multi-material recoater by Aerosint, which enables the simultaneous deposition of two different materials during the L-PBF process. Different scanning strategies were studied in order to improve the quality of the interface between the materials, which was analysed by optical and scanning electron microscopy. The CTE of the metamaterials was then evaluated by dilatometry and the results were compared with FEM simulations.

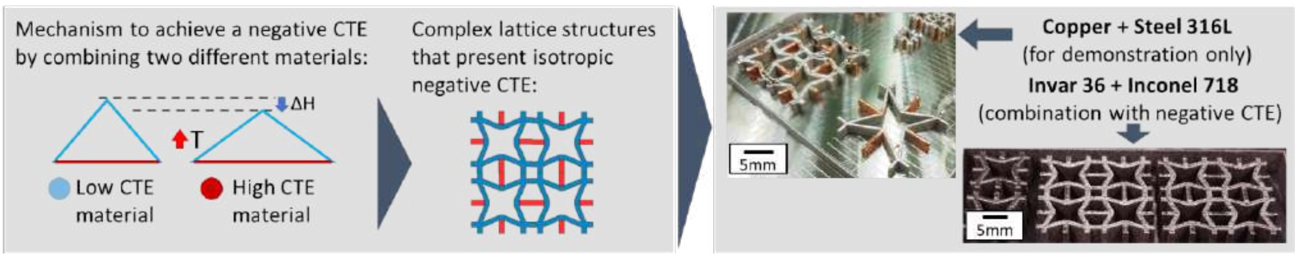

Figure 1. Schematization of how a negative-CTE metamaterial works and multi-material samples produced by L-BPF.

KEY WORDS: metamaterials, multi-material L-PBF, negative coefficient of thermal expansion, lattice structures.

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The effect of laser parameters on crystallization behavior of Zr-based Bulk metallic glass manufactured by laser powder bed fusion

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Abstract

Bulk metallic glasses have recently gained attention due to outstanding strength and corrosion behavior. Additive manufacturing of amorphous parts is confined due to the reheating and remelting of solidified layers, resulting in crystallization at heat-affected zones. Adjusting the process parameters window enables controlling the reheating effect and total heat accumulation in these regions. In this investigation, laser parameters such as laser power and scanning speed were altered to obtain a trade-off between defects and amorphous states in printed samples. X-ray diffraction and differential scanning calorimetry were implemented to reveal the effect of process parameters change on the enthalpy of crystallization.

Keywords: Laser powder bed fusion (LPBF), Crystallization, Bulk metallic glass (BMG)

X-RAY REFRACTION TECHNIQUES NON-DESTRUCTIVELY QUANTIFY AND CLASSIFY DEFECTS IN AM MATERIALS

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ABSTRACT

X-ray refraction is analogous to visible light deflection by matter; it occurs at boundaries between different media. The main difference between visible light and X-rays is that in the latter case deflection angles are very small, from a few seconds to a few minutes of arc (i.e., the refraction index n is near to 1). Importantly, deflection of X-rays is also sensitive to the orientation of the object boundaries. These features make X-ray refraction techniques extremely suitable to a) detect defects such as pores and microcracks and quantify their densities in bulk (not too heavy) materials, and b) evaluate porosity and particle properties such as orientation, size, and spatial distribution (by mapping). While X-ray refraction techniques cannot in general image single defects, they can detect objects with size above a few wavelengths of the radiation.
Such techniques, especially at the Synchrotron BESSY II, Berlin, Germany, can be used *in-situ*, i.e. when the specimen is subjected to temperatures or external loads.
The use of X-ray refraction analysis yields quantitative information, which can be directly input in kinetics, mechanical and damage models.

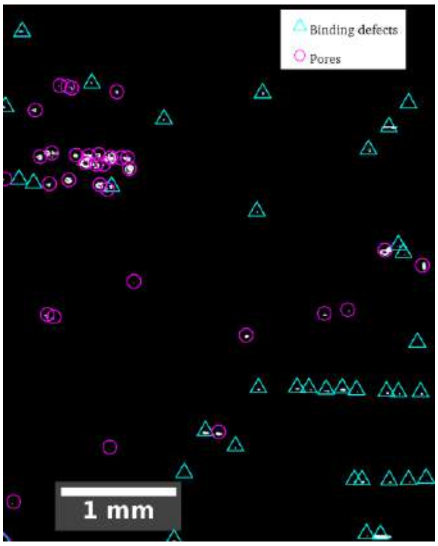

Figure 1. Distinction between round pores and binding defects (LoF) in Ti6Al4V.

We hereby show the application of non-destructive X-ray refraction radiography (SXRR, 2D mapping also called topography) to problems in additive manufacturing:
1) Porosity analysis in PBF-LM-Ti64. Through the use of SXRR, we could not only map the (very sparse) porosity distribution between the layers and quantify it, but also classify, and thereby separate, the filled porosity (unmolten powder) from the keyhole and gas pores (Figure 1).

2) In-situ heat treatment of laser powder bed fusion PBF-LM-AlSi10Mg to monitor microstructure and porosity evolution as a function of temperature (Figure 2). By means of SXRR we indirectly observed the initial eutectic Si network break down into larger particles as a function of increasing temperature. We also could detect the thermally induced porosity (TIP). Such changes in the Si-phase morphology upon heating is currently only possible using scanning electron microscopy, but with a much smaller field-of-view. SXRR also allows observing the growth of some individual pores, usually studied via X-ray computed tomography, but again on much smaller fields-of-view.

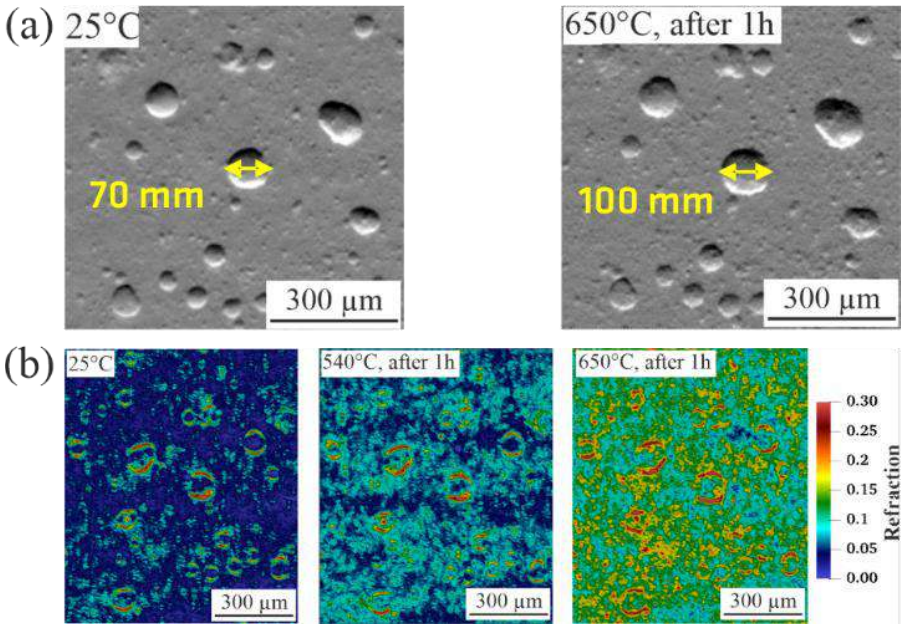

Figure 2. (a) Visualization of pore growth in AlSi10Mg. (b) Refraction images: detection of pore nucleation and growth.

Our results show the great potential of in-situ SXRR as a tool to gain in-depth knowledge of the defect distribution and the susceptibility of any material to thermally induced damage and/or microstructure evolution over statistically relevant volumes.

KEY WORDS: Al alloys; Ti alloys; PBF-LB; X-ray refraction radiography; porosity; field-of-view.

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Operando monitoring of multi-laser powder bed fusion process during high-speed synchrotron imaging

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ABSTRACT

Laser powder bed fusion (LPBF) is an emerging digital manufacturing technology that produces parts with intricate shapes using powder feedstocks. This process relies on alternating a powder layer deposition step followed by a laser scanning step using a high-power energy source to selectively fuse the powder particles until the final part is obtained. New industrial machines have been developed to employ multiple lasers working simultaneously to drive down production time, *and thus* enhance productivity. Due to the complex multi-laser scanning strategies, there is a need to investigate these unknown behaviours and unveil the underlying mechanisms governing the multi-LPBF process.

Recent progress in synchrotron X-ray facilities allows investigation of the LPBF processes non-destructively at unprecedented temporal and spatial resolution. A new rig has been developed between University College London and Renishaw plc to replicate an industrial LPBF machine, ***a.k.a.*** the Quad In situ and Operando Process Replicator (Quad-ISOPR). This unique setup incorporates a scanning head from a RenAM 500Q machine with 4 lasers and has been used to capture the process dynamics at the laser-matter interaction zone using X-ray imaging at framerates up to 500,000 Hz. In parallel, this rig is coupled with other optical instruments which are synchronised to capture signals from the top of the powder bed at the same frequency to complete our understanding of the process.

This presentation will introduce new insights into the multi-LPBF process and the full capabilities of the Quad-ISOPR.

KEY WORDS: synchrotron X-ray imaging, operando, multi-LPBF, machine design, materials science

DEVELOPMENT OF ADVANCED REPAIR DESIGN CONCEPTS FOR TURBINE COMPONENTS

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ABSTRACT

In recent decades, the development of industrial gas turbines has dictated a continuous increase of the turbine inlet temperature (TIT) target, in order to increase operational efficiency and GT performance, whilst keeping up with energy market demand for increased reliability and flexibility during the service.
In this scenario, the development of maintenance programs and repair technologies aimed at extending the life of the hot gas path turbine components as much as possible. The concept of advanced repair design will drive in next future scrap rates and maintenance costs reduction in order to be competitive on the market. During operation, high performance turbine blades and vanes undergo oxidation and deterioration due to the high operating temperatures of the gas at the surface, causing hot corrosion and thermomechanical fatigue. In many instances, an oxidation resistant weld alloy concept is used for repair, providing superior oxidation resistance compared to the original blade alloy.
This has led several OEM companies on a continuous expansion of their material portfolio for HGP repair applications and development of advanced customized alloy powders with enhanced mechanical and physical properties.
The focus of this study is the development of a novel alloy, which has been specifically designed for easy processing through powder Laser Metal Deposition (p-LMD), demonstrating improved mechanical/creep/oxidation resistance compared to the reference alloy (IN625). Improved properties of alloy powders are necessary to facilitate the extension of the repairable area of turbine blades and vanes. This is essential for achieving the increasing market requirements of enhanced

flexibility in gas turbine operation service and ensuring higher repair quality of reconditioned parts. More specifically, the previous year's repair experience showed a consistent increment in typical thermomechanical fatigue (TMF) damages in the hottest areas (>900°C), namely blade airfoil tip and platform. High oxidation resistance of the new Ansaldo alloy powder allows to increase the restoring area in most critical zones of hot gas path component, hence reducing the risk of part failure during second or third operating interval.
To achieve the target properties, a semi-empirical approach was considered. The alloy design was based on the thermodynamic and kinetic modeling to predict the solidification behavior, the phase transformation and the evolution of thermophysical properties. The mechanical and creep behavior was evaluated by means of physical models, considering the effect of different microstructural features. As a result, powders with variable composition of the newly developed alloy were fabricated at the CSM-Rina pilot plant and processed by p-LMD at the Mechanical Engineering Department of the Politecnico di Milano. The novel alloy was characterized in-depth, in terms of microstructural, mechanical, creep and oxidation resistance properties. The main results of this work are presented and discussed addressing laser processing capability, mechanical performance, and oxidation resistance of the newly developed Ansaldo alloy.

KEY WORDS: Alloy design of AM-produced alloys, advances of material performances, repairing of gas turbine parts.

REACTIVE SYNTHESIS OF CARBIDE REINFORCED ALUMINUM COMPOSITES IN AN ADDITIVE MANUFACTURING PROCESS

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ABSTRACT

Al/SiC composites have been used for many years in the automotive and aeronautical industries, with the aim of improving parts mechanical properties. More recently, the development of additive manufacturing processes such as Laser Powder Bed Fusion (L-PBF) has offered the possibility for the fabrication of parts with complex geometries on high-performance materials. Nevertheless, the implementation of the process requires a reexamination of the manufacturing method of the composite materials developed up to now by casting. Indeed, the maximum temperatures reached in L-PBF are much higher, which point to a technical issue in the elaboration of Al/SiC composites by L-PBF: the instability of SiC in liquid aluminum, from 940K, leading to the formation of a brittle and water-soluble carbide phase deteriorating the mechanical properties and the parts lifetime.

In this context, this work focuses on in-situ formation of another carbide by adding nano-sized zirconia powder to an $AlSi_7Mg_{0.6}$/SiC nanocomposite powder formulation with the objective of preventing Al_4C_3 formation. After elaboration of bulk composites in a standard L-PBF equipment, the parts are thoroughly characterized, especially in terms of phase content and microstructure, using X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). One important result is the drastic decrease in Al_4C_3 precipitation, and conversely by the in-situ formation of ZrC. Another major result is the significant change in the composite microstructure, shown in Figure 1. Adding zirconia in the initial powder allows to obtain a fully equiaxed microstructure with a high density of submicronic Zr rich precipitates after printing, instead of the columnar-equiaxed duplex microstructure observed in Al/SiC nanocomposites. Although the precipitates of Al_3Zr are well-known to be excellent nucleating agents in aluminum alloys, our work points to an alternative aluminium silicide nucleating agent, likely due to the high silicon content in the matrix.

KEY WORDS: in-situ reaction, equiaxed microstructure, nucleating agent

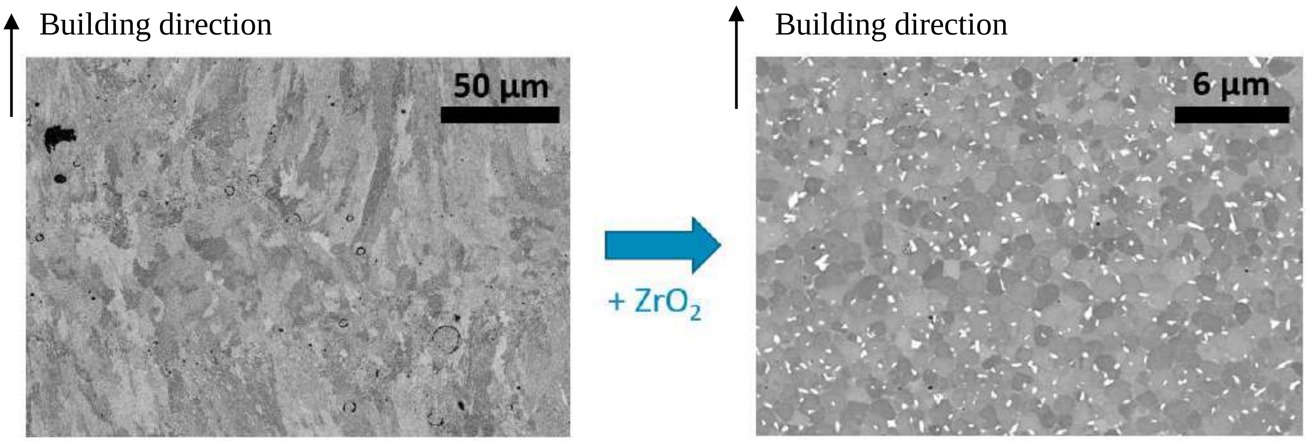

Figure 1: SEM image of Al-SiC composite duplex microstructure (left) and Al-SiC-ZrO_2 composite equiaxed microstructure (right)

An integrated computational-experimental approach for fast developing bespoke high-strength Al alloys for Laser Powder Bed Fusion

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ABSTRACT

The conventional metal alloys utilised for cast and wrought processes have not taken full advantage of the extraordinary benefits brought by Laser Powder Bed Fusion (PBF-LB) [1]. This raised the awareness among industries that extending the current alloy portfolio is a top priority for boosting the Additive Manufacturing (AM) business in demanding industrial sectors [2]. Parts with enhanced strength, good electrical and thermal resistance, and low density are often targeted for these critical applications. Therefore, driven by these motivations, a novel Al alloy grade incorporating a transition metal (TM) and nano-particles (NP) is proposed and validated in this study.

An industrially relevant commercial Al alloy system was identified at the alloy design stage. A suitable TM element that gives simultaneous reinforcement via solid solution and precipitation hardening was selected to further strengthen the standard alloy. The main target was defining a suitable amount of such strengthening element, granting enhanced mechanical performance without compromising the AM processability of the standard alloy. Therefore, the effect of the TM's progressive addition to the Al-based alloy was then predicted and assessed using an integrated computational-experimental approach.

Equilibrium calculations using the CALPHAD approach revealed the formation of new metallurgical phases containing the additional TM element. Furthermore, the solidification trajectories of various TM-dosed Al grades were assessed for conditions deviating from the equilibrium to predict precipitation sequence and cracking sensitivities during the rapid solidification in PBF-LB. To that end, a thermodynamic database for Al alloys (TCAL6 [3]) was systematically consulted in Thermo-Calc (TC) [4] using the Scheil-Gulliver assumptions with and without 'solute trapping' to investigate the effects of various solidification rates. The mass fraction of metallurgical phases formed during solidification was computed, as well as the tendency of each Al-*x*TM grade to supersaturation.

The computational results were experimentally verified with targeted experiments that involved the production of arc melted buttons of selected Al-*x*TM compositions to generate the corresponding master alloys. The surface of these specimens was subsequently laser melted to simulate the microstructure after the fast-cooling rates in PBF-LB. Preliminary microstructural analyses

involving X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) coupled with elemental mapping were conducted. Results showed a satisfactory level of correlation with TC-predictions, and the final TM amount was eventually established based on considerations involving strengthening mechanisms, crack sensitivity, PBF-LB processability, and heat-treatment design strategies.

The selected Al-*x*TM alloy composition was then manufactured via *in-situ* alloying in laser powder bed fusion after optimising the process parameters. At this stage, ceramic nano-particles were incorporated in the newly developed metal matrix to further enhance static strength and thermal stability. The processing-microstructure-performance relationships of the Al-xTM alloy with and without NP additions was extensively characterised to validate TC-calculations.

The outcomes of this research demonstrated that novel high-strength Al alloy compositions can be established by investigating the unexplored design spaces enabled by the additive manufacturing techniques. The computational-experimental method utilised in this study provided an accelerated, efficient, and robust guidance towards the fast development of printable high-strength Al alloys for demanding industrial applications. thus,study shows that the newly designed alloy overpasses significantly the mechanical performance of the corresponding industrially relevant Al alloy grade, thus validating the efficiency of the followed approach.

KEY WORDS: Laser Powder Bed Fusion; Aluminium Alloys; Alloy Design; CALPHAD; Hot cracking: Rapid Solidification; In-situ alloying.

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Phases evolution in additive manufactured TRIP custom 17-4PH alloy: opportunities for energy absorption applications

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ABSTRACT

Laser Powder Bed Fusion (L-PBF) is an additive manufacturing (AM) technology that uses lasers to melt metal powders to generate components. The recent technological development of L-PBF allows to create complex shapes and tailor the resulting microstructures so that extraordinary mechanical properties can be reached. This opens up to a new and disruptive way of thinking and designing components compared to traditionally manufactured techniques, when the aim is to provide high strength behaviour upon deformation [1]. However, the link between the process parameters imparted by lasers and the resulting microstructure is still not fully investigated. The involved cooling rates are characterised by rapid solidification which produces fine microstructure. In addition, specific process parameters are thought to induce heat treatments thus resulting in precipitates which can help hinder the movement of dislocations upon deformation [2].
In this presentation, the focus is on the control of process parameters in SLM used to produce components with a custom 17-4PH stainless steel alloy, the consequent microstructure and phases content, and the evolution of retained austenite upon elastic and plastic regimes during mechanical testing. X-ray diffraction experiment with in-situ tensile loading have been carried out for the purpose of the research at Diamond Light Source, Oxford (Figure 1). In addition, the grain structure, precipitates and solidification structures were characterised by a combination of high-resolution SEM and EBDS. The findings exhibit different mechanical properties due to different content of retained austenite depending on the laser parameters tuning, whose evolution upon deformation to transform into martensite depends on the deformation regime, elastic or plastic. These results can be used to design car protection structures which require high strength upon deformation, thus serving to the goal of energy absorption. The research also presents mechanisms associated to the recovery of austenite upon deformation cycles and offers new insights to understand the complex evolution of the microstructure during L-PBF.

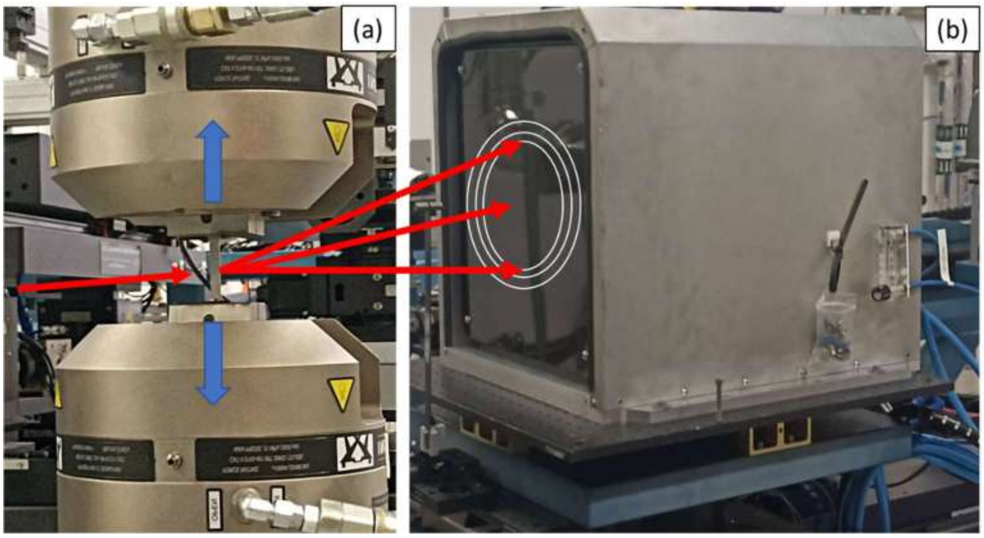

Figure 1. Experimental setup of the experiment performed at the Diamond I12 beamline: (a) incident high energy source (left red arrow) on the tensile loaded specimen (blue arrows); (b) Pilatus 2M detector with sample diffraction patterns.

KEY WORDS: SLM of 17-4PH, Microstructural control, Strain hardening, Phase transformations

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DYNAMIC MECHANICAL ANALYSIS OF THE 3D PRINTED POLYLACTIC ACID PARTS: EXPERIMENTS AND SIMULATIONS

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Thisresearch presented thermomechanical tests aimed to predict the behavior of shape memory polymer (SMP) in particular in range of glass transition temperature. In addition to evaluating the differential scanning calorimetry (DSC) and thermomechanical analysis (TMA), dynamic mechanical analysis (DMA) have been investigated. It was determined that the hyperelastic Mooney-Rivlin model with 5 parameters was adopted to predict mechanical behavior in a tensile test.
For the first time for this material and method of 3D printing, TMA experiment allowed us to evaluate the features of the thermal deformation of the sample, to obtain the values of the coefficient of thermal expansion at different temperatures, directions and running curves. From cooling run curve: at glassy state has CTE equal to 75.97 ppm/K and above Tg CTE are from 251.72 ppm/K to 269.93 ppm/K. Second heating run curve in the glassy state has CTE about 74.36 ppm/K for normal direction, 69.9 ppm/K for across direction and 71.37 ppm/K for along direction. Above the glass transition temperature, CTE shows 276.53 ppm/K for normal direction, 205.8 ppm/K for both along and across direction.
Experimentally obtained thermal expansion coefficients were subsequently used in the material description block for DMA simulation in ANSYS. Based on the results of the DSC experiment, we were convinced of the amorphous structure of the sample, determined the glass transition temperature as the SMP switching point. Due to PLA has viscoelastic properties and can deform cyclically under dynamic loading conditions in real applications, a dynamic mechanical analysis was performed at various temperatures to describe the dynamic mechanical properties of PLA materials printed with material extrusion (MEX) method of additive manufacturing. DMA tests revealed no significant difference between specimens with different printing regimes.
In the present research, the FE technique was used to simulate the dynamic response of a sample in a temperature regime. The implemented technique is based on the viscoelastic characteristics of the material, which are obtained by fitting the experimental curve to the Prony series, as well as using the time-temperature superposition method. The parameters of the viscoelasticity of the measurements were included in ANSYS to determine the properties of the material. As a test of the proposed technique, the curves of the experiment and simulation were compared. Values of the storage modulus in the range of glass transition temperature vary the results showed a similar nature of the curves. Taken together, these findings demonstrate that the simulation fits the experiments relatively well.

Keywords: shape memory polymer (SMP), material extrusion (MEX), viscoelasticity, thermomechanical testing, biodegradable polylactic acid, 4D printing.

EFFECT OF TOPOLOGY ON DYNAMIC STRAIN AGING OF ADDITIVELY MANUFACTURED INCONEL718 LATTICES

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ABSTRACT

The present study explores the effect of lattice topology on the mechanical properties and, in particular, on the occurrence of dynamic strain aging (DSA) in selective laser melted (SLM) Inconel718 strut-based lattices. Two architectures, namely BCC and FCCXYZ, were selected because of their soft and hard nature, respectively [1,2]. Additionally, a hybrid lattice with a 1:1 ratio of the two former topologies was considered. Tensile coupons with a gage length of the same dimensions as the lattice struts were also manufactured in order to investigate the mechanical behavior of the additively manufactured material. Lattices with the three topologies under investigation and single-strut specimens were heat treated well above the solutionizing temperature [3] for 1 h followed by water quenching to generate a coarse microstructure and to retain all the elements inside the γ phase as a supersaturated solid solution. The microstructure and texture of the as-built and heat-treated samples were examined at different length scales using both electron backscattered diffraction (EBSD) in a field emission scanning electron microscope (FESEM) and transmission electron microscopy (TEM). The elemental distribution inside grains as well as at grain boundaries was mapped by energy dispersive X-ray spectroscopy (EDS). The heat-treated lattices and single-strut specimens were then tested using an initial strain rate of 10^{-3} s^{-1} at various temperatures (25°C, 300°C, 450°C, and 600°C). The occurrence of different types of serrations, indicative of DSA, was monitored at all the testing conditions and for all the topologies investigated. Strain rate jump tests were also carried out on all the heat-treated specimens at the same temperatures and at a wide range of strain rates in order to estimate the strain rate sensitivity. This study allowed to determine the effect of topology on the occurrence of DSA in additively manufactured Inconel718 lattices and to derive guidelines for the design of robust architected materials by selective laser melting.

KEY WORDS: Lattice, Dynamic strain aging, Inconel718 alloy, Additive manufacturing, Mechanical property.

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Multi-Material Additive Manufacturing of Copper-Steel with tailored interfaces using Laser Powder Bed Fusion

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ABSTRACT

Multi-material Additive Manufacturing allows the integration of multiple functionalities, related to a set of unique properties offered by the individual materials, within a single part. Copper and steel multi-material parts are interesting in many industries since they combine high thermal/electrical conductivity of copper and wear resistance with excellent mechanical properties of steels [1]. However, additive manufacturing of austenitic steel-copper multi-material structures by Laser Powder Bed Fusion (L-PBF) is challenging due to their thermal & physical property mismatch and chemical incompatibility (Fe-Cu), as well as the high reflectivity of copper at the infrared laser wavelength [2]. Directly combining CuCrZr and 316L using L-PBF results in the formation of cracks in the 316L region near the multi-material interface regardless of the material deposition sequence and laser energy density. Therefore, a compositional-compatible interlayer is introduced between CuCrZr and 316L steel during LPBF processing to reduce the thermal mismatch strain/stress between dissimilar materials. A critical thickness of the interlayer is determined to avoid liquid copper infiltration along the austenite steel grain boundaries and successfully eliminate crack formation. Moreover, the electrical/thermal properties and mechanical performance of the multi-material structures with tailored interfaces are optimized by post-process heat treatments. This work successfully applies an interlayer design approach enabling crack-free CuCrZr and 316L multi-material structures with good electrical/thermal conductivity and structural strength using laser-based additive manufacturing.

KEY WORDS: Multi-material additive manufacturing, Laser Powder Bed Fusion, Copper, Steel, Interface design.

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IN-SITU HOT ISOSTATIC PRESSING COMBINED WITH X-RAY IMAGING AND DIFFRACTION OF LASER POWDER BED FUSION TI-6AL-4V

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ABSTRACT

Hot Isostatic Pressing (HIP) is often introduced to tackle the porosity issue in additively manufactured (AM) materials. For instance, HIP post-processing is recommended to improve fatigue resistance of Laser powder bed fusion (PBF-LB) manufactured parts [1, 2]. Even though HIP cannot completely remove porosity, it significantly decreases the defect population and its average size below the critical threshold value leading to early crack initiation.

In the present study, in-situ investigation of HIP procedure of PBF-LB Ti-6Al-4V parts was carried out to gain further insights into the densification mechanism occurring during HIP. The in-situ observations at high pressure and high temperature are uniquely possible at the PSICHE beamline of the Soleil synchrotron (France), thanks to the Ultrafast Tomography on a Paris-Edinburgh Cell (UToPEC) and the combination of the fast phase-contrast tomography and energy-dispersive diffraction [3, 4]. A detailed methodology was developed to ensure that the correct pressure and temperature were maintained during the experiments.

The results allowed an estimation of the global dentification rate during HIP of PBF-LB Ti-Al-4V material, as well as a detailed quantitative characterization of the influence of pore size and shape on the densification process, thereby understanding the effectiveness of HIP process on different pore categories. After 20 mins, 75% of porosity can be considered as closed or has size below the resolution of the XCT reconstruction (see Figure 1). We also observed that the smallest defects showed higher densification rate, while the defect shape did not have significant effect on such rate. The current development of in-situ HIP experiment allows experimental quantification and validation of the simulation work. Ultimately it paves the road to tailoring the HIP procedure for different materials depending on the porosity and microstructure.

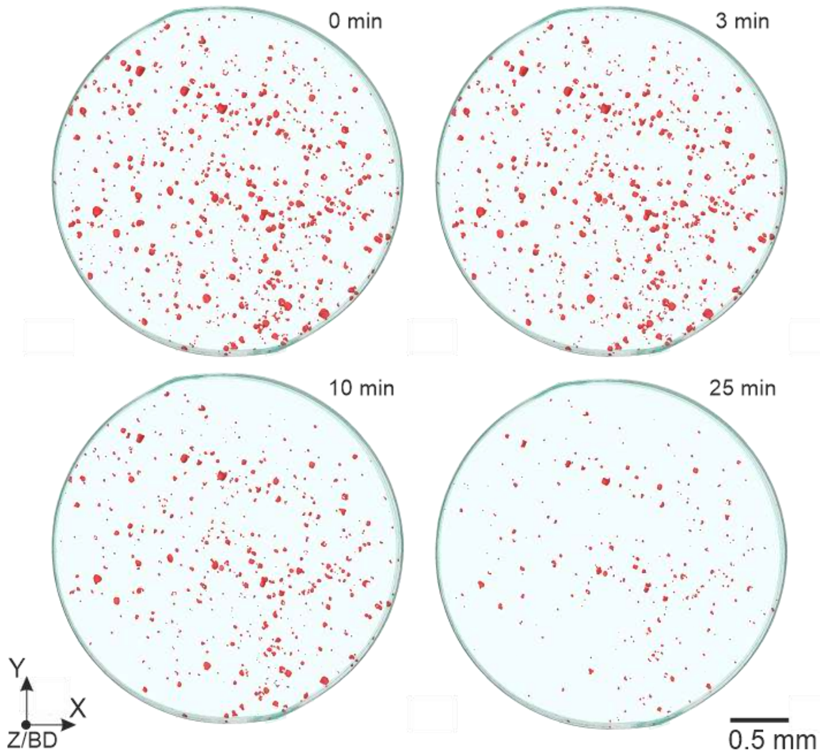

Figure 1. Projection of the porosity to build plane (XY) during HIP cycle.

KEY WORDS: laser powder bed fusion (PBF-LB), hot isostatic pressure (HIP), in-situ synchrotron X-ray computed tomography; energy dispersive diffraction; high-pressure cell.

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EFFECT OF LPBF PROCESS PARAMETERS ON THE NITI MATERIAL PROPERTIES: EXPERIMENTAL AND SIMULATION STUDY

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ABSTRACT

Among the shape memory alloys, NiTi is the most spread material due to the highest actuation energy density, biocompatibility, and corrosion resistance. However, despite the aforementioned advances, poor machining of the material prescribed to high ductility accompanied by a strongly pronounced strain hardening effect limiting the utilization of nitinol. In the last decade, Laser Powder Bed Fusion (LPBF) received increased attention and appears to be a promising manufacturing technology for intermetallic materials, including NiTi. Many efforts were made to achieve acceptable mechanical and functional properties. Furthermore, few studies have demonstrated the strong influence of LPBF process parameters on the resulting material properties, i.e. temperatures of martensitic phase transformation, reversible/irreversible strain after superelastic loop, phase composition, chemical composition, etc. However, the mechanisms of change remain unexplored at the present state of the art.

To reveal the influence of LPBF process parameters, NiTi alloy was characterized by different methods such as differential scanning calorimetry, X-ray diffraction, inductively coupled plasma mass spectrometry and mechanical tests of superelastic properties. To investigate the material properties dependece from the process conditions a numerical study was employed. The simulations were performed on KiSSAM software with high fidelity physical model based on a high-performance LBM hydrodynamic solver. The program code doesn't have any calibration and empirical parameters and takes into account all important physical effects in LPBF. For the validation of the model, own experimental data on the single tracks and single track-based thin walls was used [1,2]. Obtained results will shed light on the fundamentals of functional properties tuning by the local control of LPBF process parameters, which is considered a new concept of 4D printing.

KEY WORDS: shape memory alloy, superelastic nitinol, laser powder bed fusion (LPBF)

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EFFECTS OF PROCESS-INDUCED DEFECTS ON THE MECHANICAL PROPERTIES OF SCALMALLOY®

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ABSTRACT

Among aluminium alloys, Scalmalloy® has been designed for Additive Manufacturing (AM) Selective Laser Melting (SLM) technology, in order to provide a material uniquely light, yet ductile and resistant [1,2]. Due to its interest for the aeronautical industry, extensive research has been performed on the mechanical properties of SLM-fabricated Scalmalloy® in the last few years. The SLM process inducing inherently some defects, connections have been proposed between fracture mechanisms and main SLM defects in the literature [3]. However, very few studies have really focused on the impact of process-induced defects on mechanical properties and tackled their real harmfulness.

The present study gives insights into the negative impact of typical process-induced defects – namely, keyholes and lacks of fusion – on SLM-Scalmalloy® mechanical properties. The main long-term goal is to propose a new paradigm for aeronautical quality control, shifting from a "zero defect tolerance" policy, which is very costly, towards accepting unharmful defects, inherent to the process, and focusing on critical defects only. In this work, the effect of selected defect configurations (defect type & position) on tensile properties was investigated. Defects were introduced on purpose within different specimens during manufacturing. Such defects were characterized prior to tensile tests, via Computed Tomography (CT), to be related to the fractured surface characteristics. Tensile results were scrutinized and more specifically related to the different defects, to investigate critical configurations. This work strategy is illustrated in Figure 1. A particular attention was given to the identification of the main damage mechanisms, through Scanning Electron Microscope (SEM) fractography. A first attempt was carried out to compare the harmfulness of the controlled defects observed during tensile testing to dynamic tests, such as fatigue testing. This study comes along with a critical discussion of the possibility to reduce the number of test samples necessary to obtain statistically relevant data on AM samples containing defects.

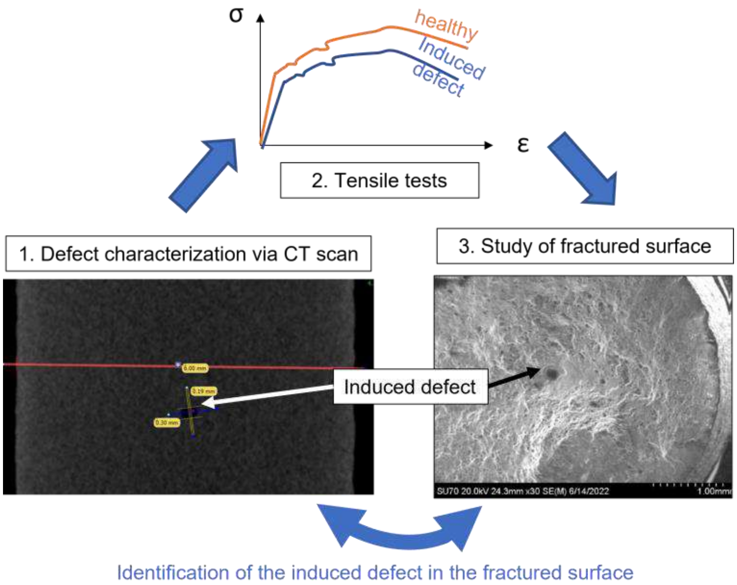

Figure 1. Main strategy of this study: correlation between mechanical properties, defect identification in pre-test CT scan and post-test fractured surface characteristics.

KEY WORDS: Additive Manufacturing, Scalmalloy ®, SLM, defects, mechanical properties.

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High-Speed Laser Cladding of $AlSi_7Mg_{0.6}$ reinforced with SiC and TiC.

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ABSTRACT

The brake disc industry needs light and high wear resistant materials. To answer this demand, industries are developing coatings made of metallic matrix composite (MMC's) of Al with TiC or SiC. These coatings can be deposited with High-Speed Laser Cladding (HSLC). HSLC[1] allows the metal particles to melt in flight by focusing the powder in the laser above the substrate, decreasing considerably the size of the melt pool. Additive manufacturing techniques such Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition (DED) have already been used to process aluminum alloys such as AA6061[2] and AlMgScZr-alloys[3]. Studies proved that these same alloys are subjected to porosity and hot cracking. Low porosity is required to ensure high mechanical properties. In addition, there are few studies of aluminum matrix compounds with particle reinforcement processed by HSLC. Zhao et al[3] showed that introducing 3 wt% of TiC nanoparticles in the matrix lead to lower porosity. However, no insight was given on the maximum content of TiC that can be added in the matrix or about the impact of the size of the particles. In this work, $AlSi_7Mg_{0.6}$ was studied for its better processability[4,5] as a potential solution for aluminum cladding using HSLC. The study was done by varying the amount of TiC and SiC (D50 of 87.7 µm & 72.5 µm respectively) and tuning the process parameters. The characterization focused on the porosity, hard phase distribution and crack formation. SiC and TiC present different behaviours within the matrix, highlighting the question of compatibility between matrix and hard phases in MMC's. Encouraging results were obtained with high hard phases content of SiC and TiC > 20 %vol. Both, TiC and SiC, showed good compatibility with the matrix in terms of bonding and process stability. Comparing conventional laser cladding with HSLC displayed the high potential of the latest advance coating methods and the necessity of pursuing further research on matrix and hard phase compatibility and on the development of HSLC tailored alloys.

KEY WORDS: Hard phases matrix compatibility, High-Speed Laser Cladding, aluminium casting alloy.

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Fabrication and characterization of a pre-industrial demonstrator for energy industry made by multi-materials WAAM for the European project Grade2XL

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ABSTRACT

The Wire Additive Arc Manufacturing (WAAM) process is an additive manufacturing technique well suited for the manufacture of metric-sized parts. WAAM is a technology of interest for many industries, including the energy industry. This communication presents the qualification process and characterization results of a hydraulic holding ring demonstrator, a safety part constituting the cut-off valves of hydraulic dams, made by WAAM. This study was carried out within the framework of the European project Grade2XL aiming at developing the multi-material WAAM additive manufacturing.
The demonstrator presented here is made of three different alloys: a low-alloy steel for the structural part, a stainless steel on the parts in contact with water for anti-corrosion properties, and a copper-aluminium alloy coating on a contact area with another part (anti-friction property). The manufacture of the demonstrator required to overcome several obstacles, such as the metallurgical and thermomechanical compatibility of the different grades, during manufacture and post-processing (especially heat treatment). After tests on small fabrications, a representative part of a fraction of the final demonstrator on a 1:1 scale could be produced and used to conduct various metallurgical, mechanical and corrosion resistance characterizations aimed at validating the WAAM process for the manufacture of the prototype intended to be implemented in the industrial layout.

KEY WORDS: multimaterial, WAAM, pre-industrial demonstrator, characterization

DESIGN DEPENDENT MECHANICAL PROPERTIES OF ADDITIVELY MANUFACTURED CELLULAR MATERIALS

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ABSTRACT

The advances in metallic additive manufacturing technologies such as Laser Powder Bed Fusion (LPBF) has enabled the creation of complex geometries with a high potential for material lightweighting. Within this set of additively manufactured structures, cellular materials — a subset of metamaterials— are commonly used. These constructions are made up of a number of basic struts connected by nodes producing a variety of geometrical patterns. The mechanical performance of the produced designs by additive manufacturing is not only derived from their structural arrangement, but also influenced by the printing geometry and orientation. These two variables affect strongly the thermo-mechanical processing history of the material and therefore in the microstructure and defect population. It is then clear that for achieving reliable and optimal cellular materials, this issue needs to be accounted in the design stage.

In this study, experimentation is combined with finite element modelling tools to extract the design dependences of the material properties in LPBF cellular structures. First, the mechanical properties of 3D printed Ti-6Al-4V struts with varying diameters and orientations were studied. With the support of computational material models, the study is scaled up to bulk lattice structures which were examined to understand the impact of the design variables on the overall lattice response and defect population. The analysis show and strong influence of the strut orientation and size on the bulk material performance of Ti-6Al-4V and how this local variance in the material properties is transferred to the overall macro-response of the cellular material. The findings highlight the significance of taking into consideration the unique properties of the unit lattice cell shape when developing a component for 3D printed metamaterials.

KEY WORDS: Cellular materials, additive manufacturing and mechanical testing.

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A MATERIAL AGNOSTIC DEEP LEARNING OPTIMISATION FRAMEWORK FOR LASER POWDER BED FUSION ADDITIVE MANUFACTURING

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ABSTRACT

Determining the optimal processing window for printing alloys using laser powder bed fusion additive manufacturing is an expensive and time-consuming process. Typically, it involves printing 3D test samples across the parameter range of interest, followed by metallurgical analysis to determine the optimal parameter set. For commonly used alloys, such as Ti-6Al-4V, these parameter sets are well known already, and a new laboratory or manufacturing centre needs little to no time to refine these settings to their specific equipment. However, this process becomes complicated when it comes to novel materials, since this entire parameter set development must be repeated from scratch, potentially requiring a large quantity of expensive powder material.

This work proposes a method to address these challenges using an unsupervised convolutional neural network using the Invariant Information Clustering [1] loss function to automatically generate the process map for an alloy based on powder-free single-track experiments. These experiments take a fraction of the time to run compared with printing full 3D samples, remove the necessity of powder material, while also significantly reducing the risk of damage to the printing hardware. The model is trained on a variety of alloy systems, those commonly seen within the additive manufacturing industry as well as some less common alloys to increase the diversity of the dataset. The model not only generates an accurate process map for the training materials, but it is demonstrated that the neural network is able to operate effectively on materials beyond of the training set, proving the versatility of the method.

Overall, the proposed model can quickly identify the processing maps of various alloys, while extending the learned features to unseen materials.

KEY WORDS: Laser Powder Bed Fusion, Process Optimisation, Neural Networks, Unsupervised Clustering.

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Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

CONTINUOUS DIRECTIONAL SOLIDIFICATION OF ALUMINIUM ALLOYS UNDER COMBINED ELECTROMAGNETIC INTERACTION

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ABSTRACT

This paper describes methods and results of experiments with electromagnetic (EM) interaction in direct chill casting of silicon rich aluminium alloys like A356 and A360. In this work directional solidification of aluminium rods with diameter of 10 to 20 mm under various EM interactions is studied. Developed EM interaction creates tiny molten metal flows directly in mushy zone which than influences heat transfer and affects grain structure and properties of alloy.

KEY WORDS: Aluminium alloy, direct chill directional solidification, magnetohydrodynamics, electromagnetic.

INTRODUCTION

Direct chill directional solidification is a method how to cast metal alloys with great control of solidification parameters like solidification velocity and temperature gradient at the solidification interface. EM interaction on metal solidification has been studied by several authors and it has been shown that various combinations of magnetic fields have significant influence on grain structure in directionally solidified ingot [1,2]. Directionally solidified rods have anisotropic microstructure [3]. Properties like malleability and tensile strength are affected by the microstructure.

Firstly, authors study applied static EM field and current flow (both AC and DC) through solidification interface. Secondly, combined static magnetic field with induced short but strong current pulses in mushy zone creating magnetic fields up to 0.5T. This creates pressure waves which also enhances the small-scale flows in mushy zone.

RESULTS

We have created experimental setup (cross section in figure 1. with explanations) which is constantly evolving to test different EM interactions. Temperature gradient here is 10K/mm which gives mushy zone thickness of 0.4mm. Static field is created by an array of permanent magnets in ring formation where field value in the centre and pointed axially is 0.4T. The direct current is of order 1 A/mm2 introduced with immersed electrode into molten aluminium through solidification interface to seed rod. Current pulses are introduced with single turn coil around crystallization channel.

By studying microstructure, we observed that EM interference can influence grain size and shape. Columnar structure of dendrites disappears, and grains are finer when magnetic field and current are introduced.

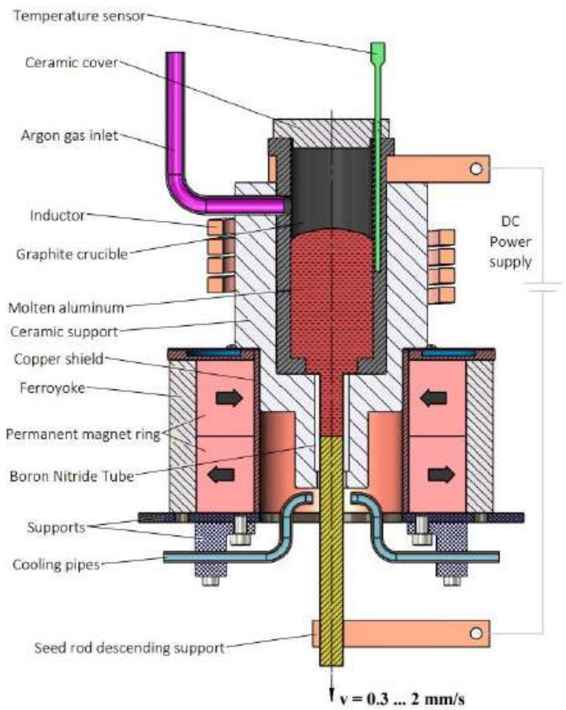
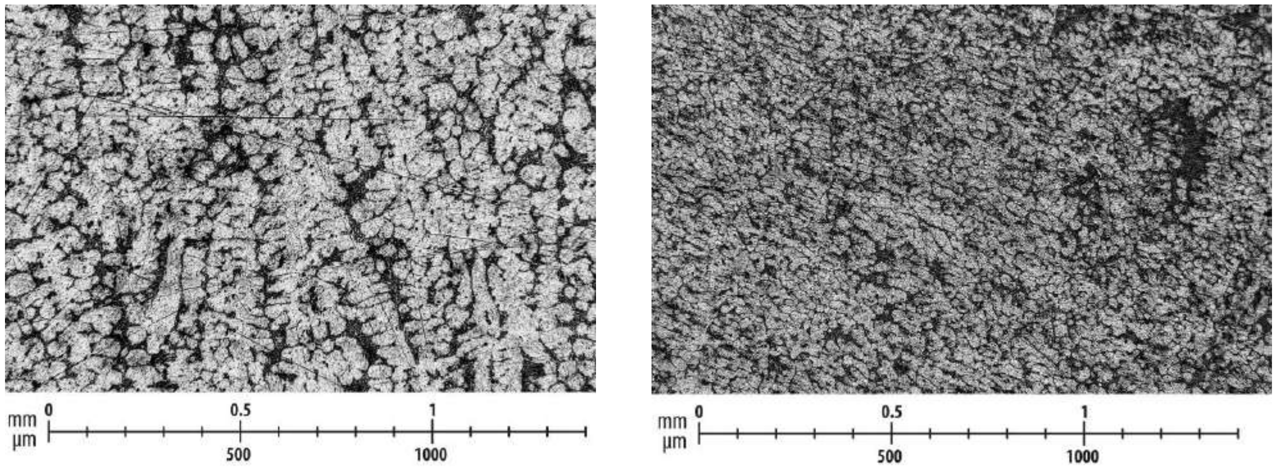


Fig.1 Cross Section of experimental setup

There are images of microstructure of A356 alloy continuously casted in figure 2.(a) and (b). Clearly can be observed columnar to equiaxed transition and refined grains.



(a) (b)

Fig.2 (a) Microstructure of reference sample; (b) Microstructure of EM interaction sample

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Die steel-based powder for 3D-printing large products DAP™-AM LTX

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ABSTRACT

In order to improve the cooling efficiency of die-casting molds and plastic injection molds, the technology development of additive manufacturing, in which water-cooling holes can be arranged three-dimensionally, has been progressing[1]. H13 powder has been conventionally used for 3D-printing of molds, but H13 is subject to frequent cracking due to thermal stress during 3D-printing. For this reason, maraging steel powder has been used for 3D-printing of molds. However, maraging steel contain cobalt, which can be harmful to the human body. Therefore, there has been a need for a cobalt-free powder that can make large-sized molds.

The developed metal powder DAP™-AM LTX enables additive manufacturing of large die-casting molds without cracking by optimizing the composition of H13.

KEY WORDS: Additive manufacturing, Aluminum die-casting molds, Plastic injection molds, Martensitic transformation,

Crack suppression mechanism of DAP™-AM LTX during 3D-printing

The typical composition of DAP™-AM LTX is shown in Table 1. DAP™-AM LTX does not contain cobalt. The addition of nickel and adjusting other chemical composition can reduce the strain generated in the 3D-printing products.

Fig.1 shows how DAP™-AM LTX suppresses the strain which occurs cracking during cooling process of 3D-printing. In the case of H13 powder, martensitic transformation occurs between 300°C and 400°C during 3D-printing. Therefore, H13 is subjected to warping force due to internal stress. The strain generated at this time makes it easy to crack if the hardness of 3D-printing product gets to be higher due to martensitic transformation. On the other hand, DAP™-AM LTX is designed to have the Ms point of approximately 200°C, which is lower than that of H13, by adjusting its chemical composition. As a result, DAP™-AM LTX can remain austenite, and it gets to be flexible enough to absorb the strain during 3D-printing. After mitigating strain, martensitic transformation of DAP™-AM LTX starts and hardening starts. Fig. 2 shows an example of a simulated molding of DAP™-AM LTX. In recent years, there has been an increasing need for larger die casting molds made by additive manufacturing. No cracking was observed on the surface of large-sized samples (over 150×150 mm) made from DAP™-AM by 3D-printing.

Table1 Typical chemical composition of DAP™-AM LTX.

Fe	C	Si	Ni	Cr	Mo	V
Bal.	0.25	0.1	6	5.2	1.2	0.4

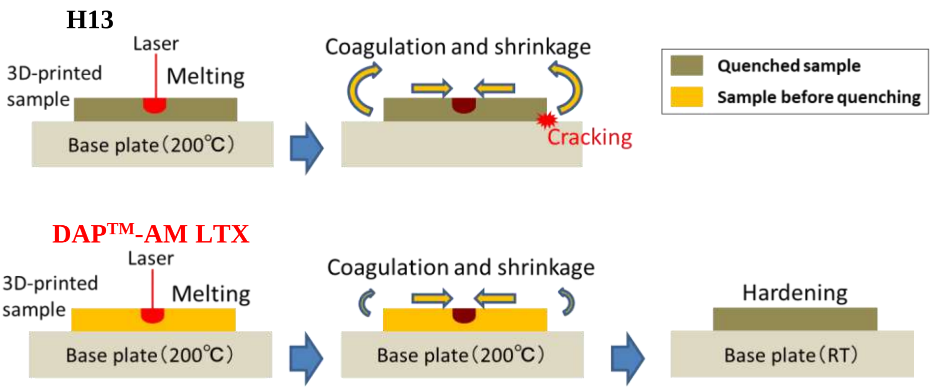

Fig.1 Schematic illustration of strain improvement mechanism of DAP™-AM LTX.

Fig.2 3D-printed sample of DAP™-AM LTX.

Mechanical Properties of DAP™-AM LTX

Fig.3 shows the relationship between tempering temperature and hardness of DAP™-AM LTX in comparison with wrought H13. As-3D printed hardness of DAP™-AM LTX is approximately 50HRC. Subsequent tempering increases the hardness, and it culminates to 52HRC at 550℃. Fig.4 shows the tensile properties of DAP™-AM LTX. 0.2% proof stress and tensile strength of DAP™-AM LTX are almost equal to those of H13. On the other hand, Charpy impact value is higher than that of H13 of the same hardness.

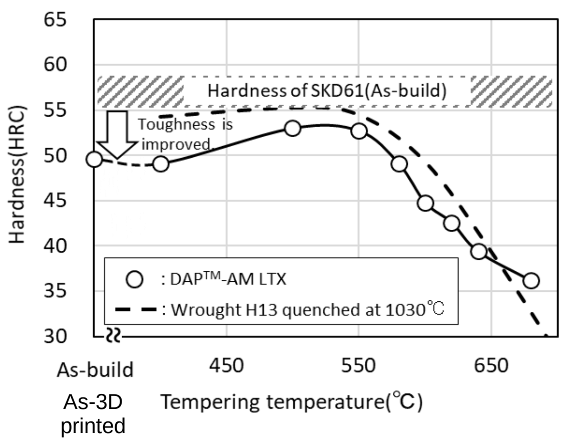

Fig.3 relationship between tempering temperature and hardness of DAP™-AM LTX.

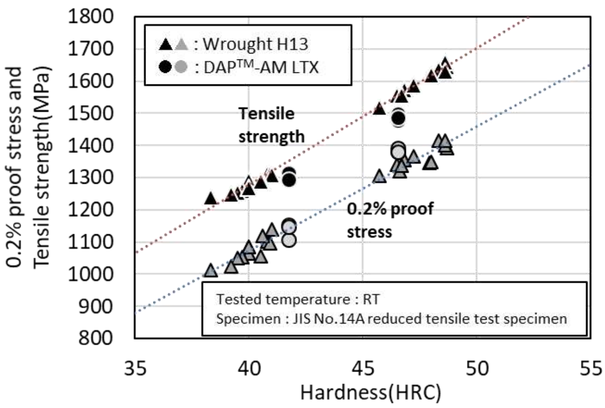

Fig.4 Tensile properties of DAP™-AM LTX.

Conclusions

DAP™-AM LTX does not contain cobalt as the specified chemical substance, and is designed to have lower martensitic transformation temperature than that of H13. It can control strain and suppress cracking during cooling process of 3D-printing. Consequently, it is possible to make large-size molds without cracking. In addition, the die made from DAP™-AM LTX can provide better performance than that made from wrought H13 steel. Therefore, it is expected to be widely applied as die-casting molds and plastic injection molds.

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Additive manufacturing of large surface area lattices as a basis for noble metal-free high entropy alloy electrocatalysts

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ABSTRACT

The energy transition from fossil-based to zero-carbon energy sources and the decarbonization of industrial processes require cost-effective and efficient solutions for the large-scale production of green hydrogen. Additive manufacturing opens up new possibilities, especially in part design and layout, such as freely designable and complex porous structures and lattices with a large surface area. Since the activity of a catalyst depends significantly on its specific surface area and pore size, shape, and number, lattices offer a great potential for catalyst applications both as a substrate for catalyst deposition and as an electrode itself. Materials currently used in electrocatalysis are often made of rare and expensive noble metals, which makes these processes unprofitable on a large scale and makes the development of new catalysts or electrode architectures inevitable. Alternatively, high entropy alloys provide a new research space for noble metal-free or lean electrocatalysts. This is due to the possibility of solid solution high entropy alloys with five or more principal elements to provide a multitude of different active sites (also active sites not available for single elements and their simple combinations) with individual elemental arrangements.

In this study, based on a powder feedstock characterization, lattice structures with different cell sizes are manufactured of NiCr19Fe19Nb5Mo3 (Inconel® Alloy 718) by powder bed fusion of metals using a laser beam (PBF-LB/M according to DIN EN ISO/ASTM 52900). High specific surface areas are achieved during the build process without post-processing by utilizing a lattice-optimized exposure strategy using a state-of-the-art continuous wave laser. The fabricated lattice structures are then tested as electrodes (anode and cathode) in a laboratory-scale water electrolyser to determine cell voltage and overpotentials for oxygen and hydrogen evolution reactions as a function of pore architecture. Next, structures with optimized pore design are used as a substrate material for depositing various high entropy catalysts starting with a well-known model material system – Cantor alloy. Catalyst modified electrodes are prepared using a polymer/metal precursor spraying synthesis. Electrochemical measurements are then repeated to investigate the activity of electrodes produced in this way.

KEYWORDS: Additive Manufacturing, Powder Bed Fusion of Metals using a Laser Beam, Lattice, High Entropy Alloys, Electrocatalysis, Oxygen Evolution Reaction, Hydrogen Evolution Reaction, Cantor Alloy

IN-SITU NEUTRON STUDIES ON LASER POWDER BED FUSION OF METALS AND ALLOYS

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ABSTRACT

Laser powder bed fusion (LPBF) is one of the most widely-used additive manufacturing (AM) methods. During the building of the components layer by layer, the spatially varied thermal cycles that the material undergoes result in the formation of thermal expansion mismatches causing residual strains (RS), defects and alternations in the microstructures. The understanding of how a material reacts to the complex thermal history in the LPBF process holds the key to controlling the microstructure and RS. Therefore, there is a strong drive for operando monitoring of the laser-material interactions and the associated microstructure changes, e.g. defects formation, phase transformations and crystallographic textures. Very recently, studies exploited high-speed X-ray diffraction and imaging to monitor in real-time the topmost layer where the powder material comes in contact with the laser and forms a melt pool [1-8]. However, the preceding layers beneath the melt pool, which are still affected by the introduced heat, are yet unexplored in situ due to the limited penetration depth of X-rays. Neutrons, on the other hand, penetrate deep into many metals, up to a few cm, and hence enable further observations down to the heat-affected zone (HAZ).

To complement the available methods of real-time monitoring during LPBF, the first in-situ neutron measurement device (n-SLM) to be implemented at SINQ beamlines of the Paul Scherrer Institut (PSI) has been developed (**Fig. 1**). This novel device is designed to accommodate various modes of measurements with neutrons, i.e. diffraction and imaging, including Bragg edge imaging [9, 10] and polarization contrast imaging [11]. Neutron diffraction with the n-SLM aims for example to follow the effects of the inherent heat treatment, built plate preheating and/or laser reheating on the evolution of microstructure, defects and RS along the principal directions within a defined gauge volume in the bulk of the specimen. These effects can also be resolved spatially using full-field Bragg edge imaging, averaging the information through the thickness along the beam direction. Polarization contrast imaging, on the other hand, provides spatial analyses on phase transformations from non-magnetic powder material to magnetic phase fractions in the printed specimen with sufficiently high temporal resolution. Additionally, the imaging techniques can be coupled with computed tomography to resolve the phenomena in 3D. The n-SLM is also capable of accommodating auxiliary process monitoring methods, e.g. thermal cameras, thermocouples and Acoustic Emission (AE) sensors.

In this contribution, in-situ investigations in the context of RS and phase transformations using the n-SLM device at SINQ, PSI, Switzerland will be presented. The talk will focus on technical aspects of the n-SLM and the applied methods for the wider user community as well as results from specific investigations on non-weldable alloys and multi-materials.

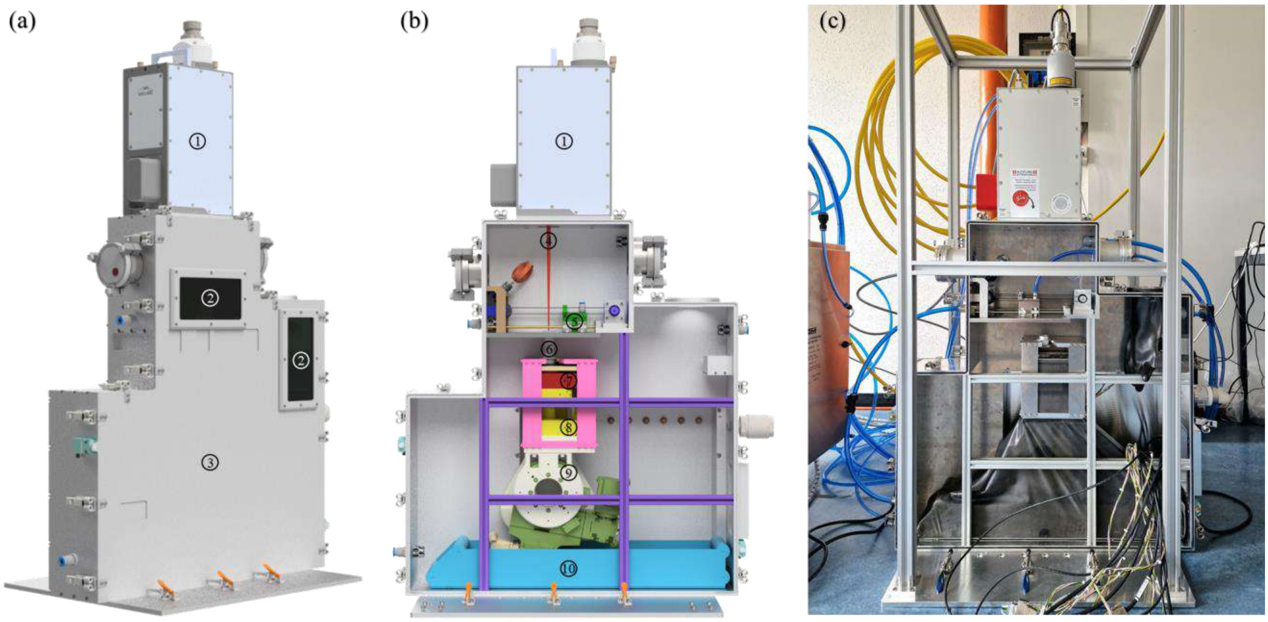

Fig 1. (a), (b) Rendered 3D models of the front view and open chamber of the n-SLM device, respectively, and (c) picture of the developed n-SLM device: 1) 3-axis scanning unit; 2) observation windows; 3) chamber door; 4) laser beam; 5) powder deposition system; 6) build plate holder; 7) rotation stage; 8) Z-stage; 9) goniometer stage and 10) linear translation stage.

KEYWORDS: laser powder bed fusion, real-time monitoring, neutron characterization methods, non-destructive measurements.

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On the influence of design on the fatigue performance of additively manufactured structured materials

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ABSTRACT

Additive manufactured has enabled a new range of architected metallic metamaterials with intricate geometries that has the potential to greatly expand the range of properties achievable compared to bulk alloys. This type of structured materials is called to boost the performance of biomedical, aerospace and automotive components with increased lightness, new functionalities or superior specific mechanical properties.

However, the high surface-to-volume ratio of these architected materials due to their intricate geometries combined with the surface characteristics inherited from the additive manufacturing process can result in complex fatigue behavior, which is a significant concern for their use in technological applications [1,2].

To address this issue, this study employs a systematic multiscale approach to examine the interconnection between metamaterial design, microstructure, defects, and fatigue properties. The study uses commercially available aluminium and titanium alloys processed by selective laser melting. By combining experimental fatigue testing, computational modelling and defect quantification, the impact of processing conditions and design geometry on microstructural defects and surface quality is analysed and connected to the fatigue life of the metamaterials. The results show a strong influence of the local struts characteristic length and the distribution of local strut orientations on the macroscopic life of the metamaterial which shall be accounted for in the design stage.

KEY WORDS: fatigue, cellular materials, LPBF, metamaterials, defects.

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Effects of Deposited Bead Layers and Microstructure on Additive Manufacturing Process Conditions of Inconel718 Alloy

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ABSTRACT

As environmental regulations are strengthened worldwide and interest in eco-friendly technologies for waste reduction and resource recycling increases, the need for research on remanufacturing of mechanical parts using metal additive manufacturing processes in the manufacturing industry is increasing. The Directed Energy Deposition (DED) process can create desired metal shapes on irregular surfaces through line-by-line deposition. Recently, Inconel 718 alloy has been actively researched using dissimilar material bonding due to its excellent mechanical properties from cryogenic to high temperatures and excellent weldability. In this paper, experiments were conducted based on the experimental design method to optimize DED process using IN718 material. The ratio of the width to the depth of deposited beads was obtained through conditional experiments with laser power, powder feed rate, and scanning speed as parameters, and EBSD analysis was performed to find out the microstructure characteristics of the deposited parts. The grain size was compared according to the ratio of deposited bead layer, and a tensile test was additionally conducted to analyse the mechanical properties. As a result of comparing the S-S curve for each condition, it was confirmed that the specimen laminated with bead ratio of the densest condition with the average grain size of 92.36 μm had relatively excellent mechanical properties. It is expected to be used in the remanufacturing industry by applying the optimal conditions of DED process using IN718 alloy material.

KEY WORDS: Additive manufacturing, Direct energy deposition (DED), Remanufacturing, Inconel 718 Alloy, Microstructure characterization

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ABSTRACT

Titel: cradle2cradle: New products from waste. Why not recycle all metals?

Abstract:
Over the past decades Reco has constantly updated is capability to produce secondary raw materials. A wide variety of metals and alloys that were extracted from 'waste' is available for use in AM projects.

Customers have high demand for
- highly conductive (+125%) drive cables for electric vehicles
- and extremely lightweight housings for electric drives
- lithium, cobalt and nickel based alloys to build new batteries

All our powders available in 99,5-99,99998% purity and up to 20 nano fineness

KEY WORDS: Secondary raw materials for AM from 'waste'. Ultra fine and ultra clean. Low LCA (Life Cycle Assessment), low CO^2 footprint

REFERENCES

Mechanical and microstructural characterization of a bimetallic material additively manufactured by using Dual Wire® laser Directed Energy Deposition

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ABSTRACT

Traditional metallic additive manufacturing technologies such as Powder Bed Fusion and Directed Energy Deposition have been developed and optimised for the fabrication of components made out of one single material. However, the utilisation of such technologies for the development of multimaterial components has become quite interesting for a wide range of industries. Indeed, the combination of the ability to control the geometrical complexity and to produce multimaterial components shows an interesting challenge to overcome. Thus, the ability of joining dissimilar materials using additive manufacturing technologies is key on improving performance and extending durability of components.

Meltio has developed a dual wire-fed laser Directed Energy Deposition head system capable of producing components made from two different metallic materials in one single print. The dual wire-fed system allows for the creation of products with optimised material properties. As an example, a product could be printed with one material for toughness and another for hardness and corrosion resistance, resulting in a product that is both strong and durable yet plastically deformable enough to meet the needs of the end user.

To the best of the authors' knowledge, this is the first time, a dual wire-fed laser DED is employed for the manufacture of components made from SS 316L and Inconel 718 and to investigate the effect of the design of geometrical structure at the interface between both materials on the mechanical and properties.

The study presented here aims to evaluate the feasibility of joining Stainless Steel 316L with Inconel 718 by using a dual wire-fed laser DED system developed by Meltio and to examine correlation between the structural geometry at the interface between the two materials and the resulting mechanical properties. This study also investigates the effect of several heat treatments on the microstructure at the interface between the two materials and individually on both materials.

Dual wire-fed laser DED is used to produce the as-build coupons and tensile specimens with three different geometrical structures at the interface. The three geometrical structures to be investigated are simple flat, mushroom-like and pin-like. The microstructure at the interface between the two materials is characterised by using Optical Microscopy, Energy Dispersive X-ray Spectroscopy and Scanning Electron Microscopy. Mechanical strength is evaluated by performing tensile testing and hardness.

The results show no evidence of intermetallic compounds or precipitates at the interface between the two materials on the as-build specimens and an improvement on the mechanical strength of the specimens with a complex geometrical structure at the interface level.

KEY WORDS: **Bimetals, Mechanical joints, Interface Geometrical Structure, Multimaterial, Structural Control by Design, Dissimilar Materials, Dual Filament.**

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DESIGN, PROCESSING AND MECHANICAL PERFORMANCE OF ADDITIVELY MANUFACTURED ENERGY ABSORBING METAMATERIALS

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ABSTRACT

Additive manufacturing (AM) is creating significant interest around the world. The use of metal AM, such as titanium or aluminium alloys, combined with latticing is opening the door to novel metamaterial structures leading to a whole new range of lightweight functional components called to revolutionise the energy absorption efficiency for ballistic and shielding applications.
However, these new cellular structures present a wide variety of characteristic lengths (differing from conventional manufacturing) resulting in an unknown range of microstructures and material properties within the same component [1,2]. On top of that, the mechanical properties of these cellular structures under extreme dynamic conditions are still not completely understood due to a lack of systematic experimental data and mechanical understanding in the literature.

Current design tools in research and industry do not account for these heterogeneities which can lead to incorrect designs or even early failure of the component, thus vanishing the benefits of these AM metamaterials. In this work, this problematic will be addressed by a carefully designed systematic experimental campaign under extreme conditions to address the effect of lattice orientation, strut diameter and cell size. The work focuses on aerospace grade Ti6Al4V alloy and LPBF (Laser Powder Bed Fusion) as additive technology. First, different cellular structures with the same unit cell (Body Centered Cubic) are systematically printed varying independently the orientation of the struts, the diameter of the struts and the unit cell size. Second, the strut elementals in the different sample geometries are then analysed to extract the population of defects and changes in the microstructure as a function of the design variables. Finally, the samples are then mechanically tested under dynamic conditions using the split-Hopkinson bar technique. In all cases, the tests are filmed to analyse the local characteristics of the deformation process.

The results show a strong dependency on the orientation, size and unit cell geometry on the mechanical properties affected not only by the material-agnostic structural design but also by local changes in the mechanical properties of the struts such as defects or microstructure. This emphasises the importance of accounting for these material variabilities in the design stage of additively manufacturing impact absorbing metamaterials.

KEY WORDS: impact behaviour, Ti-6Al-4V, cellular materials, LPBF, dynamic properties, metamaterials.

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DEVELOPMENT OF HIGHLY-FILLED METAL POWDER FILAMENT FOR FUSED FILAMENT FABRICATION

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ABSTRACT

Fused Filament Fabrication (FFF) is a material extrusion additive manufacturing (MEAM) process that enables the production of functional prototypes and end-use parts with complex geometries.[1] In this work, a new highly-filled metal powder filament with an optimized binder composition for FFF technology have been designed and developed.

For this purpose, the rheological behaviour and printability of feedstocks (mixture of binder and metallic powder) with different compositions were studied. The binders are composed of three components which provide strength, fluidity and flexibility, necessary features for the final filament to have good quality and therefore, good printability. Two different thermoplastic elastomers have been tested. For the study of the different feedstocks with the two elastomeric components, the amount of metal powder was fixed at 50 vol.%. Once the rheological properties of the feedstocks were analysed, filaments were extruded from each of the feedstocks and printing tests were performed. The feedstocks based on one of thermoplastic elastomer was discarded due to its low printability and the investigation continued with another one, which showed very good printability.

Afterwards, the effect of increasing the volume loading of the metal powder was studied, in order to know the critical powder volume concentration (CPVC). For this purpose, the rheological properties of three feedstocks with loadings of 50, 55 and 60 vol.%, respectively, were studied. With the results obtained, the critical powder loading in the feedstock was set at 55 vol.% and from this, the final filament was extruded to perform the rest of the present work.

Printing parameters of the green parts were optimized on a desktop 3D-printing. The selected geometry was a toroid of 15 mm of external diameter, 10 mm of internal diameter and 5 mm of height. The binder was removed from the parts in two steps. A solvent debinding step in an organic solvent, where the mass loss of the soluble components was studied as a function of time (at 50°C and with magnetic stirring). The maximum mass loss reached was 92.7% at 3 h. The rest of the binder was removed in a thermal debinding step at the binder degradation temperature. Air carrier gas was used to generate an oxidative atmosphere that improved the removal of the carbon content.

Finally, the optimization of sintering process was carried out between 1300-1400ºC during 1 h. The sintering atmosphere selected was $Ar/5\%H_2$ to generate a reducing atmosphere to reduce the oxides generated during the previous processes. The density of the final parts, as well as cross-section analysis to check the porosity and microstructure and shrinkage of the parts obtained in each sintering steps were performed. In addition, LECO analysis to quantify the amount of carbon and oxygen in the final parts and microhardness was carried out. The maximum density achieved was 85.5% with a shrinkage of 23% of the part volume at 1375ºC, therefore, this sintering temperature was established as the optimum sintering temperature.

KEY WORDS: Fused Filament Fabrication (FFF), material extrusion additive manufacturing (MEAM), metal powder, highly-filled filament.

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LASER POWDER BED FUSION OF SOFT MAGNETIC BULK METALLIC GLASSES

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ABSTRACT

Fe-based soft magnetic bulk metallic glasses (BMGs) have shown unprecedented magnetization saturation and coercivity values and are thus envisioned as potential candidates to increase the efficiency of electromagnetic components [1]. Laser powder bed fusion (LBPF) allows to manufacture relatively large BMG parts while retaining an amorphous microstructure due to high local cooling rates. However, in practice, the thermal cycles generated in the layer-wise LBPF process tend to cause undesired crystallization [2]. To date, finding optimum LPBF processing conditions that yield, simultaneously, high densities and high fractions of the amorphous phase, that give rise to the required mechanical and magnetic performance, remains a challenge.

This work aims to provide a thorough study of the relationship between LPBF processing parameters such as the laser power, the scan speed, and the hatch distance, and the resulting (micro)structure and properties of a commercial Fe-based BMG alloy. The feedstock amorphous powder is processed using a pulsed-wave laser system for fine (micro)structure control. Oftentimes, the processing parameters that yield the densest prints also cause severe crystallization upon solidification. On the other hand, the parameters that allow the material to retain the amorphous microstructure tend to leave structural defects, mainly due to lack of fusion [3]. Therefore, a complex parameter optimization process was carried out to achieve the best compromise between a high degree of amorphous phase and a low number of defects. Complementary experimental techniques such as X-ray diffraction, calorimetry, image analysis, magnetic and micromechanical testing were used to characterize the (micro)structural and multi-scale properties evolution with respect to the processing parameters. This study defines guidelines for the successful additive manufacturing of Fe-based BMGs by pulsed laser powder bed fusion.

KEY WORDS: Bulk Metallic Glasses, Laser Powder Bed Fusion optimization, Relationship between LPBF parameters and microstructure, soft magnetic behavior and mechanical properties.

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Nitinol developments for laser powder bed fusion: towards materials with locally controlled properties

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ABSTRACT

Near equiatomic nickel titanium alloys present specific behaviours such as shape memory effect or pseudo-elasticity. These properties make them particularly interesting for aerospace and medical applications. However, manufacturing of NiTi parts presents some difficulties due to poor machinability: excessive tool wear, high cutting forces, surface degradation. Additive manufacturing of NiTi would allow to widen the manufacturable geometries and thus extend its use.

Laser powder bed fusion (LPBF) of NiTi is being more and more studied but presents some challenges [1]–[5]. Indeed, as the material is subjected to heating-melting-cooling-solidification repeated cycles, the microstructure, residual stress, chemical composition and phase transformation behaviour can be altered by the process. The austenite and martensite start and finish temperatures may then deviate drastically from those of the precursor material resulting in non-appropriate transformation temperatures regarding the intended application. This shift is linked to Ni vaporization during the process as it seems to increase with increasing energy input [6]. Controlling this shift is key in bringing LPBF of NiTi to the next step. It is hence important to understand the correlation between process parameters and transformation temperature shift for the entire process chain: from the original ingot to the powder to the end product. If the material's behaviour can be predicted, the adequate properties for the end product can be obtained.

In this study, the influence of process parameters on material properties was analysed. Parts were produced under different scanning conditions and substrate temperatures. Sample integrity was investigated using optical microscopy. Shape memory behaviour was studied using DSC analysis in order to determine phase transformation temperature as well as energy involved during transformation. This study highlighted the possibility to tune the shape memory behaviour by adjusting scanning parameters, leading to the possibility to obtain different mechanical behaviours from the same powder: superelastic, pseudo-elastic and shape memory. This opens up the possibility for manufacturing multi-properties or functionally graded NiTi components.

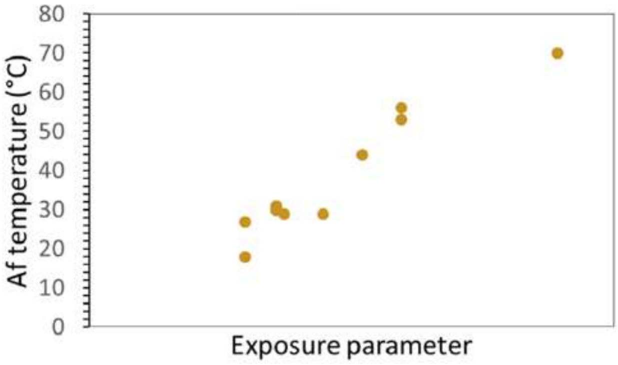

Figure 1: Correlation between Af temperature and exposure parameter

Moreover, the increase of substrate temperature (up to 400°C) lead to a reduction of cracking while preserving a low porosity rate. It was also shown that substrate temperature has a weak influence on transformation temperatures and energies comparing to conventionally used temperature.
These different results clearly attest to the interest of using a high temperature substrate to produced NiTi parts with a structural integrity and the possibility to control shape memory behaviour.

KEY WORDS: 4D printing, shape memory alloys, functionally graded materials, controlled properties.

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Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

OPTIMIZING LPBF PROCESSES FOR METAL LATTICE STRUCTURES USING SIMULATION AND DATA MANAGEMENT STRATEGIES

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ABSTRACT

Metal additive manufacturing (MAM) is a rapidly evolving field that has revolutionized the production of complex geometries with unprecedented design freedom. Lattice structures, in particular, have garnered significant interest due to their unique combination of high strength, low weight, and excellent energy absorption properties. However, the inherent complexity of MAM processes, such as Laser Powder Bed Fusion (LPBF), poses challenges for achieving optimal quality and performance of lattice structures. Porosity is a critical issue that can affect the mechanical properties of metal lattice structures manufactured by LPBF, and it is influenced by various process parameters such as laser power, scanning speed, and layer thickness. Therefore, there is a need for effective data management strategies that enable the collection, analysis, and utilization of data to optimize the processing parameters for improved quality control and performance of lattice structures.

In addition to effective data management, simulation has emerged as a critical tool for optimizing LPBF processes and ensuring the quality and performance of metal lattice structures. Simulation techniques can provide valuable insights into the microstructure and mechanical properties of lattice structures manufactured using different processing parameters. Furthermore, simulations can help predict the thermal residual stresses that arise during LPBF, which can cause distortion and affect the mechanical properties of the final product. Particularly, residual thermal stresses pose a significant risk in the production of lattice structures using LPBF, as these structures often feature intricate geometries with high surface area-to-volume ratios. Such geometries can result in significant thermal gradients and residual stresses, which can lead to deformation and cracking. Therefore, understanding the nature and magnitude of these thermal stresses is crucial to ensuring the quality and performance of the final product.

In this work, we will explore the potential of effective data management and simulation techniques in optimizing LPBF processes for metal lattice structures comprised IN625, Ti64, 316L and AlSi10Mg. Specifically, we will utilize experimental data to optimize the processing parameters and minimize the potential for porosity. Next, we will use simulation techniques to predict the microstructure (grain size distribution) and estimate the strength of the materials manufactured using these optimized processing parameters. Finally, we will simulate the thermal residual stresses that a lattice geometry would experience when manufactured by LPBF, using the optimized parameters. By combining experimental data and simulation techniques, we aim to enhance the quality and performance of metal lattice structures manufactured using LPBF, and to provide valuable insights into the behavior of these structures under thermal loads.

KEY WORDS: Lattices, LPBF, Data Management, Process-Property Relationships, Process Parameter Optimization, AM Simulation

LPBF manufacturing of Inconel 625 small struts with an open architecture instrumented set-up. Influence of build strategy and strut size on resulting microstructures.

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ABSTRACT

Laser powder bed fusion (L-PBF) has mostly achieved industrial maturity for building dense intermediate-sized parts (10 mm^3 to 40 cm^3). However, studies on smaller parts remain poorly documented, especially for struts with small diameters[1] (<2 mm) which are a basic component of any lattice structure.

The aim of this study is to understand the size-effects alongside the L-PBF process parameters on the microstructural properties of struts made of Inconel 625, with the use of a homemade open architecture L-PBF instrumented system.

The work evaluates possible correlations between process parameters (various scan strategies), strut's diameter (between 0.2 mm and 2 mm), melt-pool sizes (observed with in-situ high-speed imaging), local cooling rates (estimated with a simplified numerical modelling) and resulting microstructures.

Initial results suggest a strong link between the shape and size of melt zone and the morphological and crystallographic texture of objects, especially for small struts. Moreover, the model highlights a correlation between the cooling rates and the solidification cells size, particularly in relation to scan strategies and strut diameters.

These results provide a useful insight for optimizing the L-PBF process applied to structure lattices, and achieving desired properties in the final product. Altogether, the combined "instrumented LPBF / numerical modelling/ Post mortem analysis" approach offers a powerful tool for improving the quality and efficiency of L-PBF manufacturing applied to little objects.

KEY WORDS: L-PBF, instrumented system, Inconel 625, struts, size effect, scan strategy, microstructures, solidification cells, melt pools, modelling

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Comparative study of pulsed and cw laser powder bed fusion of $AlSi_{10}Mg$ alloy

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ABSTRACT

Up to now, few studies have considered the possible benefits of non continuous laser irradiations on the materials manufactured with laser powder bed fusion (L-PBF), even if some industrial tools offer the possibility to use specific discontinuous laser melting (Renishaw systems [1]). Recent experiments carried on Inconel718 [2] and AISI316L [3] indicate that pulsed wave emission improves geometrical accuracy because of a less extended and more stable melt-pool. Other investigations have shown that the cristallographic texture could be influenced by the emission mode [1].

Microstructural changes in pulsed mode built alloys may come from the different heat distribution compared with continuous regime during which the matter is exposed to the energy source uninterruptedly. Hence, thermal gradients between melt pool and solid matter are higher in pulsed wave regime and lead to higher cooling rates and thinner microstructures. As melt pools solidify between pulses, liquid movements are more stable and foster a good near net-shape design.

In this study, with the use of a small homemade instrumented set-up, we compare the L-PBF manufacturing of $AlSi_{10}Mg$ samples using either a continuous wave (cw) laser or a modulated pulsed wave (pw) laser with various frequencies (between 5 kHz and 20 kHz).

Small cubes and struts are built under neutral gas flow with both emission modes, but similar average energy conditions so as to underline the specific influence of temporal modulation on melt-pool dimensions or shapes, and post-mortem microstructures (crystallographic texture, solidification cells). A distinction is made between pw conditions generating discontinuous melt-pools (with inter-pulse solidification), and pw conditions inducing a quasi-continous fusion regime.

KEY WORDS: L-PBF, $AlSi_{10}Mg$ alloy, pulsed wave, microstructure.

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Nanocoated Copper Powder for Improved Offline and In-situ Absorption during Laser Power Bed Fusion

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ABSTRACT

Laser powder bed fusion (LPBF) fabrication of copper adds significant value to high-performance applications, particularly in cases where complex geometries and high conductivity are required, such as heat sinks or antennas [1]. However, the LPBF fabrication of copper is currently limited by the low near-infrared absorption and high thermal conductivity of copper, resulting in suboptimal quality of the formed parts. Modifying copper powders with higher absorption material is a practical and cost-efficient solution to compensate for the insufficient energy for melting, which offers great advantages over upgrading the equipment to higher power or short-wavelength laser equipment [2]. The ongoing research about modifying copper powder for LPBF primarily focuses on alloying or mixing with other additives to improve its density and resulting properties [3]. The impact of these modifications on the absorption and melt pool behaviours during the LPBF process is still not fully understood.

In this study, mussel-inspired nanocoating was applied to copper powders with the goal of improving their absorption through the creation of a uniform and full-coverage nanoscale layer. The effects of the nanocoating on the melt pool morphology and laser absorption were investigated. To accurately measure the offline absorption and in-situ absorption, a custom absorption system was developed for this study. The absorption results from both tests showed an increase in absorption rates after the nanocoating was applied to copper powders. These findings demonstrate the effectiveness of this nanocoating strategy for improved energy efficiency during the LPBF process; in other words, it can further enhance the productivity by increasing processing speed. Inert gas fusion and optical emission spectroscopy are used to measure the nanocoating-induced impurities and evaluate the coating constituents that have vaporised during the laser-material interaction. Therefore, this nanocoating strategy, which potentially provides a transient absorbent, holds promise for achieving a balance between improved energy absorption and minimal induced impurity.

This effective fabrication of copper also provides valuable insights for the LPBF fabrication of other highly reflective metals, such as silver or gold. The range of applicable materials for LPBF is expected to expand in the future, offering greater versatility and flexibility in the production of high-quality metal components.

KEY WORDS: Copper, powder coating, energy absorption, laser powder bed fusion.

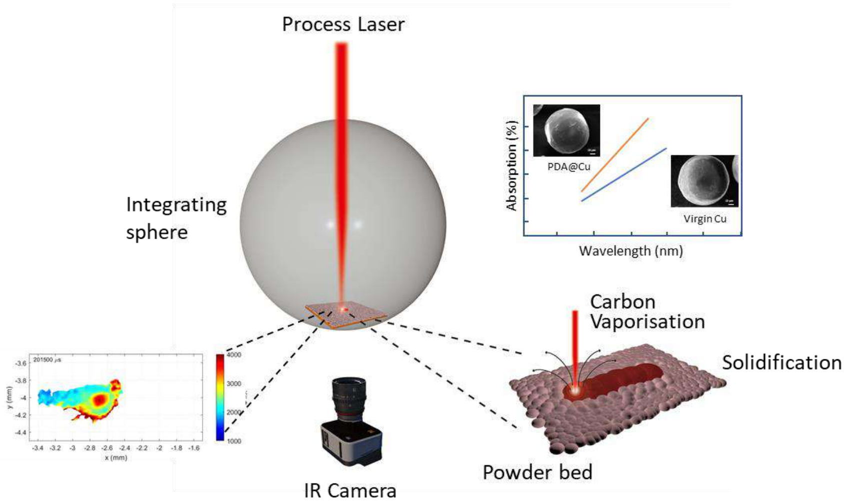

Figure 1. Schematic of the in-situ absorption measurement and transient absorbent provided by the nanocoating strategy.

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Influence of bias and ways forward for effective data-driven approaches for metal additive manufacturing

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ABSTRACT

Data analytics and machine learning (ML) have emerged as powerful tools capable of efficiently providing insights to the complex process for additive manufacturing (AM). Despite significant experimental efforts invested in the industry, extensive open access and quality datasets have been yet available for AM. However, vast amounts of experimental data representing the ground truth are hidden within data reported in literature. This study compiles over 2000 data entries reported from literature to evaluate and identify bias within reported data that may severely hinder the extraction of ground truth; and subsequently, an effective use of data-driven approaches for AM. The analysis reveals considerable biases in the collected data caused by some common practices of reporting data in literature. Multiple ML models were trained on the collected data to provide a basis for investigating the influence of the biases on the ML model performance. This study subsequently shows severely negative impacts of the biases. In addition, the currently excessive use of consolidation as the sole quality indicator exacerbate the negative impact. This presentation will also discuss ways to improve reporting practices and data quality, and propose to introduce additional variable of mechanical properties to better represent the build quality beyond consolidation.

KEY WORDS: Data analytics, machine learning, processing maps, additive manufacturing, alloys

Functionally graded additive manufacturing of Inconel 625-CuCrZr: from process parameter optimization to microstructural evolution and mechanical properties

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Functionally Graded Additive Manufacturing (FGAM) is a layer-by-layer fabrication process that involves the in-situ variation of composition and/or microstructure within a component to achieve locally tailored properties. A new material system for FGAM fabrication that has gained tremendous attention for aerospace applications consists of the highly-heat conductive CuCrZr alloy and Inconel 625 superalloy. The use of these materials provides the dual advantage of high heat dissipation from the CuCrZr alloy and exceptional mechanical properties from the Inconel 625 superalloy. Yet, the fabrication of such components suffers from some challenges such as severe residual stresses and delamination at the composition transition interface due to the high thermophysical properties mismatch between the two alloys. In this study, a systematic investigation was conducted to properly fabricate single-track wall FGAM by gradually varying the composition from 100% Inconel 625 on one side to 100% CuCrZr on the other side, via a dual powder feeder Laser Directed Energy Deposition (LDED) system. To avoid the lack of fusion (LOF) defect, the laser power was linearly adjusted based on the composition from 500 W for 100% Inconel 625 to 1000 W for 100% CuCrZr. Furthermore, to preserve the structural integrity of such FGAM product, the metallurgical phenomena taking place during deposition were studied using optical microscopy, SEM, EDS, and EBSD on the transversal cross-section at different compositionally varied regions. Results from microhardness indentation show the variation of hardness in different regions. EBSD analysis results reveal the grain structure from hundreds to just a few micrometers in line with compositional variation across the build direction.

KEY WORDS: Functionally graded additive manufacturing, CuCrZr-Inconel 625 alloys, Laser directed energy deposition, microhardness, grain structure

Advanced Laser Powder Bed Fusion through adaptive processing parameters and *in situ* heat treatments

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ABSTRACT

Laser Powder Bed Fusion (LPBF, also known as SLM, Selective Laser Melting) is a well-known Additive Manufacturing technology, among the most studied in literature for metals and alloys. A number of drawbacks however still limit its range of applications, among which: (i) the stochastic nature of some of the defects, reducing the reproducibility of parts quality; (ii) the need for adapting laser processing parameters when changing the shape, size or topology of the part; and (iii) the often narrow safe processing window, which makes it difficult to optimize defect content, microstructures and residual stresses at the same time.
To solve some of these issues, we perform *operando* experiments in the Synchrotron, to follow defects formation and microstructure changes, during LPBF or upon *local* laser heat treatment. These experiments are monitored with X-Rays (imaging or diffraction) as well as with acoustic emission. In parallel, we develop a multiscale finite element model predicting thermal fields in the processed zones, such as to propose optimal time-dependent laser parameters. These adaptive processing parameters can provide remedies to defects, non-optimized microstructures and detrimental residual stresses.
Examples of the above strategy are presented on cracking phenomena in a Ni-based superalloy, keyhole porosity formation and healing in 316L steel, phase transformations in Ti-6Al-4V, and crystallization in a metallic glass.

KEY WORDS: Laser Powder Bed Fusion, *Operando* X-ray imaging and diffraction, Laser Heat Treatment, Acoustic Emission, Finite Element modelling.

THE INFLUENCE OF INTRINSIC ADDITIVELY MANUFACTURED COMPONENT PROPERTIES ON SUBSEQUENT BRAZED JOINT FORMATION

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ABSTRACT

It is well documented that the microstructure obtained from the additive manufacture (AM) of metals varies considerably from that of metals manufactured via traditional, subtractive manufacturing techniques [1, 2, 3]. However, the influence of this over subsequent component joining steps has not yet been investigated widely. This research aims to understand the influence that these texture differences, as well as the inherent roughness of an as-built part, have on a joining process called brazing, which involves the melting of a filler metal between base materials at temperatures over 450 ^{o}C [4].

Brazing is a process which has been used in many industries, including aerospace [5] and nuclear fusion [6], but is quoted to require smooth surfaces with average roughness values (R_a) of 0.6 - 1.6 µm [4]. This is an order of magnitude less rough than the typical surface finish of an AM part which means the native AM surface is often machined down before brazing can occur. However, literature suggests that an increase in surface roughness can aid the braze alloy in flowing over the surface, by inducing capillary action [7, 8].

This contribution will discuss the microstructural and mechanical results of brazed joints between materials, highlighting the role of the native AM surface roughness and the influence of the AM texture to the final joint. It combines information generated from XCT, EBSD and SEM-EDS to create a full understanding of the joints produced using AM surfaces, and directly compares them to the machined equivalent.

The investigation of AM parts manufactured in various orientations relative to the build direction, when compared to machined parts, show different interactions between the brazing filler and the metal, where the machined side is more likely to undergo a phase change at the joining interface. This suggests that there is great potential for utilising AM processing, as it indicates that structural changes on the machined side of joints can be suppressed by the use of AM microstructures. The research also suggests that AM surfaces can be used in their native state to produce good joints, minimising the need for additional machining steps.

KEY WORDS: Advances in processing, brazing, microstructural influence

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Investigation of Microstructure and Magnetic Properties of Fe-3.5Si-1.5Al Ferritic SteelFabricated via Laser Directed Energy Deposition

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ABSTRACT

1. Introduction
It has been reported that the samples fabricated via metal additive manufacturing processes exhibit unique microstructures. For example, the transition of columnar to equiaxed grain by process conditions, supersaturated non-equilibrium microstructure, and texture formations have been previously studied using powder bed fusion processes. The texture of the matrix plays an important role in the magnetic properties of ferritic steels, e.g., electrical steel sheets. Therefore, we investigated the microstructure of Fe-3.5Si-1.5Al (mass%) ferritic steel samples fabricated via the laser-directed energy deposition (L-DED) process and measured the magnetic properties.

2. Experimental procedure
The rectangular samples of 20 x 20 x 70 mm^3 were built with a laser power of 750W and a scan velocity of 40 mm/s. Fully alloyed Fe-3.5Si-1.5Al gas atomized powder was applied for the fabrication using L-DED. The relative densities of the built samples were measured by the Archimedes method. The microstructure on the plane parallel to the building direction was observed by a scanning electron microscope (SEM). The distributions of the crystallographic

direction of the samples were investigated by the electron backscattering diffraction (EBSD) analysis.
Magnetic properties were measured by the single sheet tester (SST) integrated by magnetizing current method. The specimens of 5 x 50 x t1 mm^3 with two measurement directions parallel (BD sample) and perpendicular (PD sample) to the building direction were obtained from the L-DEDed samples. The specimen prepared from bulk material (Bulk sample) was also prepared for comparison.

3. Results

The densities of the samples were around 7.50 g/cm^3, resulting in high relative densities of more than 99.4 % (the true density was estimated at 7.54 g/cm^3). The SEM observation revealed the microstructure of the L-DEDed sample consisted of coarse columnar grains growing across the melt pool traces. The inverse pole figure (IPF) maps obtained from EBSD analysis confirmed the average grain length exceeded 1 mm. In addition, the intense <001> texture along the BD was confirmed (Fig. 1), which suggested that the grains were grown epitaxially.
The magnetic properties obtained from the SST indicated that the L-DEDed and bulk Fe-3.5Si-1.5Al samples have the following characteristics (Fig. 2). (1) The BD sample, which exhibited the strong <001> texture along the measurement direction, had the highest B_8 (the permeability at a magnetizing force of 800 A/m) and the lowest coercivity (H_C). (2) The B_8 and H_C of the PD sample were equivalent to that of the Bulk sample. (3) The BD sample realized the lowest hysteresis loss. The superior magnetic property of the BD sample as electromagnetic steel was expected to be achieved by the <001> texture, which is the axis of easy magnetization for ferrritic steel [1].

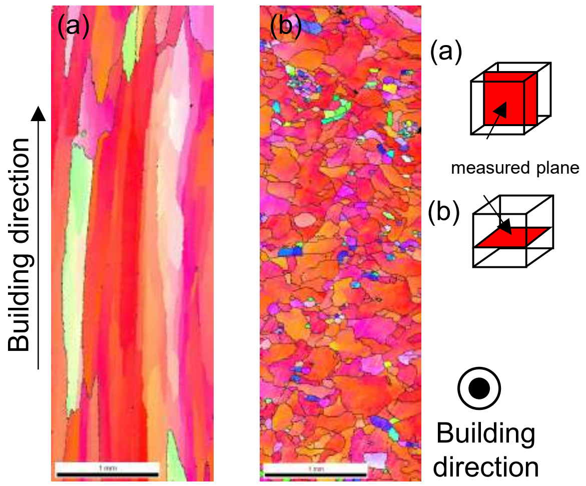

Fig. 1 IPF mappings of the sample fabricated via L-DED process.
(a) Plane parallel to BD (b) Plane perpendicular to BD.

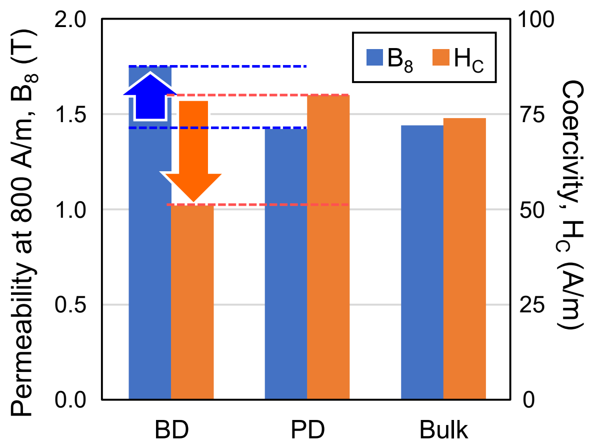

Fig. 2 Magnetic properties of the Fe-3.5Si-1.5Al samples.

KEY WORDS: Directed Energy Deposition, epitaxial growth, soft magnetic steel, columnar grain.

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MECHANICAL AND CORROSION RESPONSES OF MINOR AND TRACE ELEMENTS IN CoCrMo ALLOY POWDERS ON ADDITIVELY MANUFACTURED DENTAL CROWNS AND BRIDGES

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ABSTRACT

Selective Laser Melting (SLM), one of the metal additive manufacturing methods, is an alternative to the conventional method of producing (investment casting and CNC milling) procedure for dental crowns and bridges (DCB) now already a part of the dental laboratories. Current SLM devices offer metallic DCB made of CoCr alloys compromising at a fraction of the time and cost, demonstrating great potential to replace the conventional techniques. Even though CoCrMo alloy powders are the well-known material for the SLM application, small differences in the chemical composition can create different mechanical and corrosion responses. In addition, the powder composition is critical for the mechanical and chemical bonding that allows the ceramic and metal materials to adhere to each other. Therefore, this study investigates the effect of minor and trace elements on the chemical compositions of CoCrMo powder alloys, used in SLM to produce DCB parts, in terms of mechanical and biological response. At that point, three CoCrMo alloys powders were determined which included different minor and trace elements as well as weight percentages. Firstly, optimum SLM process parameters have been determined for both powder alloys by producing bulk specimens. Both specimens went under density and microstructural analysis. Secondly, optimal heat treatment has been determined with respect to literature and market findings. The heat treatment has been applied to relieve the thermal stress on the SLM manufactured parts. Finally, the tensile test, corrosion test and de-bonding crack initiation test specimens CAD files were generated and produced in SLM with respect to optimum process parameters. To relieve the thermal stress on the specimens, optimum heat treatment has been conducted. The final parts have been tested according to metallic dental applications standards as mentioned above. The mechanical and the corrosion effects of these three alloys will be discussed with respect to the results.

KEY WORDS: CoCrMo alloys, additive manufacturing, Selective Laser Melting (SLM), dental applications, dental crown and bridges.

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3D BIO PRINTED BIODEGREDABLE COMPOSITE MATERIAL FOR PEDIATRIC CRANIOMAXILLOFACIAL IMPLANTS

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ABSTRACT

The research and development of the ideal artificial bone substitute materials to replace autologous and allogeneic bones for repairing bone deformities is still a challenge in clinical orthopaedics [1]. The conventional manufacturing methods (such as solvent casting, particle leaching, gas foaming, and thermally induced phase separation) are not applicable to creating pre-determined complex anatomical geometries. Additive manufacturing is a growing field in bone tissue engineering. Additive fabrication also offers reproducibility, high accuracy, and rapid production of patient-specific scaffolds. The creation of appropriate biomedical composite materials is crucial to the reach clinical application of these novel biomaterials. Recently, poly (lactic-co-glycolic acid) PLGA-based artificial bone substitute materials are attracting increasing attention since their suitable biocompatibility, mechanical properties, degradability, and capabilities to promote bone regeneration. PLGA/nHA weight ratio, printing parameters, physical characterization of constructs after printing, and in vitro and or in vivo tests were examined to understand their compatibility with bone tissue engineering applications [2,3,4]. These applications have provided a starting point to give a solution for pediatric craniomaxillofacial (CMF) implant treatments. Therefore, the method developed in this paper is dedicated to children, as such CMF implants do not hinder the physical growth of these developing children. Medical-grade PLGA was mixed with hydroxyapatite nanoparticles (nHA) to fabricate 3D porous scaffolds by Fused Deposition Modelling (FDM) – pneumatic method (Allevi 1 by 3D Systems) in this study. Lattice geometries have been introduced last decades as a new scaffold design [5]. Gyroid, which is one of the Triply Periodic Minimal Surface Lattice types, has been chosen both for osteointegration and self-supporting features for biological response and producibility respectively. Optimum nHA weight percentages of the final PLGA/nHA composite material and production parameters were determined. Mechanical tests, and in vitro and in vivo studies were completed in accredited institutions according to the standards. In this article, the producibility of innovative patient-specific geometry design with this biodegradable composite material will be discussed.

KEY WORDS: Bioprinting, biodegradable composite, CMF implants

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Microstructure and mechanical properties of an austenitic stainless steel 316L process by Wire Arc Additive Manufacturing

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ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is an of additive manufacturing technology inherited from welding. This technique allows the construction of large parts thanks to a high deposition rate. The 316L austenitic stainless steel is a material widely used in the energy sector. On the contrary to LPBF, there is very little studies which examines this microstructure and these mechanical properties. The objective of this work is to examine the as-built microstructure, its evolution with thermal treatments and to evaluate mechanical properties. A 3D dimensional block was fabricated using WAAM. The microstructure was characterized at the melt pool scale using optical microscopy and at the grains scale by EBSD. It reveals a microstructure with very large grains and a strong texture composed of two preferential orientations: <110>//BD and <100>//TD ; and <100>//BD and <010>//TD, see **Figure 1**. At the intra-granular scale, there is a significant fraction of delta ferrite (~8%) as already observed in some studies [1] [2]. Different heat treatments were performed to dissolve the ferrite. It shows that the kinetics of dissolution depends on the position in the solidified melt pool.

The mechanical properties in the as-built state in three different directions are evaluated by digital image correlation. The impact of the microstructure on the anisotropy is evaluated, as well as on the TWIP effect, which is studied by analysing the microstructure after deformation.

KEY WORDS: WAAM; Microstructure; mechanical properties; austenitic stainless steel

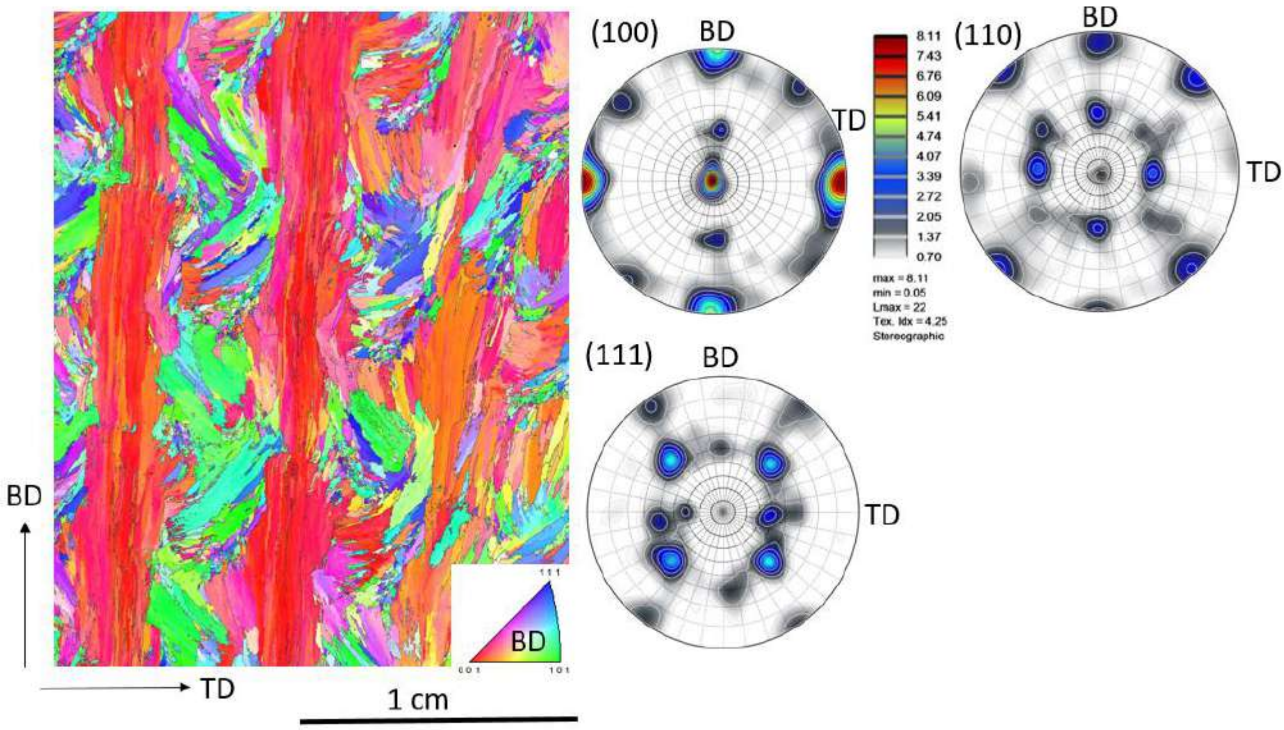

Figure 1 : IPF EBSD map of the as-built microstructure with the associated poles figures.

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At the Intersection of Metal Additive Manufacturing and New Generation Orthopaedic Implants: Comparative success of EBM and SLM technologies in lattice structured Metal Implants

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Repeating cellular geometries called lattice structures are applied to the surface of implants, where they come into contact with bone, to create the trabecular intersection that allows mimicking cancellous or cortical bone in many ways.[1] On the other hand, lattice structures exist under the umbrella of design for additive manufacturing phenomena since AM technologies make it possible to produce such complex multiscale structures.[2] The producibility of lattice structures with these technologies and the differences between Electron Beam Melting (EBM) and Selective Laser Melting (SLM) in terms of osseointegration are still being investigated by researchers.[3,4] Nevertheless, EBM and SLM technologies are well-known powder bed fusion additive manufacturing (PBF-AM) methods for manufacturing trabecular implants used in arthroplasty. Although these manufacturing techniques are chosen for mass production of these implants, they have differences in principle and operation.

Figure 1. EBM (left) and SLM (right) produced diamond lattice Ti6Al4V structures.

The aim of this study is to conduct comprehensive analysis of different types of lattice structures manufactured by EBM and SLM in terms of producibility, production precision, as well as mechanical and biological properties in the scope of the production requirements of trabecular orthopedic metal implants.Eight different lattice unit cells that are currently available in the nTopology library were examined. The lattice structures have been designed with respect to three parameters: porosity percentage, strut thickness, and cell size. While the porosity percentage has been varied from 60 % to 80 % with a 5 % incrementation, the strut thickness has been chosen as 0.4 mm considering the manufacturing limitations of EBM and SLM. A Python wrapper script was implemented onto nTopology flow to get cell size values that correspond to the required porosity percentages. Finite element analysis has been conducted with static loading boundary conditions. The maximum Von Mises stresses of the lattice specimens were evaluated as Ti64 ELI material with known yield points. The stiffness matrix of the structure was obtained with the homogenization tool of nTopology. With the assumption of transverse isotropy, the approximate elastic modulus was calculated from this matrix. The two most similar lattice cells to the cancellous bone in terms of elasticity were selected for further study. Before manufacturing lattice specimens with EBM and SLM, optimum process parameters have been obtained by creating design of experiment for different production parameters specific to machines. Bulk samples were produced with these parameters for both SLM and EBM devices. SLM samples were heat treated to observe the β-phase similar to EBM samples. Density test and microstructural analysis were performed, and lack of fusion areas and dendritic structures were examined. With the optimum process parameters, samples of the two lattice types were produced. The strut thicknesses and the presence of free powder particles were analysed under SEM. Compression, cytotoxicity and osseointegration tests were conducted. The compression characteristics of the geometry, cytotoxicity, and the difference created by EBM and SLM in osseointegration will be discussed further in the light of the data that were obtained.

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INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING (ICME) FRAMEWORK FOR THE DEVELOPMENT OF NOVEL DISPERSION-STRENGTHENED (DS) ALLOYS FOR ADDITIVE MANUFATURING

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ABSTRACT

Towards the development of high-performance alloys with superior high-temperature properties, dispersoid-strengthened (DS) alloys manufactured via additive manufacturing (AM) present a promising opportunity for design of high-performance components (e.g. gas burner heads). Challenges arise in alloys not designed for AM due to complex laser-material interactions. Hence, the integration of multi-scale multi-physics experimental and computational methods, i.e. integrated computational materials engineering (ICME), in alloy design for AM is a promising approach to address this issue. This presentation emphasizes the use of an ICME framework to accelerate the development of DS alloys, focusing on process-structure-properties-performance relationships. The process-structure relationship was quantitatively analysed for a Fe-18Cr steel containing TiN nanoparticles. A combined finite-element method (FEM) and multi-phase field method (PFM) approach was used to reveal the mechanisms that govern the microstructure evolution during laser powder bed fusion (LPBF), specifically with respect to the columnar-to-equiaxed transition (CET). TiN particles were considered implicitly through the seed-density model in the PFM, including their influence on heterogeneous nucleation as well as the Zener pinning effect. Capturing the interplay of LPBF processing conditions and nanoparticle characteristics allowed for understanding the competing behaviour of thermal gradient and particle activation (as nucleation site). This was, in turn, determined to be the mechanism for CET during solidification of an additively manufactured DS alloy (cf. figure 1) and enabled precise microstructure design to achieve high-performance components.

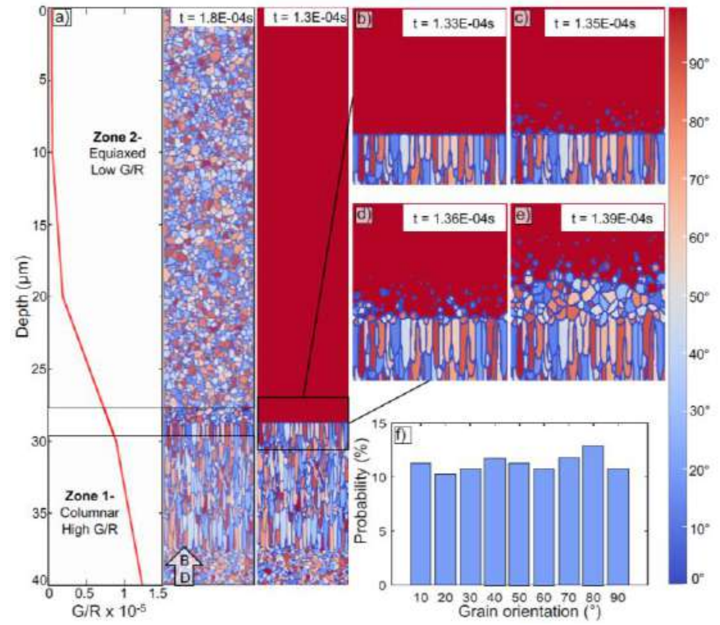

Figure 1. Solidification and grain evolution simulation: (a) Final microstructure from the simulations compared with G/R extracted from the melt pool simulations showing columnar and equiaxed zones at high and low G/R ratios, respectively. (b) Microstructure evolution before the onset of equiaxed transition. (b), (c), (d), and (e) show the microstructure evolution at different time steps with nucleation and growth of equiaxed grains. (f) Grain orientation histogram for the low power parameter.

KEY WORDS: Dispersion-strengthened alloys for AM, ICME, high-temperature materials, columnar-to equiaxed transition

Microstructural grading through laser scanning parameter modification for L-PBFed IN939

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ABSTRACT

Laser based additive manufacturing (AM) techniques enable a degree of control of solidification conditions, and hence of the resulting microstructure, that has long been of interest, since this can be utilized to produce components with site-specific properties. The majority of studies regarding microstructural grading focus on complex scanning strategies [1–3], since modifying laser scanning parameters can induce defects in the components, thus damaging their mechanical properties [4]. Furthermore, most of the current literature focuses on alloys with good weldability, like stainless steels or IN718, for the window of processability is larger.

In this study, we show precise microstructural control in IN939 (a hardly weldable alloy [5]) components produced by L-PBF. Using a standard industrial scanning strategy (meander/stripes pattern, with 67º layer rotation between layers), and by simply modifying the hatch distance, we manufacture parts containing different distributions of two microstructure domains: one with long columnar grains with strong <100> texture, the other with more equiaxed grains and weaker crystallographic textures. Post-processing heat treatments are then applied to the manufactured samples. We carry out a thorough characterization of the multi-microstructure samples (grain size and orientation, precipitate formation) at different levels, using both optical and scanning electron microscopy, EBSD mapping, and TEM, in both the as-built and heat-treated conditions. The effect of the domain size and distribution on the printed microstructure, on the microstructural evolution with heat treatments, and on the mechanical properties is investigated.

Such control of the microstructure and the understanding of their evolution upon heat treatment allows for new approaches in part design, enabling the industrial production of parts with site-specific microstructures and properties.

KEY WORDS: Microstructural control by design, thermal treatments of AM parts, Ni-based superalloys.

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ADDITIVE MANUFACTURING OF A D2 TOOL STEEL MODIFIED WITH NICKEL (NI): A PROMISING MATERIAL FOR MOULD AND TOOLING

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ABSTRACT

Industry 4.0 has accelerated the adoption of advanced additive manufacturing (AM) processes in the mould and tooling industry, such as laser powder bed fusion (L-PBF), which enables the production of 3D metal tools with intricate designs that are often not possible with traditional subtractive processes, such as internal cooling channels in moulds. The choice of materials available for this process is still limited due to defect formation, i.e. residual stresses, cracking and warpage. As far as L-PBF of steels is concerned, low carbon steels, such as stainless steels and maraging steels, are successfully produced with good quality. Despite their successful production, the wear resistance of these steels makes them unsuitable for moulds, especially when exposed to harsh conditions, such as when polymers reinforced with abrasive fibres are injected, as is widely used in automotive parts. Due to excellent wear resistance, high carbon tool steels, such as AISI D2 steel (~1.55 wt%), are an excellent choice for these extreme conditions, but they present some challenges due to low wettability and cracking that occurs during rapid solidification in L-PBF due to martensite formation causing high residual stresses.

The objective of this work was to improve the L-PBF processability of AISI D2 steel by modification with pure nickel (Ni) in concentrations up to 5 wt%. Suitable raw powders of the modified material were prepared by milling and processed by L-PBF. With the aim of comparing and better understanding the behaviour of the L-PBF processed material, its mechanical performance, wear resistance and microstructure was investigated and compared with a conventionally produced pure D2 material to evaluate whether the modified material with improved L-PBF processability can be a viable alternative for use in moulds subjected to harsh conditions, taking advantage of the geometric freedom offered by L-PBF. The results allow obtaining an alternative material for the difficult-to-process D2 steel, which has similar mechanical properties and wear resistance and can be processed with L-PBF. The developed material can be a good choice for the critical zones of moulds where higher wear resistance is required.

KEY WORDS: Additive manufacturing; laser powder bed fusion; tool steels; moulds; tooling.

Microestructural control of additively manufactured Ti-6Al-4V upon *in-situ* Selective Laser Heat Treatment

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ABSTRACT

In Laser Powder Bed Fusion (LPBF) of Ti-6Al-4V alloy, the typical as-built microstructure contains of fully acicular α'-martensite, which suffers from low ductility. This can be improved by decomposing the martensite upon post heat treatments, which are often time and energy consuming and question the efficiency of the LPBF process. This study presents a new concept of *in-situ* Selective Laser Heat Treatment (SLHT), as a secondary treatment, which can control the as-built microstructure and activate the martensite decomposition towards obtaining a lamellar α+β microstructure within a short time scale (~30s). SLHT consists of multiple surface rescanning of the printed part with very low energy density triggering solid-state phase transformations. In this investigation, SLHT has been performed through *operando* synchrotron X-ray diffraction to shed light on the dynamics of the martensite decomposition on cuboid and thin-wall geometries, along with thermal finite element simulations. The *operando* diffraction data illustrates, for both geometries, a gradual formation of the β phase together with peak narrowing of the α/α', indicating the diffusion nature of martensite decomposition. Furthermore, upon fine adjustment of the laser parameters in the SLHT cycles, the temperature profile has been modulated to have a controlled cooling rate, which preserved the β phase, a product of the decomposition, up to room temperature. Moreover, the derived temperature profiles from the *operando* diffraction was utilized to calibrate the numerical simulations. The results together with complementary microstructural analysis demonstrate a fast kinetics of the martensite decomposition under *in-situ* SLHT. The calibrated numerical simulation can define the laser parameters for SLHT routes for a given temperature regime which are meant to be implemented at selected locations during the LPBF process, saving time and leading to architected microstructures. The approach can be extended to any given material suffering from inferior mechanical properties in the as-built LPBF state.

KEY WORDS: Laser Powder Bed Fusion, Ti-6Al-4V, *Operando* X-ray diffraction, Martensite decomposition, Microstructure, Selective Laser Heat Treatment

HIGH STRENGTH HYBRID EX-SITU/IN-SITU REINFORCED ($Ti+B_4C$)/Al-Cu-Mg METAL MATRIX COMPOSITE MANUFACTURED USING LASER POWDER BED FUSION

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ABSTRACT

The occurrence of solidification cracking has been limiting the adoption of high-strength aluminium alloys, such as 2xxx series Al-Cu alloys, by solidification-based additive manufacturing (AM) techniques and thus their utilization for light-weight high-strength applications [1,2]. Several investigations have been conducted focusing on solving the solidification cracking issue in these Al alloys and one of the most effective ways has been proven to be grain refinement induced by inoculation [3–5]. Accordingly, new alloys have been developed [5] and the fatigue performance of these newly developed alloys is yet to be explored.

Therefore, this study focuses on the fatigue performance of a crack-free, laser powder bed fusion processed, high strength aluminium matrix composite (AMC), which is a metal matrix composite (MMC) composed of ex-situ/in-situ formed Ti-B-C based reinforcements in a Al-Cu-Mg matrix alloy. The unique as-built (AB) microstructure, as well as the quasi-static and the dynamic performance of this L-PBF processed AMC, will be shown. In addition, the effect of hot isostatic pressing (HIP) on microstructure and mechanical property evolution is revealed.

High density and crack-free parts are visualized by X-ray microcomputed tomography (µ-CT), followed by cross sectional examination of microstructure by scanning electron microscopy (SEM). The average grain size and orientation is measured by electron backscatter diffraction (EBSD) analysis, while transmission electron microscopy (TEM) analysis is employed for identification of the precipitates. Mechanical properties are studied by conducting microhardness measurements, tensile and SN fatigue tests.

The main results obtained in this study can be summarized as follows:

- Crack-free dense parts (99.7 ± 0.1 %) with equiaxed grains are achieved in as-built state with an average grain size of 1.2 ± 0.4 µm.
- Interdendritic microsegregation (Mg and Cu) is identified in the AB microstructure, while dissolution of the grain boundary segregation and precipitation of new phases, such as (Al_2Cu, TiB_2, TiC), are detected in the HIP microstructure.

- High fatigue performance is recorded for the AB condition, 10^7 cycles are reached at the maximum applied stress of 250 MPa.
- Fatigue life is further improved significantly after HIP, 10^7 cycles are reached at the maximum applied stress of 330 MPa.

In conclusion, hybrid ex-situ/in-situ reinforced (Ti/B_4C)/Al-Cu-Mg metal matrix composite can successfully be manufactured using laser powder bed fusion allowing to obtain high density parts with excellent fatigue strength. In addition, application of hot isostatic pressing can improve the fatigue strength at 10^7 cycles by 32% for this MMC.

KEY WORDS: Metal matrix composites, fatigue life, laser powder bed fusion, new and tailored alloys for additive manufacturing

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DESIGN AND DEFORMATION BEHAVIOUR OF HIGH -MANGANESE STEEL LATTICE STRUCTURES PROCESSED BY LASER POWDER BED FUSION FOR ENERGY-ABSORPTION APPLICATIONS

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ABSTRACT

Additive manufacturing (AM) is a novel manufacturing technique that allows rapid production of near net-shaped components with complex geometries such as lattice structures with energy-absorption functionality for lightweight applications [1, 2]. In this respect, laser powder bed fusion (LPBF) stands out as one of the suitable additive manufacturing (AM) techniques for production of lattice structures with small strut thicknesses owing to its high resolution (small laser spot size) and process flexibility (powder-bed approach) [3].

As a member of second generation advanced high-strength steels (AHSS), high-manganese steels (HMnS) have been reported as suitable alloys for production of lattice structures by LPBF [4]. Different deformation mechanisms, e.g., transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP), can be activated in HMnS by alloy design approach through tailoring stacking fault energy (SFE) of the alloy. For instance, with increasing Al concentration (from 0 up to 5 wt.%) in X30Mn22 HMnS, the SFE of the alloy was increased and therefore the prevalent deformation mechanism changed from TRIP to TWIP, and then to dislocation slip accompanied by reduced mechanical twinning. In addition to bulk materials, the same alloy design approach was also utilised for lattice structures. Deformation behaviour of LPBF-processed lattice structures of X30Mn22, X30MnAl22-1, and X30MnAl22-5 alloys with f_2cc,z unit cells was investigated under compression [5]. The active deformation mechanisms in the lattice structures followed the same trend as identified within the bulk materials, except more pronounced TRIP effect was observed in X30MnAl22-1 lattice than in bulk X30MnAl22-1. The results revealed that HMnS lattice structures have higher weight-specific energy-absorption capacity in comparison to well-established AM materials such as Ti6Al4V and AISI 316L. Nevertheless, strain localisation at z-strut (vertical strut) nodes of the lattice structures resulted in formation of brittle ε-martensite phase in X30Mn22 and X30MnAl22-1 at the early deformation stages and consequently led the failure of these structures. **Figure 1.a** shows digital image correlation (DIC) analysis performed on X30Mn22 lattice under compression. The disintegration of the struts, which caused a drop in the force-displacement curve and ultimately the collective failure of the lattice, started from the high-strain regions, where brittle martensite phase was formed.

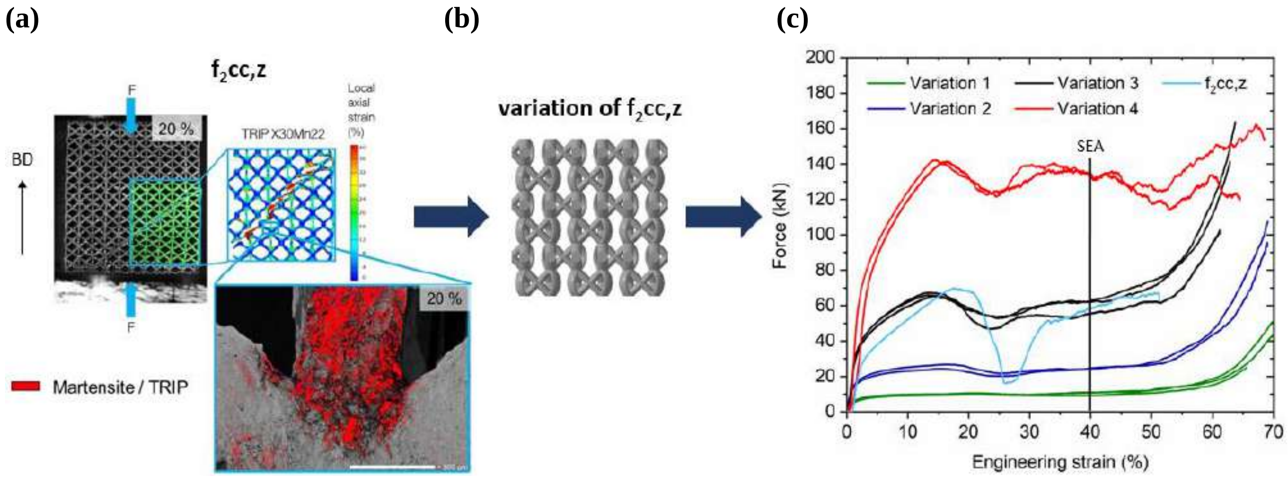

Figure 1. Cell design optimisation of HMnS lattice structure: (a) Strain localisation in f_2cc,z. (b) New design (modification of f_2cc,z). (c) Force vs. strain curves of the proposed structures, as a basis for energy-absorption analysis.

In order to avoid strain localisation and the resultant early TRIP effect without compromising on energy-absorption capacity, a new geometry that is based on the modification of f_2cc,z structure was proposed. In line with the scope of this contribution, the straight vertical struts of the f_2cc,z structure were replaced by curvy ones in the new structure (illustrated in **Figure 1.b**) in order to ensure a better load distribution along orthogonal directions to the applied load and thereby preventing strain localisation at the nodes where the vertical struts intersect the cross-struts. **Figure 1.c** shows the mechanical behaviour of the proposed structures of X30Mn22 with different relative densities and indicates that the proposed structures are more stable in the plateau region and the energy-absorption capacity could be further increased.

KEY WORDS: Laser powder bed fusion, lattice structures, design optimisation, energy absorption.

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Evolution of microstructural heterogeneities in additively manufactured low-alloy steel

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ABSTRACT

Dual-phase (DP) steels are one of the most commonly used advanced high strength steels in existing cars due to their composite like nature promoting the combination of low yield strength and high ultimate tensile strength, which in turn provides a wide range of mechanical properties. Today's technological developments raise the possibility to produce well-established alloys besides the conventional manufacturing methods. As such, additive manufacturing (AM) of metallic components has gained significant importance in the scientific community and industry owing to its disruptive capability to shorten component design and production, while simultaneously enabling the fabrication of geometrically complex parts with minimized waste. Thereby, many competitive industries began to integrate AM for part development and production of the end-use parts.

During AM processes, alloys experience distinct thermal histories associated with the repeating melting-solidification and heating-cooling cycles alongside with steep temperature gradients and significantly high cooling rates leading to various phase transformations. As such, spatially variable thermal profiles facilitate formation of locally dependent microstructures and material properties that can only be achieved by AM. So far, many alloys were utilized in AM. However, low alloy steels (e.g. DP-type steels) have not been intensively investigated in the context of AM, but are of high industrial interest. The unique characteristics of the AM processes can enable the re-design of microstructures, hence, can introduce novel microstructures and tailored mechanical properties in DP steels by offering high degrees of freedom with respect to the manipulation of ferrite-martensite morphology and distribution.

In this presentation, we aim to demonstrate the range of microstructures and material properties obtained by laser powder bed fusion (L-PBF) and post-AM heat treatments by utilizing a dual-phase low alloy steel powder with a composition similar to widely used DP600. Samples were produced by L-PBF and two heat-treatment strategies were applied to obtain ferrite and martensite DP microstructures. The corresponding as-built and heat-treated microstructures were characterized in detail and the underlying physical mechanisms are discussed with respect to the microstructure evolution and mechanical properties alongside with their correlation to chemical and morphological heterogeneities.

Keywords: Additive manufacturing, laser powder bed fusion, low-alloy steel, dual-phase steel, microstructural heterogeneities

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NUCLEATION BURST IN ADDITIVELY MANUFACTURED IN718: WHAT CAN BE LEARNED FOR ALLOY DESIGN FROM THE ISRO-MEDIATED NUCLEATION MECHANISM?

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ABSTRACT

The authors have recently highlighted the mechanisms leading to fine grain structures in additively manufactured Inconel 718 alloy. While the ISRO nucleation mechanism is involved, the process leading to grain refinement is much more complex and involves precise control of process parameters and alloy chemistry [1,2]. In this paper we present the latest results from the study of Inconel 718 alloy produced by additive manufacturing by a wire laser process. These results are then discussed and compared with other recent advances in steel and aluminium alloys using the same grain refinement mechanism. Finally, some design rules to promote ISRO mediated nucleation in alloys for additive manufacturing processes will be proposed.

KEY WORDS: Wire-laser additive manufacturing, Microstructures, Nickel alloys.

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Generating and characterizing functionally graded steel microstructures by L-PBF

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ABSTRACT

Laser powder bed fusion (L-PBF) has the potential to create novel functionally graded microstructures (FGMi) with properties tailored to specific applications. However, locally altering the process parameters to create such microstructures can affect the relative mass densities and thus the material performance. In this work, we introduce a new double exposure approach to realize FGMi by in situ heat treatment in L-PBF. The results demonstrate improved parameter flexibility without affecting the relative mass density compared to a single exposure of the investigated low-alloy steel 30CrMoNb5-2. The systematic investigation regarding the impact of process parameters enables microstructures in the hardness range from ca. 380 – 510 HV10. In particular, the introduction of cooling pauses between individual exposure tracks increases the hardness of the structure. Tensile testing shows a 21.3% increase in UTS when compared to non-in situ heat-treated samples (single exposure). Both homogeneous in-situ heat-treated samples and discrete and continuously graded samples (see Figure 1) demonstrate the potential of the novel method. The tempering state of the resulting martensitic microstructure is analysed by the image quality (IQ) of EBSD measurements. Tempering of the martensitic structure causes dislocation reduction, carbide precipitation and crystal structure changes and thus the IQ. The analysis reveals micro-gradations within individual laser tracks and macro-gradations throughout the sample (see figure 2). To conclude, the presented double-exposure approach for in situ heat treatment offers new flexibility regarding the generation of FGMi by L-PBF and thus, in combination with EBSD-based analysis, could pave the way for the future development of high-performance materials.

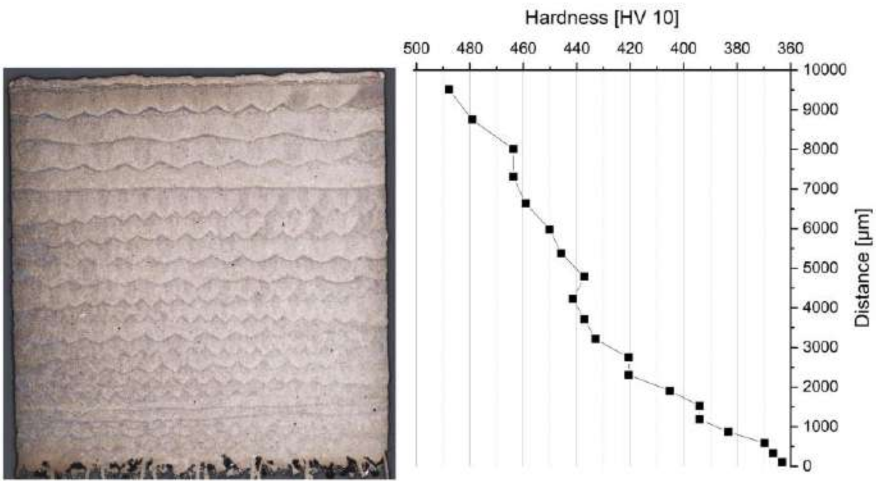

Figure 1. Demonstration of a continuously graded microstructure. Measurement method: Micro-hardness. In-Situ heat treated by the secondary exposure.

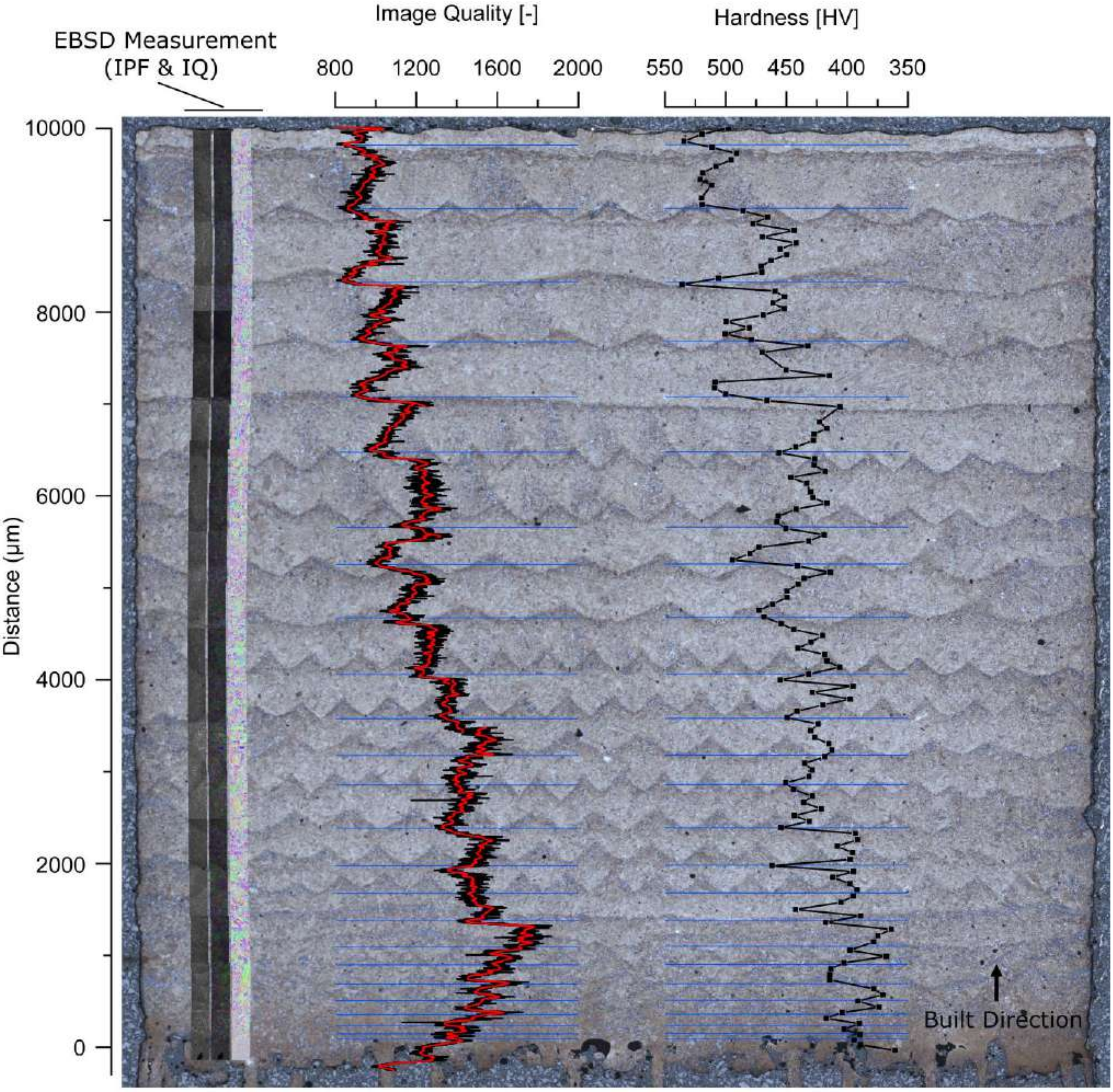

Figure 2. Summary of results regarding the FGM demonstrator material presenting a linear graded hardness along the built direction and a corresponding IQ distribution. See appendix for high-resolution curves and images. In red: Curves resulting from FFT-filter to demonstrate the average trend. In blue: Position of austenitisation borders within measurement zone.

KEY WORDS: Laser Powder Bed Fusion; process parameter development; functionally graded microstructure, in-situ heat treatment, graded steel microstructure, double exposure, EBSD analysis

Evolution of microstructure in additively manufactured NiTi architectured materials

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ABSTRACT

Nitinol (NiTi) exhibits a reversible strain of up to 8% and energy dissipation due to its remarkable superelasticity, which has the potential to change the way we design and manufacture energy-absorbing architectured materials. For metallic materials with energy absorption properties, local yield damage or inelastic buckling generally leads to unrecoverable deformation. In this research, NiTi architectured materials featuring a superelastic response, recoverable energy absorption, and damping were successfully modeled and manufactured using laser powder bed fusion (L-PBF). The influence of NiTi as a constituent material on the thermomechanical properties of architectured materials was studied on various length scales. At the mesoscale, effective mechanical properties and transformation behaviors were investigated using numerical models. An effective transformation surface was developed based on the extended Hill's model, which showed that anisotropy is temperature-independent. Stable cyclic deformation and damping behavior were successfully achieved in compressive tests, further illustrating that the progressive martensitic transformation is the main deformation and energy dissipation mechanism. At the microscale, inhomogeneous microstructure and local superelasticity due to varying thermal profiles were investigated. A comparative study between the body-centered cubic (BCC) and octet structures designed in this research showed that local microstructures significantly affect the macroscopic superelastic response of NiTi architectured materials. The microstructure evolution in the BCC structure with different relative densities is discussed. The computational and experimental study proposed in this work enables tailoring the superelasticity by combining architecture design and microstructural control. The studied architectured materials have potential applications as reusable shock absorbers in aerospace, automotive, maritime, and vibration-proof structures.

KEY WORDS: NiTi, architectured materials, martensitic transformation, stress hysteresis.

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ACCELERATING THE DESIGN AND DEPLOYMENT OF TAILORED ALLOYS FOR ADDITIVE MANUFACTURING

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ABSTRACT

Rapid design and deployment of new metallic alloys is critical to meet the demands of leading-edge technologies. The current design-to-deployment timescale is on the order of decades. While modern innovations in advanced manufacturing have begun to shorten this cycle, they have also expanded the demand for new optimized alloys. Materials design approaches have not kept pace with this demand. Further, while new classes of alloys promise groundbreaking improvements to properties, the mechanistic origins of these properties are poorly understood, presenting fundamental challenges for optimization and certification.

Here, we present progress toward establishing a Materials Acceleration Platform (MAP), a design framework that integrates data science and machine learning, thermodynamic and physical modeling, process science, and state-of-the-art experiments to provide a means to rapidly engineer materials with targeted performance. The use of additive manufacturing (AM) is key to our design strategy. In the context of metals-based AM, the alloys that have been considered have almost exclusively been those developed for standard manufacturing processes, such as conventional steels (i.e., 316L stainless steel), Ni-Cr–based superalloys (Inconel 718/625), and titanium alloys (largely Ti-6Al-4V). A need exists to develop alloys that are designed specifically to take advantage of AM process conditions. Growth in AM materials diversity is beginning to play a larger role in driving advancement of AM technologies.

In addition to MAP development, recent work will be shown toward designing alloys with controlled microstructures for tailored AM materials. Our MAP is being developed using refractory high entropy alloys (RHEAs). HEAs have demonstrated significant improvements in properties [1] under extreme conditions, including high strength and ductility [2,3], radiation resistance [4], and corrosion resistance [5]. Alloy synthesis makes use of a Directed Energy Deposition (DED) AM system, equipped with an Alloy Development Feeder that allows for rapid assessment of alloy sub-systems and down-selected candidate alloys. Results will be presented that highlight our alloy screening strategy and initial optimizations of phase stability and mechanical properties for HEAs, as well as ongoing work with Ti-based alloys [6].

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KEY WORDS: Alloy design, materials discovery, high entropy alloys, machine learning.

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IN-SITU AND HIERARCHICAL INVESTIGATION OF ALLOYS AND COMPONENTS FOR ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM) of metallic alloys is an innovative process that has been extensively studied and continuously developed in recent years. However, there are still a number of scientific issues to be addressed in terms of process parameter optimization and materials specifically tailored for AM.

In this work, different materials tailored for AM produced by different AM processes are characterized on AM relevant scales. Among the various AM techniques, laser-based metal additive manufacturing enables the layer-by-layer production of near-net-shape metallic components with complex geometries that cannot be achieved using the design constraints of traditional manufacturing [1]. Among the AM techniques, Laser Powder Bed Fusion (LPBF) stands out as it is used to produce near-net-shape metallic components with complex geometries and higher material efficiency, typically replacing multiple conventional components with savings in material, tooling and assembly costs.

However, this technique is only applicable to single materials and has size limitations. Therefore, as a second route, we are also investigating the production of multi-material AM components with integrated multifunctionality and without size limitations by combining directed energy deposition (DED) and metal spraying technologies, using specially developed materials with incorporated nanotechnologies to enhance material properties.

Since the mechanical properties and performance of final AM parts are inherited for the entire

processing history and the material used, and are therefore sensitive to features at entangled characteristic scales (microstructure, melt pool, layer, struts, part…), the relevant scales range from several centimeters down to the submicron range. Therefore, the aim of our study is to develop a correlative imaging approach that allows the linking of the relevant scales mentioned above in order to address the scientific challenges of AM. The beamlines ID16B [2] and BM18 [3] at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, make this approach possible.

The 3D microstructural evolution of a Ti-Fe alloy processed by LPBF is studied at high resolution as a function of heat treatment at 850 °C using in-situ synchrotron nano-tomography (s-XCT) at the ID16B beamline. High-resolution holotomography (HT) scans (voxel size = $(35\ nm)^3$) were acquired at different stages of the thermal treatment with a total scan time of about 23 minutes. Preliminary observations reveal the presence of β-Ti and TiFe phases and a morphological evolution of the TiFe phase during heat treatment at 850 °C from very fine and skeleton-like interconnected structures in the as-built condition to coarser, more disconnected structures as heat treatment progresses. The evolution of shape, size and distribution of these phases will be studied in relation to processing and heat treatment conditions, as well as their spatial distribution in the melt pool.
In addition, component-level investigations were carried out on the BM18 beamline, which allows hierarchical phase-contrast tomography with large fields of view (~ $30x30\ cm^2$). A turbopump impeller component manufactured by LPBF from the Ti-Fe alloy investigated on the ID16B beamline was hierarchically characterized at resolutions of $(13\ \mu m)^3$ down to the highest resolution of $(2\ \mu m)^3$. Preliminary results reveal the geometry and surface topology of the part, as well as structural defects and unmelted powder grains inside the part. In addition, the study of components with integrated multifunctionality, such as embedded optical fibers, produced by Wire Arc Metal Additive Manufacturing (WAAM) or by Atmospheric Pressure Plasma Deposition (APPD) applied multi-layer structures provides insight into the interaction between multi-material interfaces and occurring defects from embedding, as well as features such as porosity.

KEY WORDS: in-situ thermal treatments for AM-produced alloys, 3D characterization, in-situ synchrotron tomography, hierarchical imaging for AM, multifunctional AM components, alloys and components produced by LPBF and WAAM, Ti alloys for AM, APPD.

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Hybrid additive manufacturing of multi-material metallic structures by using a combination of metallic foils and powders

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Abstract

Laser Powder Bed Fusion (LPBF) is a cutting-edge method for fabricating complex metallic parts that uses a laser to melt thin layers of metallic powder. While LPBF offers unique advantages such as computer-controlled lasers and printability of complex parts, there is a growing demand to add multi-material printing capability to expand its usefulness. To accomplish this, recent technical developments tried to upgrade the hopper and recoater systems to deposit multiple powders, and multi-laser systems were also installed to scan multiple materials in a single layer. However, due to large intermixing zones and thermal conditions, the use of a combination of powders resulted in poor interfacial zones, with the formation of pores and cracks which increases the chance to delamination and failure. The current study proposes using metallic foils as the second material feedstock to address this issue. To investigate the effects of using foils instead of powders, a combination of Ti-6Al-4V/AlSi12 alloys, which are commonly used for aerospace applications, was chosen. The AlSi12 side was manufactured using a conventional LPBF method, and a thin layer of Ti-6Al-4V foil (t=100 um) was then deposited on the surface of the LPBFed AlSi12 part. The processing window leading to different classes of the interface was investigated, and thermodynamic simulations and microstructural investigations were used to study phase evolution and microstructural changes at the interface. According to the findings, using foils instead of powder results in a new microstructure in comparison with a powder-powder combination. It was also clear that by using foils instead of powder a flawless and pore-free high-resolution interface with a sharp change in chemical composition is accessible.

Hybrid additive manufacturing of multi-material metallic structures by using a combination of metallic foils and powders

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Abstract

Laser Powder Bed Fusion (LPBF) is a cutting-edge method for fabricating complex metallic parts that uses a laser to melt thin layers of metallic powder. While LPBF offers unique advantages such as computer-controlled lasers and printability of complex parts, there is a growing demand to add multi-material printing capability to expand its usefulness. To accomplish this, recent technical developments tried to upgrade the hopper and recoater systems to deposit multiple powders, and multi-laser systems were also installed to scan multiple materials in a single layer. However, due to large intermixing zones and thermal conditions, the use of a combination of powders resulted in poor interfacial zones, with the formation of pores and cracks which increases the chance to delamination and failure. The current study proposes using metallic foils as the second material feedstock to address this issue. To investigate the effects of using foils instead of powders, a combination of Ti-6Al-4V/AlSi12 alloys, which are commonly used for aerospace applications, was chosen. The AlSi12 side was manufactured using a conventional LPBF method, and a thin layer of Ti-6Al-4V foil (t=100 um) was then deposited on the surface of the LPBFed AlSi12 part. The processing window leading to different classes of the interface was investigated, and thermodynamic simulations and microstructural investigations were used to study phase evolution and microstructural changes at the interface. According to the findings, using foils instead of powder results in a new microstructure in comparison with a powder-powder combination. It was also clear that by using foils instead of powder a flawless and pore-free high-resolution interface with a sharp change in chemical composition is accessible.

Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

Assessing Hydrogen Embrittlement in Inconel 625 Fabricated via Laser Directed Energy Deposition

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ABSTRACT

In this study, we assessed the hydrogen embrittlement of Inconel 625 (IN625) produced by laser direct energy deposition (L-DED) and wrought processes using slow strain rate test (SSRT). We identified hydrogen trap sites by correlating the microstructure with the hydrogen desorption behavior obtained from thermal desorption spectroscopy (TDS). Both the DED and wrought specimens were subjected to hydrogen charging using an electrochemical method, with hydrogen embrittlement increasing as the charging duration extended from 12 to 24 hours. Fracture analysis revealed that both samples transitioned from ductile dimple fractures to brittle cleavage fractures near the surface upon hydrogen charging. Furthermore, electron backscatter diffraction (EBSD) microstructure analysis demonstrated that the DED sample exhibited a higher dislocation density than the wrought sample. The hydrogen trapping positions, determined through TDS analysis, were identified as diffusive hydrogen trap sites, with the DED specimen primarily trapping hydrogen at dislocation and the wrought specimen at interstitial lattice defects. Transgranular crack were observed on the fracture surfaces of both hydrogen-charged specimens, and the hydrogen embrittlement mechanisms of hydrogen-enhanced localized plasticity (HELP) and hydrogen-enhanced decohesion (HEDE) were discussed based on previous findings.

KEY WORDS: Inconel625, Directed Energy deposition, Wrought, Hydrogen embrittlement, Thermal desorption spectroscopy

A Study on the Grain Refinement of Inconel718-ZrO_2 Deposits Fabricated by Directed Energy Deposition

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ABSTRACT

In the fabrication of Inconel 718 (IN718) deposits using the directed energy deposition (DED) process, grain coarsening has been observed due to high heat input, leading to degraded mechanical properties. In this study, we aimed to refine the grain structure of deposits obtained by mixing IN718 powder with ZrO_2 nanoparticles. The powders were mixed using a swing planetary mixer, adjusting the ZrO_2 nanoparticle concentration (1 wt.%, 2 wt.%) and size (20 nm, 200 nm). Deposition process parameters were modified by altering laser power (150 W, 200 W, 250 W) and scan speed (600 mm/min, 800 mm/min, 1000 mm/min).

The IN718-200 nm, 2 wt.% ZrO_2 deposit exhibited equiaxed grains under the conditions of 250 W and 1000 mm/min, presenting the finest grain structure among all tested deposits. Pole figure (PF) analysis under these conditions revealed prevalent discontinuous solidification, with a wide distribution of poles during solidification and the weakest crystal orientation texture strength. Furthermore, the refined deposit structure and decreased anisotropy resulted in an average hardness improvement of 26 to 39 HV across all regions, including surface and interface areas, compared to other deposits.

The observed transition from columnar to equiaxed grains is attributed to the heterogeneous nucleation mechanism of ZrO_2, with the effect maximized under specific heat input conditions. This research successfully refined grain structures, reduced anisotropy, and enhanced hardness in IN718-ZrO_2 deposits fabricated by the DED process using the cost-effective and readily available ZrO_2 nanoparticles as an alternative to rare earth additives.

KEY WORDS: Additive manufacturing, Inconel718, Grain refinement, ZrO_2, Solidification

Compositional modification of an aluminum alloy 7075 via high frequency vibration and its processability on Laser Powder Bed Fusion

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ABSTRACT

The list of metallic materials commercially available for Additive Manufacturing is still quite limited. Particularly for aluminium alloys, there are only a few metallic systems commercially available. High-strength aluminium alloys are quite difficult to process via AM due to the high sensitivity to hot cracking during solidification causing cracks along the build direction. Some solutions have been already applied to mitigate hot cracks such as preheating the base plate and modifying the chemical composition, to reduce the temperature gradient during cooling and then allow grain refinement. Alloy modification includes the addition of elements acting as nucleation sites during solidification such as the case of Zr, Si and Sc in the alloy system Al7075.
The most common alloying processes include the coating of the matrix particles with nanoparticles via mechanical alloying, wet solutions or atomisation among others. These processing methods may involve distortion of the matrix particles or increase processing cost and time.

The study presented here investigates the feasibility of modifying the aluminium alloy Al7075 with nanoparticles by using a high-frequency vibration mixing method while minimising the impact on the morphology of the matrix material and allowing fast and straightforward scalability from laboratory to production.

This study aims to successfully process by L-PBF an aluminium alloy Al7075 through alloy modification with Zr and Si. The manufacturing process begins with high-frequency vibration mixing of the matrix material with a batch of Zr or Si nanoparticles (2 and 4 wt% respectively), followed by the manufacture of coupons and specimens on an EOS L-PBF equipment with a modified chamber capable of processing small quantities of material.
Process parameters optimisation is executed aiming to maximise the density of coupons with minimal or no evidence of cracks. The optimised parameters are used for producing tensile specimens. The mechanical and metallographic characterisation is performed by using optical microscopy, density measurements, Vickers hardness and tensile testing.

The results obtained during the execution of this study indicate that high-frequency vibration mixing does not produce any distortion of the geometry of the matrix particles, the nanoparticles are homogeneously distributed throughout the matrix material and the microstructure of the as-built specimens show a modified aluminium alloy with no evidence of hot cracks presented.

KEY WORDS: hot cracking susceptibility, high strength aluminum alloys, high frequency vibration mixing, alloy modification, powder bed fusion

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PROCESS PARAMETER OPTIMIZATION OF POWDER BED FUSION ADDITIVE MANUFACTURING FOR FE-3.4SI ALLOY BY COMBINATION OF MELT POOL OBSERVATION AND MACHINE LEARNING

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ABSTRACT

In this study, the Powder Bed Fusion (PBF) additive manufacturing process was optimized by analyzing the shape and size of the molten pool of Fe-3.4wt.%Si. The experimental cross-sectional morphology of the molten pool and single-pass is observed and a process optimization map was derived by a combination of the observation and machine learning. The PBF process was performed in a nitrogen atmosphere with less than 1% oxygen and the platform was maintained at 100ºC. The main process conditions considered in this study were laser power (50 - 200 W), scan speed (100 - 1100 mm/s), input energy (0.2 - 1.2 J/mm), and beam size (100 - 200 μm). Hatch spacing and layer thickness were kept constant at 80 μm and 40 μm, respectively. A cross-sectional morphology of the melt pool from the single-track experiment, such as width, depth, height, and the width-to-depth ratio was analyzed according to the PBF process parameters. By measuring the width-depth ratio of the molten pool, the molten pool mode was determined as conduction mode (below 0.5), transition mode (between 0.5 and 0.75), and keyhole mode (above 0.75) [1]. Process conditions play an important role in determining the shape of the molten pool. So, through machine learning, the dimensions of the molten pool according to the process conditions were predicted and an optimal process condition map was created. The 5x5x5 mm^3 cube test samples were produced under the process conditions predicted as the optimal processes and most of the samples had a high density with a porosity of less than 1%. A cross-sectional analysis of the melt pool from a single-pass confirmed that defect-free process conditions can be economically derived.

KEY WORDS: Optimization of Additive Manufacturing, Laser Powder Bed Fusion, Soft Magnetic Materials, Microstructure, Melt Pool

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Crack mitigation for Custom 465® steel made via laser powder bed fusion

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ABSTRACT

The occurrence of cracking during the additive manufacturing (AM) process hinders the continuous development and industry adoption of AM technologies. Past research efforts towards crack mitigation have mainly been focusing on single-phase face-centred-cubic (FCC) alloys, where the matrix does not experience any phase transformation during the solidification or subsequent cooling processes [1,2]. However, this situation leaves many important classes of structural metals unchecked, e.g., the martensitic steels. Custom 465® alloy is an up-and-coming precipitation-hardened martensitic stainless steel. This material is reported to have a much higher strength (~600 MPa) than the conventional 17-4PH steels, but with similar toughness and corrosion resistance. However, it is found that under the standard laser-powder bed fusion (LPBF) processing, extensive cracking is present in the as-built condition. In the current study, we investigated the mechanism of cracking for Custom 465®. The findings would serve as one of the guidelines for the other alloy systems which also suffer from cracking via AM production.

KEY WORDS: Cracking; Additive Manufacturing; Custom 465®; Martensitic Stainless Steel.

Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

Design of sustainable aluminum alloys for high-temperature applications

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ABSTRACT

Designing new structural alloys with high strength-to-weight ratio can reduce our energy consumption for key industries like aerospace and land transportation. Aluminium alloys have been widely adopted largely due to this reason. However, a key limitation for the aluminium alloys is their narrow servicing temperature, typically below 200 °C. Above this temperature threshold, more expensive alloy species, e.g., titanium alloys, need to be employed. In this work, we aim to design an aluminium-iron alloy which has microstructural stability above 200 °C. Aided by the rapid solidification feature inherent to the metal additive manufacturing process, nanoscale metastable precipitates were found to be present in the as-built materials, instead of the conventional stable but detrimental precipitate variants. Moreover, the use of iron as the main alloying element reduces its negative influence during the recycling process, hence improving the alloy's sustainability.

KEY WORDS: Alloy design; Sustainability; Al-Fe alloy; Additive Manufacturing; High-temperature.

IMPROVED STRENGTH PROPERTIES OF LPBF INCONEL 718 THROUGH PROCESS OPTIMIZATION AND THERMOMECHANICAL TREATMENT

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ABSTRACT

The use of LPBF in the aerospace sector promises significant advantages from manufacturing complex and integrated parts such as turbine blades or combustion chambers with an internal network of cooling channels [1]. However, the limits of the component geometries that can be achieved economically as well as the LPBF materials properties still pose sizable challenges. Despite the large number of studies carried out to date, further research is required to unravel the correlation between process parameters, subsequent heat treatments and the resulting mechanical and microstructural properties. The LPBF solidification process determines the microstructure and texture and has a complex dependence on the laser parameters, which, if not optimized carefully, can lead to unexpected loss of alloying elements, high residual stresses, cracking and other defects.

In this study, the effects of the LPBF process parameters and subsequent heat treatments on the resulting mechanical and microstructural properties of Inconel® 718 will be presented. The parameters were optimized and a suitable heat treatment designed to improve the properties of the material by adapting its microstructure and reducing the formation of Laves- or δ-phase precipitates. Orientation effects due to texture or layered non-fusion defects were considered for mechanical characterization using tensile specimens. Different heat treatment conditions including double ageing and HIP were studied and mechanical properties correlated with the corresponding microstructures and phase compositions, which have been quantified by high-energy x-ray diffraction. The strategy for achieving an optimal strength-ductility trade-off in LPBF IN718 will be discussed.

KEY WORDS: Inconel 718, laser powder bed fusion (LPBF), heat treatment, high energy X-Ray diffraction (HEXRD).

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Mechanical properties of Al-Mn-Cr-Zr based alloys tailored for powder bed fusion-laser beam

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ABSTRACT

Powder bed fusion-laser beam (PBF-LB) process is unique as it provides rapid solidification (cooling rates of 10^3-10^5 K/s [1], [2]). These benefits can be leveraged in alloy design to avoid solidification defects such as hot cracking and achieve fully dense samples (>99.8% relative density). The Al-Mn-Cr-Zr based alloys were designed to have high supersaturation of solutes, with Mn, Zr contents about three times the equilibrium amount while maintaining low amount of precipitates in as-built condition (<1%). Additional alloy design features involved higher amounts of Zr beyond solubility limit and addition of Mg for grain refinement of primary Al and higher solid solution strengthening respectively. The alloys have previously shown a strong precipitation hardening response of 40 HV via direct ageing between 350°C-375°C, reaching values corresponding to high strength Al alloys [3], [4].
This study investigates the mechanical response of the alloy system. The objective is to understand the structure-property relationship of these alloys, to identify the strengthening mechanisms, and the loss in ductility for different conditions (as-printed and peak aged). Samples were heat treated at two temperatures 350°C (HT1) and 375°C (HT2) for optimised hardening response for that variant. Seven machined samples each along build direction (XZ) and perpendicular to build direction (XY) were then tested in as-printed and two heat treated (HT1, HT2) conditions for all three alloy variants. A total of 126 tensile samples were thus tested to establish a statistically significant mechanical response of the alloy system and benchmark against available Al alloys. Fractography was conducted to understand the failure mechanisms after heat treatment. The fatigue tests were conducted in the HT2 condition where 30 samples along build direction (XZ) were tested for all three variants. This was again done to establish a clear S-N curve with run-out at $2*10^6$ cycles, which corresponds to the fatigue limit of the alloys. Complimentary fractography was done to understand the failure mechanisms. To elucidate the strengthening mechanisms of the alloys, transmission electron microscopy was conducted on peak aged samples to calculate the mean size and volume fraction of Al-Zr nanoprecipitates which are identified as the primary strengthening phase.
In conclusion, this study sheds light on these novel Al-alloy systems from the perspective of structure-property relationship. The alloys are shown to be competitive with other high strength Al-alloys. However, this study also shows that via controlled alloy design enabled through the PBF-LB process, this alloy system can produce medium strength (250 MPa yield), high elongation (25%) [5] to high strength (500 MPa yield), reasonable elongation (5%) alloys. Additionally, the low scatter in tensile and fatigue properties generated show a stable printing process, good quality powder and post processing treatments.

KEY WORDS: Aluminium alloys, Mechanical properties, Alloy design

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FROM COUPLING A CONTINOUS WAVE LASER WITH AN SEM TO ENHANCING MECHANICAL PERFORMANCE OF A DED STAINLESS STEEL

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ABSTRACT

One of the most important goals of research on engineering of stainless steels is to design microstructures that exhibit better mechanical properties than currently possible. The advent of metal additive manufacturing (AM) has opened up the possibility to design steel microstructures that present unprecedentedly high strength. However, this increase in strength is often accompanied with a decrease in ductility.

At the origin of this strength-ductility tradeoff lies the hierarchical microstructure arising from the highly non-equilibrium processes occurring during any metal AM process. In the case of stainless steels, the most commonly used AM techniques are laser powder bed fusion (LPBF) and laser metal deposition (LMD – a directed energy deposition-type technique). The melt pool dynamics, rapid solidification and solid-state thermal cycling occurring during both these processes result in a microstructure exhibiting physical and chemical heterogeneities ranging in size from a few tens of nanometers to several hundreds of micrometers. The primary contribution to the strength of the material arises from the smallest of these features, which are the precipitates, microsegregation cells and dislocation cell structures. Typically, LPBF stainless steel microstructures exhibit smaller features than the LMD ones, and hence the former exhibit higher strength and lower ductility than the latter.

Ductility of an AM steel can be improved by altering its microstructure. A commonly used strategy is annealing (isothermal heat treatment), which results in an increase in the sizes of physical and chemical heterogeneities. However, increasing the feature sizes inevitably results in the decrease in strength.

In this work, a new strategy is proposed to engineer the microstructure of LMD 316L stainless steel in such a way that it improves its strength without any decrease in ductility. The strategy involves using as-built LMD 316L stainless steel as the base material and performing post-process laser scanning on its surface using parameters similar to those used in LPBF processes. The sandwich microstructure has the as-built LMD microstructure at its core and a microstructure resembling an LPBF microstructure on its surfaces.

Identifying the appropriate laser scanning strategy to engineer microstructures with desired responses requires performing a parametric study in conjunction with microstructure characterization before and after lasering. To facilitate such studies, a novel coupling between a continuous wave (CW) laser and a scanning electron microscope (SEM) has been designed. In this talk, this CW laser-SEM coupling and the series of studies conducted with it that led to the design of sandwich microstructures exhibiting improved strength-ductility tradeoff and other mechanical performance will be presented.

KEY WORDS: microstructure engineering, post-processing, mechanical properties, scanning electron microscopy, lasering.

SELECTIVE LASER MELTING OF BULK METALLIC GLASSES FOR ENERGY APPLICATIONS

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ABSTRACT

The on-going energy crisis demands an extensive research into new alternatives for enhancing the energy efficiency in electric motors. As a probable solution to this, soft magnetic materials (SMM) portray excellent properties with high saturation flux density (B_S) and low coercivity (H_C)[1]. SMMs possess the ability to cater to this need, as they can substantially increase the efficiency in electric motors by reducing the core losses. Although promising, soft magnetic Fe-based amorphous metals need further research to overcome production challenges, as the need for high cooling rates to generate a significant fraction of the amorphous phase severely limits their production to thin ribbons resulting from rapid solidification processes such as melt spinning. Earlier work on additive manufacturing (AM) parameter optimization of an Fe-Si-B-based bulk metallic glass (BMG) has, however, shown promise for the fabrication of relatively large net-shape rotors [2].

In this work we carry out process optimization for producing an Fe-based metallic glass composition (Fe-Si-B-Cu-Nb) using the selective laser melting (SLM) process. Process optimization is highly complex, as printing conditions favoring high densities usually lead to low fractions of the amorphous phase. Here, exhaustive iterations on 3 major SLM printing parameters, namely, laser power (W), scan speed (mm/s), and layer thickness (μm) are performed to produce simple geometry specimens. Next, the SLM parameters, the density of parts, the heat affected zone (HAZ) or meltpool morphologies, and the degree of amorphicity have been correlated with the mechanical and magnetic properties. In order to achieve this, complementary structural characterization techniques, including scanning electron microscopy (SEM), X-ray diffraction (XRD), and differential scanning calorimetry (DSC) have been utilized in conjunction with image analysis tools. The mechanical and magnetic behavior was subsequently characterized via nanoindentation tests and using a vibrating sample magnetometer (VSM), respectively. The outcome of this work will provide guidelines for the design

of soft magnetic bulk metallic glass components with more complex geometries and improved energy efficiency.

KEY WORDS: Additive Manufacturing, Bulk Metallic Glasses, Selective Laser Melting, Soft Magnetic Materials, Heat Affected Zone, Degree of amorphization.

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DEVELOPMENT OF HIGH STRENGTH ALUMINIUM ALLOYS LEVERAGING RAPID SOLIDIFICATION DURING LASER-POWDER BED FUSION

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ABSTRACT

The unique thermo-kinetic characteristics of laser-powder bed fusion (L-PBF) can be exploited for development of high strength Al alloys. There is an increasing trend to move away from conventional alloys used for traditional manufacturing processes like casting and forging to innovative alloys in L-PBF [1]. This talk will review ongoing research on development of new aluminium alloys with transition metals (Fe, Cr, Si, Ti, Zr, etc.) having low diffusion coefficients in the aluminium lattice, which are proposed as heat-resistant alloys which can be processed by L-PBF [2]. AlFeCrX (X=Si, Ti, Zr, etc.) metal powders have been fabricated via gas atomization and their characteristics such as morphology, composition and intermetallic phases have been evaluated. In addition, characterization of the melt pool shape has been considered in order to optimize the printing process parameters, such as laser power and scan speed, and avoid defects in the new developed compositions. Using the optimized LPBF parameters, highly dense (~99.8%) samples have been fabricated. Nevertheless, the microstructures and mechanical properties obtained depended strongly on the composition and the input energy densities due to the combinations of laser processing parameters.

KEY WORDS: Laser-powder bed fusion (L-PBF); rapid solidification; aluminium alloys; transition metals; microstructure; mechanical properties.

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PBF-LB MANUFACTURING AND MICROSTRUCTURAL ANALYSIS OF ALUMINUM/TiC MMCs

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ABSTRACT

Aluminum offers lightweight potential and good corrosion resistance which is required in many applications. Unfortunately, the mechanical properties like tensile strength, elastic modulus and wear resistance are often insufficient. The introduction of hard ceramic particles induces several strengthening mechanisms which can offset these drawbacks. The properties of these Aluminum Matrix Composites (AMCs) are dependent on shape, size, content, and distribution of the reinforcement phase. Laser Powder Bed Fusion (PBF-LB) is a technique that offers the potential to overcome limitations in geometry complexity and machining that is connected to classical casting routes of AMCs. To access the full potential of combining additive manufacturing and AMCs, restrictions in fabrication must be elucidated, and the effect on microstructure and mechanical properties needs to be investigated.
In the current study, powder blends have been prepared by mixing TiC particles of different size (micro- and nano-scaled) with powder of a common aluminum casting alloy (AlSi7Mg0.6). The processing difficulties, primarily parameter window shift and powder flowability, were investigated. While the TiC microparticle composite shows a beneficial expansion of the process window, the TiC nanoparticle composite reveals a movement of the process window towards higher laser powers (compared to the pure matrix material). Regarding the powder flowability, the nanoblend offers the desired behavior, while the flowability of microparticle blend suffers significantly by TiC addition. Both aspects define an upper limit for the particle content. Investigations by SEM and EDS technique revealed the particle distribution in the final parts and indicate a high stability of TiC in liquid aluminum. Furthermore, the microstructures exhibited distinct sintering of TiC nanoparticle agglomerates, forming TiC microparticles in the final composite. The impact of TiC on the final grain size by heterogeneous nucleation has been elucidated via EBSD analysis. It could be shown that the grain refining efficiency depends on particle size as well as content and is spatially inhomogeneous for low particle contents. Higher TiC contents, however, lead to a fully grain refined microstructure. Finally, hardness measurements have been conducted to evaluate several influence factors on the strength: particle size, particle content and processing conditions. Hardness increasements of more than 10 % have been attained. The examinations could demonstrate the feasibility of PBF-LB fabricated dense AMCs, offering enhanced mechanical properties without texture. Despite the difficulties that are present in this approach, an exploitation of the advantages offered by PBF-LB is possible.

KEY WORDS: metal matrix composites, aluminum matrix composites, composites, advances in processing, grain refinement, strengthening

PROCESSING OF CP TITANIUM IN REACTIVE CO_2 AND N_2 ATMOSPHERES

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ABSTRACT

Processing of titanium in PBF-LB is commonly performed in argon (Ar) and helium (He) atmospheres due to its high affinity for oxygen (O_2) and nitrogen (N_2). The high reactivity of titanium in these atmospheres can be exploited for in-situ precipitation in Ti-containing powder blends. In a steel matrix, for example, titanium oxide and nitride are well known grain refiners and improve hardness by particle reinforcement. High heating and cooling rates in PBF-LB together with a comparatively low reactivity of iron-based materials mean that only powder blends with a high Ti content can be expected to display a significant interaction with the process atmosphere. Pure titanium, however, is too reactive to be manufactured in atmospheres like pure carbon dioxide (CO_2) and N_2 as laser exposure leads to ignition of the powder. Nevertheless, we would like to study the reaction between Ti and reactive process gas atmospheres to understand the processes occurring between atmosphere and material during manufacturing. We solve this problem in the current study by re-melting pure Ti in the absence of powder. This enables the investigation of the interaction between Ti and CO_2 and N_2 in a safe manner.

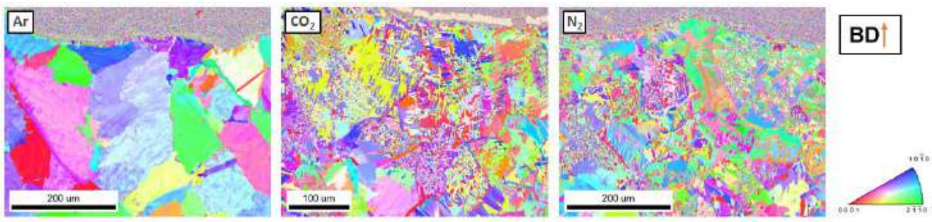

Figure 1 Surface microstructure of laser re-melted CP Ti in Ar, CO_2 and N_2

We first printed CP Ti in an Ar atmosphere. To prevent ignition, the powder is removed after the build. Next, samples are re-melted in Ar, CO_2 and N_2 with different laser powers (100 – 800 W), scan speeds (250 – 700 mm s^{-1}) and different spot sizes (80 µm and 400 µm) to reveal the influence of the process parameters on the material-gas interaction. Before re-melting, PBF-LB processed CP Ti shows large, elongated grains with a strong texture in build direction. The uptake of N, O and C from both reactive atmospheres leads to the formation of martensite within, and recrystallized grains in between the melt pools. Grains in the vicinity of melt pool boundaries are ultra-fine compared to the inner part of the melt pool. In comparison, Ar re-melted samples show no martensite but large equiaxed grains. Furthermore, the formation of a dendritic layer on top of CO_2 and N_2 re-melted samples are observed. The layer thickness increases with heat input and correlates to the melt pool size. The formation of Ti-carbide and -oxide for CO_2 re-melting and Ti-Nitride for N_2 re-melting, respectively, is revealed by EDS.

KEY WORDS: Alloy Design, Material-Gas Interaction, Titanium, Process Atmosphere.

EXPLORING DYNAMIC MECHANICAL PROPERTIES OF AlSi10Mg LATTICE STRUCTURES MANUFACTURED BY SELECTIVE LASER MELTING VIA EXPERIMENTAL AND NUMERICAL ANALYSIS

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ABSTRACT

Lattice structures have attracted a lot of attention lately in the additive manufacturing industry with their high specific modulus and high specific strength, as well as their energy absorption capacity. Selective laser melting (SLM), an additive manufacturing method, has many advantages over traditional methods in the production of complex geometric structures such as lattice structures due to its design flexibility [1]. Lightweight AlSi10Mg alloy has high strength and good mechanical properties, making it a popular choice for aerospace and automotive applications.

AlSi10Mg lattice structures are particularly effective at absorbing and dissipating impact energy during crashes or collisions. Moreover, lattice structures deform in a way that dissipates energy, acting as a shock wave that travels through subsequent layers [2]. This ability to absorb and dissipate energy can help to prevent or reduce the penetration of a projectile. In order to effectively design a lattice structure for ballistic penetration, numerical models, such as the Johnson-Cook material properties model, are an important tool to simulate the behavior of materials under high strain rate conditions.

Despite the several experimental and numerical studies concerning on finding suitable Johnson-Cook model parameters of additively manufactured AlSi10Mg [3-5], there is a still need for a comprehensive experimental study to identify all relevant parameters. In addition, studying the dynamic mechanical properties of different AlSi10Mg lattice structures could provide valuable insight into their ballistic penetration performance.

To address these gaps, in this study, Johnson-Cook material and failure model parameters of AlSi10Mg alloy produced by SLM by utilizing series of experimental tests, including room temperature and high temperature quasi-static and dynamic compression and tensile tests. The samples for these tests as well as lattice structures that were tested under SHPB test setup to reveal their dynamic mechanical properties were produced on an SLM device (Ermaksan Enavision 250). A laser power of 320 W, a scanning speed of 800 mm/s, a hatching distance of 100 µm and a layer thickness of 30 µm processing parameters were used for manufacturing of the specimens. Auxetic, diamond and face-centered cubic (FCC) topologies were selected for the lattice structures.

The numerical high-strain tests of AlSi10Mg lattice structures were modelled in the Ls-Dyna simulation package. The deformation behaviour of the lattice structures was simulated by using the self-obtained Johnson-Cook model parameters. As an example, the experimental and numerical

model views of an FCC lattice structure with 1.09 mm strut-diameter and 4 mm unit cell size before and after compressive SPHB test are presented in Figure 1. The total deformation rate, the type of deformation and the strain rate values of the numerical model are in good agreement with those of the experimental results.

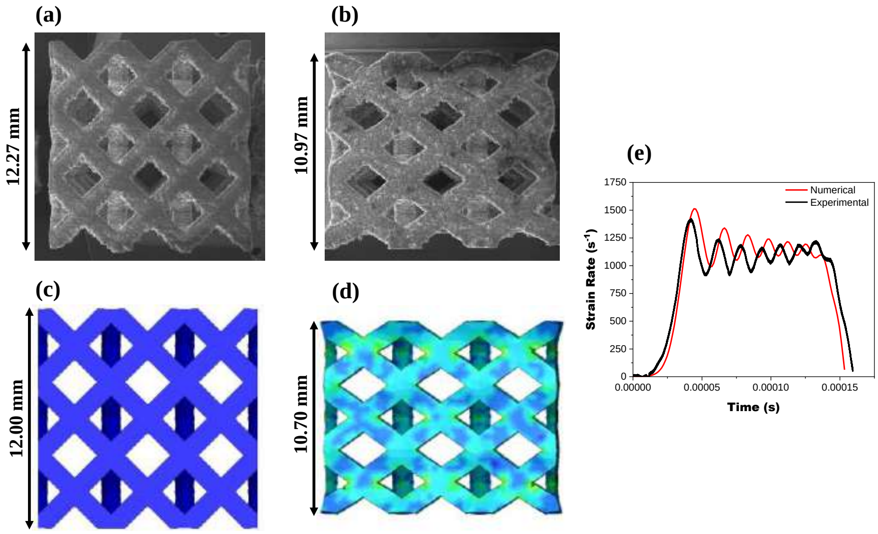

Figure 1. (a, b) Scanning electron microscope (SEM) image and (c, d) the numerical model of an FCC lattice structure. ((a, c) as-built and (b, d) after the SHPB test at a strain rate of 1100 s^{-1}). (e): Strain rate vs. time curves obtained from experimental and numerical test

The dynamic compressive behaviour of AlSi10Mg alloy lattice structures under various strain rates is investigated via SPHB tests and numerical methods. Through this investigation, we derived the Johnson-Cook model parameters of additively manufactured AlSi10Mg, which accurately simulated the dynamic behaviour of the lattice structures. The findings of this study will be useful for future investigations into the ballistic penetration of AlSi10Mg lattice structures.

KEY WORDS: Selective laser melting, lattice structures, AlSi10Mg, split-hopkinson pressure bar, dynamic mechanical properties.
ACKNOWLEDGEMENT: This work has been supported by The Scientific and Technological Research Council of TURKEY (TUBITAK) under the Project Grant No: 221M604.

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NEUTRON IMAGING CHARACTERIZATION OF FUNCTIONALLY GRADED STRUCTURES BUILT BY LASER POWDER BED FUSION

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ABSTRACT

Additive Manufacturing (AM) has been extensively used for 3D printing of metallic structures consisting of single alloys. Recently Multimaterial Additive Manufacturing has gained increasing interest for bimetal structures manufactuting, due to the freeform fabrication and the ability to control compositional changes within a few hundred micrometers [1]. One pair of alloys that have been prioritized is stainless steel with copper and its alloys, as the combination of high strength and wear-corrosion resistance of the former with the high thermal and electrical conductivity of the latter, constitute this bimetals as possible candidates for die-casting, machine tooling and for components of power generators. Until now, the emphasis has been given to fabricating bimetal stainless steel-copper alloy parts, by depositing one alloy over the other, either through Laser Powder Bed Fusion (LPBF) or Direct Energy Deposition (DED) [2], [3]. However, such structures suffer from defects in copper (lack of fusion, keyhole porosity) attributed to the high thermal conductivity, low absorptivity, and high reflectivity of copper. On the other hand, depending on the processing parameters, these materials are prone to relatively strong texture development which can greatly affect the mechanical properties, the anisotropy, and the preferred deformation mechanisms.
By premixing powders of different alloys, it is possible to deposit both alloys within the same layer, with varying compositional ratios. The advantage of this approach is that the concurrent printing of 316L and CuCrZr can alleviate the insufficient melting of copper, as convection flow from liquid steel and conduction heat from the solid steel will increase the total heat input to the copper part.
Here we studied bimetal LPBF-built samples consisting of 316L stainless steel and 316L-CuCrZr mixed at different wt.% ratios, employing Neutron Bragg Edge Imaging [4] to characterize crystallographic texture and residual stress distributions across the interfaces and polarization contrast neutron imaging [5] to map the formation of ferrite (BCC), attributed to the diffusion of Ni (austenite stabilizer) from steel to copper.

KEY WORDS: functionally graded structures, Laser Powder Bed Fusion, Bragg edge imaging, Polarization contrast neutron imaging.

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USING MACHINE LEARNING TO OPTIMIZE LASER-POWDER BED FUSION (L-PBF) PARAMETERS OF METALLIC MATERIALS

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ABSTRACT

The final properties of parts made via laser-powder bed fusion (L-PBF) are extremely sensitive to the processing parameters such as power, time exposure, hatch distance, etc. As such, it is a significant challenge to identify the optimal operating parameters to produce parts rapidly and reliably with the desired properties without defects [1]. Artificial intelligence (AI), and in particular machine learning, is an innovative tool that can be employed for process optimization and predicting the microstructural and mechanical properties of fabricated parts [2]. However, to generate a robust machine learning model, sufficient amount of training data is required, which is time-consuming and very expensive using L-PBF. In this study, transfer learning artificial neural network (TR-ANN) is proposed to overcome this inconvenience and optimize the processing parameters in AlSi10Mg alloy additive manufacturing [3]. To generate the processing window, firstly base model is trained by the data from literature and next, training the target model is carried out by the data experimentally obtained from printed AlSi10Mg samples. The TL-ANN models predicted the density, melt pool depth, and melt pool width of the AlSi10Mg printed parts with an R^2 score of 0.977, 0.966, and 0.987, respectively. In addition to validate the performance predictions made by the TR-ANN machine learning model, this approach is generalized for different metallic materials, such as SS316L and a new aluminium alloy (AlFeCrSi) specifically designed for L-PBF.

KEY WORDS: Machine learning, Artificial neural network, Transfer learning, LPBF, AlSi10Mg, SS316L; AlFeCrSi.

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Solid-Liquid Additive Manufacturing & Induction Melting fabrication of 316L reinforced Al & Cu metal-metal composites

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ABSTRACT

Composite metallic structures gain interest as possible candidates in technological applications, where combined properties provided by different alloys are required. Multiple fabrication processes have been utilized for such structures, including extensive plastic deformation [1], powder metallurgy [2] and solid-liquid compound casting [3, 4], where a molten alloy is cast within the substrate of another coated and preheated alloy. Additive Manufacturing (AM) can set new horizons in the field of compound casting, providing geometrically complex structures, which do not only act as substrates for the casting of the second alloy, but also play the role of a reinforcing structure, increasing the overall mechanical performance of the final metal-metal composites.
In our study, a prototype AM + Induction Melting process is proposed. Laser Powder Bed Fusion is used to print lattice structures made of 316L, which are then infiltrated with CuCrZr or AlSi10Mg powders, followed by melting through induction heating, resulting in the formation of Al or Cu matrix composites. Neutron Tomography of the as-printed 316L structures (ICON Beamline PSI) reveal the 3-dimensional distribution of pores, while Neutron Bragg Edge Imaging (POLDI Beamline) is utilized for the strain and texture analysis of the 316L-Cu composites. Polarized Neutron Imaging (BOA Beamline) depicts the distribution of ferrite on the interfaces between 316L and copper. For the 316L-AlSi10Mg composites, EDS elemental mapping and XRD analysis show the presence of multiple binary (Fe-Al) and ternary (Fe-Al-Si) intermetallics in the vicinity of the interface. Nano-hardness maps and compression tests are utilized for the evaluation of the mechanical performance of the composite materials.

KEY WORDS: metal-metal composites, laser powder bed fusion, induction melting, neutron imaging

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MULTI-MATERIAL LASER POWDER BED FUSION: INVESTIGATION OF CO-PROCESSABILITY AND PROCESS LIMITATIONS

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ABSTRACT

Additive manufacturing (AM) reunites high flexibility in terms of achievable geometries[1] and near zero material waste[2] due to its near-net shape manufacturing capacity[3]. Among AM technologies, laser powder bed fusion (LPBF) is known for its fine features[2], making it suitable to manufacturing small components, and also for its material flexibility. A large variety of metals and metallic alloys can be employed[4] with near full density, due to full melting of the powder in this process. According to Neirinck et al. (2021)[2], the next evolutionary step in AM industry is expected to come with the development of multi-material processes. Chen et al. (2020)[1] associate this to the fact that these techniques allow bimetallic structures to be designed in multiple shapes and with smaller process thermal stress, which benefits the interfacial bonding between the different materials. In this sense, multi-material laser powder bed fusion (MMLPBF) expands the advantages of LPBF by providing a wider design space, opening new possibilities in 4D printing and allowing functional parts to be produced without further joining and assembly operations. The technique also has potential to save expensive feedstock, since selective deposition would allow it to be placed only where required in the design.

However, MMLPBF is not just another step in the evolution of LPBF but must be researched extensively to comprehend its limitations in terms of geometry, resolution, and materials. Current solutions for MMLPBF resort to selective deposition/removal, nozzle-based deposition, or electrography, which are limited in deposition precision. However, due to the melting nature of the process, resolution is not governed exclusively by equipment limitations, but also by material intermixing. Laser exposure strategies to control penetration into the neighboring materials are thus fundamental to achieve structures with desired properties. The degree of intermixing is also affected by the location of each material within the workpiece. Wei and Li (2021)[5] highlight that denser elements sink to the bottom of the melt pool and gather near its boundary. However, physical phenomena such as Marangoni convection and recoil pressure also influence melt pool formation and its characteristics. Additionally, designs that generate heat accumulation, such as sharp corners and overhangs, can increase the presence of defects in the printed part. Therefore, systematic studies on geometry limitations are also crucial for the breakthrough of MMLPBF. In this context, bimetallic structures obtained in this study are characterized through optical and scanning electron microscopy and x-ray diffraction to investigate how part quality is influenced by manufacturing strategies, promoting a clearer understanding in terms of the limitations of the process. It is observed that the printing resolution is affected by the nature of the feedstock, given the material-dependency of phenomena that govern melt pool formation. Additionally, the presence of a second feedstock in the powder bed affects heat transfer, creating limitations in terms of geometry that are not directly transferable from single-material LPBF.

KEY WORDS: multi-material, additive manufacturing, laser powder bed fusion, bi-material feature resolution.

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Influence of nanoparticles on the surfaces of fluidized-bed modified metal alloy powders for additive manufacturing.

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ABSTRACT

The need to produce complex parts in an efficient, easy, and simple way makes additive manufacturing (AM) a key element in the industrial future [1]. The savings in time, material and cost, the versatility of AM, the possibility of providing new properties and improving characteristics make AM an area of interest at industrial level. However, there are a few problems in the industry for obtaining metal or metal-ceramic components by AM. There is a limited range of raw materials available for use in AM equipment. In addition, there is a lack of understanding of the composition - processing - microstructure relationships and the relationship between the raw material used and the properties of the final components produced [2]. The final components may present microstructural defects such as: large columnar grains, cracks, pores, particular compositional variation without melting, etc. [3]. To overcome the problems and defects, it is necessary to produce feedstock with characteristics adapted to AM, such as the introduction of second phase particles that provide properties or help to control the microstructure or grain growth. These strategies are under development and so far, have not been achieved successfully or in the required quantities. To achieve the functionalisation of large quantities of powder, this work proposes to use techniques based on fluidised bed reactors (FBR) [4].
The main objective was the design and development of a new fluidised bed technology to enable the large-scale development of new smart hybrid powders, which can be used in additive manufacturing processes. In this work, the flow, density, composition, and roughness properties of modified powders for AM were evaluated. Surface modification of ametallic host powder (Al2024) with a ceramic (SiC) guest powder was carried out in a fluidised bed reactor. SiC nanoparticles were produced by milling and were dispersed in colloidal suspensions. The zeta potential and rheological properties of the suspensions were studied to determine their stability and homogeneity and their maximum solids content was determined by means of a mathematical model. Different additives were evaluated to ensure the of the adhesion guest SiC nanoparticles onto the host Al particles. The surface modification process was carried out in a fluidised bed reactor which was characterised to determine the minimum fluidisation rate. The SiC nanoparticles were atomised and deposited onto the Al2024 and homogeneously modified Al2024 powders with SiC nanoparticles were obtained. The modified powders were characterised by different techniques to observe the influence of SiC nanoparticles on the Al2024 particles. Optimal characteristics were found to be used in equipment in AM processes, and the powder surface modification process is suitable to be taken to industrial level.

KEY WORDS: Additive manufacturing, surface modification, fluidized bed, zeta potential.

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Additive Manufacturing of Oxide Dispersion Strengthened (ODS) Alloys

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ABSTRACT

Oxide dispersion strengthened (ODS) alloys such as ODS Ni alloys or ODS steels offer an unmatched combination of deformation-, creep-, coarsening-, oxidation- and corrosion resistance. However, while these fundamental material properties are exceptionally well suited to power generation and engines, the manufacture of components using ODS alloys are currently subject to severe economic and technical barriers. Conventional wisdom is that powder metallurgy (PM) is the only available method to create ODS alloys from powders to which oxides were added via ball milling: if these composite powders are melted via traditional methods, their oxide dispersoids are lost via one or more of coarsening, dissolution, agglomeration into inter-dendritic space, and floating to the surface of the ingot ('slagging"). The low machinability of these highly-reinforced alloys motivates research in additive manufacturing as an alternative fabrication method, in particular via rapid melting and solidification. Therefore, there has been an increasing interest in the fabrication of ODS alloys via laser-based powder-bed fusion (L-PBF) or laser direct metal deposition (DMD) in the recent years.
This presentation summarizes the research activities in the field of AM of ODS alloys performed at Empa and Northwestern University over the last ~10 years. During this time, a variety of different solid-solution strengthened and precipitation strengthened Ni alloys **[1–5]**, Al alloys **[6]**, γ-TiAl and Ti alloys **[7–9]** as well as steels were reinforced with nanometric oxides (Y_2O_3, HfO_2, Al_2O_3) and successfully fabricated by L-PBF and DMD. The main findings with regard to microstructure formation during AM, microstructure stability during heat treatments as well as the mechanical performance at elevated temperature of some selected ODS alloys will be presented and the main 'lessons learned' with regard to the AM fabrication of such alloy will be discussed.

KEY WORDS: ODS alloys, laser powder bed fusion, microstructure stability, creep performance

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Microstructure control of additively manufactured Ni-based superalloy with high gamma prime volume fraction to improve high temperature mechanical properties

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ABSTRACT

Additive manufacturing is an innovative manufacturing technology for realizing complex structural parts. In particular, the selective laser melting (SLM) can produce highly precise parts with high dimensional accuracy. By applying the SLM to manufacturing of hot parts of the industrial gas turbine, improvement of gas turbine efficiency becomes possible thorough realization of advanced cooling structure.[1] Ni-base casting alloys are applied to the important hot parts of the gas turbine. Therefore, an evaluation of the applicability of the additively manufactured Nickel-based superalloys to manufacturing of hot parts was carried out.

Although SLM-type additive manufacturing technology is suitable for accurately building fine complex structures, it is essentially inevitable to include small defects in the material because it is formed by stacking small molten beads. Since the size and amount of defects are greatly affected by the building conditions, it is very important to adjust the conditions properly. The effect of building conditions on the generation of defects in a material was investigated. The energy density in laser irradiation varies depending on the building conditions, and if the density is too small, defects due to insufficient melting occur. On the other hand, if the energy density is too large, defects due to overheating occur. Therefore, it is necessary to control the building conditions in the appropriate range.

A major issue in the application of additive manufacturing to Ni-based high strength alloys is the compatibility of material strength and crack suppression in building. Although strengthening by gamma-prime phases is the most effective for the alloys, addition of Al or Ti to increase the amount of the gamma-prime phase greatly reduces weldability. Cracks are more likely to occur during building, and they occur along grain boundaries. Investigation of the alloy composition to suppress crack generation was tried on the Ni-base alloy similar to IN 939. As a result, it was succeeded the modification as a weldable high-strength alloy. On the other hand, solidification in the SLM process progresses extremely fast, so very fine crystal grains are formed. The additively manufactured alloy has fine columnar grains, and it indicates strong anisotropy in tensile strength, creep strength and ductility. Especially, tensile and creep ductility of the additively manufactured alloy in perpendicular direction to the building direction were low, and it seemed to be easy to fracture along the grain boundary of the fine columnar grain. In order to improve the high-temperature strength properties, the change of the fine grains was tried. In addition, the control of precipitation of carbides in additively manufactured alloy is also important. The precipitation of carbides in the additively manufactured alloy is greatly different from that of cast alloy because of the rapid solidification. In order to secure the strength properties of the additively manufactured alloy, it is important to control the precipitation of carbides peculiar to additively manufactured alloy. The

adjustment of the precipitation behavior based on the phase equilibrium calculation results was carried out. Finally, the strength properties of the additively manufactured alloy were improved through the microstructure control, and verification of the hot parts in the actual plant is currently advanced.

KEY WORDS: additively manufactured Nickel based superalloys, selective laser melting, high temperature mechanical strength.

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Development of Tantalum-Tungsten Metal Matrix Composites by L-PBF

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ABSTRACT

In particulate metal matrix composites (MMCs), a metal matrix phase is reinforced by particles leading to enhanced properties potentially exceeding the characteristics of its constituents. The addition of a reinforcement material to a metal matrix can enhance its mechanical performance by combining advantageous properties like strength and ductility. Additive manufacturing (AM) and laser powder bed fusion (L-PBF) in particular, open up the potential to produce MMCs with near-net-shape as well as the possibility to create new material combinations. However, a detailed understanding of the behavior of the materials and their interaction during the process itself is necessary to produce a material that inherits favorable material properties.

A new material combination of tantalum (Ta) as metal matrix and spherical tungsten (W) particles as reinforcing phase is chosen to achieve a highly dense MMC with expedient strength and ductility. The relatively small difference in the melting points of W (3422 °C) and Ta (3020 °C) complicates melting of the Ta matrix without fusing the W particles. Reflectivity measurements of the separated metal powders reveal that the lower energy absorption of the Ta powder even enhances this challenge. In order to find suitable L-PBF process parameters, single laser track experiments are conducted with a powder mixture of W and Ta to determine the melting and not just yet melting laser energy range. Based on these results, experiments including a master-slave exposure strategy are conducted. In this regard, a pre-heating laser is followed by a second laser with adjusted energy input. The specimens are then investigated and evaluated by metallographic means.

KEY WORDS: laser powder bed fusion, metal matrix composites, master-slave exposure strategy.

Challenges in PBF-LB/M Processing of Al5052 Aluminium Alloy

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ABSTRACT

The interest in laser beam powder bed fusion (PBF-LB/M) additive manufacturing (AM) of aluminium is constantly growing. Currently, the most popular group of AM-dedicated alloys is based on the Al-Si system (4xxx series), while other Al-alloy groups are in the minority.

This work presents the main technological challenges in PBF-LB/M processing of the 5xxx series. Al5052 alloy is used as an example. Discussions include insights into the hot and liquation cracking of aluminium alloys. The analyses include process parameters' impact on porosity, cracks, and microstructure. Results are presented to illustrate the challenges mentioned above. Potential directions to overcome the challenges are also introduced.

Background. Aluminium alloys, due to their properties such as low density (2.8 g/cm^3), good thermal and electrical conductivity, high strength-to-density ratio (up to 200 MPa/kg) and corrosion resistance, are widely used in aerospace, space, marine and automotive industries [1]. The most common aluminium alloys categorization is based on the main alloying elements ratios (9 groups). These 9 groups can also be classified at a higher level according to their reinforcement mechanisms. Therefore, the 2xxx, 6xxx and 7xxx series alloys belong to the group of precipitation-hardening alloys. Casting alloys (1xxx, 3xxx, 4xxx and 5xxx) are characterized by a strain-hardened reinforced mechanism. So far, the most popular aluminium alloys processed by PBF-LB/M are cast alloys of the 4xxx series, such as AlSi12, AlSi10Mg, and AlSi9Cu3. However, series 5xxx is also gaining attention due to its high corrosion resistance [2]. PBF-LB/M processability is achieved, for example, by adding Sc [3]. Nevertheless, despite good weldability, 5xxx series aluminium alloys are challenging to process in the LPBF technology, mainly due to their tendency to hot cracking during solidification. The reason for the hot cracking trend of these alloys is their high volume shrinkage, high coefficient of linear thermal expansion and significant difference between liquidus and solidus temperatures [4]. In addition, the tendency to micro-segregate major alloying elements or impurities (e.g. Mg, Si, Cu) further lowers the pour point.

Methodology. Based on the literature, Thermo-Calc simulations and empirical data from processing other aluminium alloys, the initial PBF-LB/M process window for Al5052 was set up. The initial process parameters were used to further optimise and select the process parameters. Samples are evaluated by the porosity level (ultimately striving to obtain the lowest possible porosity, and elimination of cracks). The following analyses were carried out:

(1) Thin-wall test based on multi-factor DOE. Evaluation of the quality of thin walls includes the analysis of such factors as wall thickness, their perforations, continuity and the amount of sintered powder on the side surface;

(2) Selection of process parameters (process window for bulk samples), crack density analysis depending on the geometry of the samples – evaluation of porosity, geometry and cracks;
(3) Metallographic analysis of bulk specimens and hardness measurements.

Results. The obtained specimens have a hardness of 60±5 HV0.3, comparable to the conventional Al5052. Printed alloy is characterized by a typical microstructure for aluminium alloys processed by PBF-LB/M, namely fine cellular-dendritic network and columnar grains oriented with printing direction. In addition, all fabricated samples are characterised by solidification cracks (Fig. 1) and gaseous pores — the level of cracks and pores dependents on process parameters and sample geometry.

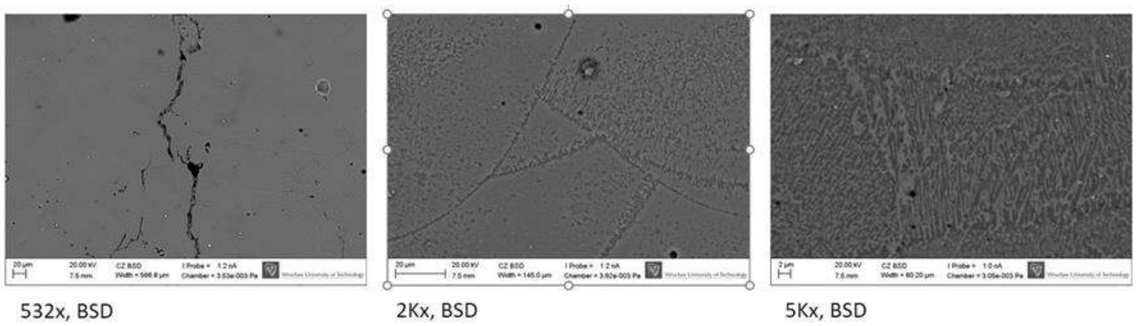

Figure 1. (a-c) Analysis of the microstructure as well as the size and orientation of grains on the example of a sample made of Al5052 alloy. Weck's reagent, SEM.

Conclusions. The process parameters optimization can decrease cracking. However, cracks were not successfully eliminated. Possible solutions to eliminate cracking within PBF-LB/M printing of Al5052 alloy is to add alloying elements, which can reduce the hot cracking tendency in the alloy.

KEYWORDS: aluminium alloys, PBF-LB/M, microstructure, process parameters

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ACKNOWLEDGEMENTS. This research was funded by the National Centre for Research and Development in Poland (Grant No. LIDER-XII/0117/L-12/2020: New generation aluminum-based alloys processed by laser additive manufacturing for industrial applications (AddAluMat)).

Composite Extrusion Modeling, a promising tool to manufacture a FeCrAlMoTiNi High Entropy Alloy

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ABSTRACT

Composite Extrusion Modelling (CEM) technology is a 3D printing additive manufacturing (AM) process, which combines the advantages of this type of processing with the ease of adaptability at an industrial level for companies using Metal Inyection Moulding (MIM) as a processing route. Since CEM is based on feedstock knowledge developed for MIM, adapting it as a manufacturing route for MIM companies can provide them with an edge in terms of increased production speed, as well as reducing production costs by avoiding the use of moulds. Furthermore, by optimizing the sintering process after CEM-printing, it is eliminated the need for subsequent heat treatments, which are essential in other laser-based AM technologies.

A responsible and sustainable use of raw materials can be achieved, as the starting powder is not restricted in terms of particle size or morphological properties. Due to the absence of a powder bed required in other AM technologies, it also involves a smaller volume of raw material. In this way, CEM avoids the high level of material waste in powder form, resulting in a much more efficient use of raw materials. Compared to powder bed laser systems, CEM offers the advantage of being able to manufacture materials from any powder mixture, making it possible to manufacture metal matrix composites, cermets, or any dissimilar alloy. It is possible to print any mixture that can be sintered.

As a result of establishing a niche use for a growing sector, any breakthrough or proposal has a significant impact. From a scientific and industrial point of view, it is a relatively young technology (it was developed in 2018), so its development for a specific alloy has a high scientific impact.

In this work, the processing of the free Co high entropy alloy (HEA) FeCrAlMoTiNi [2], is proposed. This novel family of alloys has opened new doors due to its novel design principles. It is one of the most attractive lines of research the development of calculation tools for the prediction of phase formation in relation to its composition. However, previous work indicated that manufacturing techniques and conditions play a key role in the final microstructure (chemical vs. physical tuning).

To optimize the design, the extrusion speed is varied to maximize layer density and homogeneity. Then, after debinding the green parts, the sintering conditions are optimised, temperature-wise. Finally, a microstructural study is carried out and compared with previous results obtained after the manufacture of this original composition by other conventional and advanced sintering techniques.

KEY WORDS: Composite Extrusion Modeling, Process Optimization, High Entropy Alloys, Microstructural characterization

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Direct-Ink Writing of Titanium with Steel Spaceholders for Orthopedic Implants

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ABSTRACT

Titanium has experienced clinical success as a bone implant material due to its high fracture toughness, excellent corrosion resistance, and favorable biocompatibility properties. However, titanium has drawbacks in long-term implant reliability because of stress shielding (due to high stiffness) and poor bone integration. In this work, a low-stiffness titanium scaffold is additively manufactured via direct-ink writing (DIW) of a slurry of titanium powders and short steel fibers. After sintering of the Ti/steel printed struts, the steel spaceholder fibers are removed electrochemically. The scaffold then exhibits two levels of porosity, desirable for low stiffness and high osseointegration for orthopedic implants. First, the millimeter-wide channels within the printed lattice (macroporosity) allows for nutrient transport and vasculature/bone growth; second, dissolution of the steel spaceholders creates a microporous network which can promote cell movement and anchoring. Optical and scanning electron microscopy confirms the micropores size, orientation, and fenestrations within the struts. Uniaxial compression testing verifies that the scaffold has a low stiffness, reducing the effects of stress shielding. Synchrotron microtomography, performed at various stages through the process on the same specimen, reveals the evolution of porosity at various stages of the process, from printing, to sintering, to electrochemical dissolution.

KEY WORDS: Direct-Ink, Extrusion, Titanium, Steel, Spaceholder, Osseointegration, Microporosity

THE EFFECT OF SUBSTRATE SURFACE AND PROCESS PARAMETERS ON THE INTERFACE BETWEEN SUBSTRATE AND AM PART PRODUCED IN PBF-LB.

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ABSTRACT

Additive manufacturing (AM) can produce hybrid and lightweight components with complex geometries. Hybrid components can refer to a variety of things, such as parts made using a combination of two or more AM processes, components that integrate multiple alloys, or parts created by merging additive manufacturing with traditional manufacturing. These components could possess distinctive properties or features having the potential to revolutionize sectors like the aerospace and automotive industries by reducing fuel consumption and emissions while improving product performance. This research focuses on producing components having a combination of two alloys, out of which one alloy is processed by the traditional manufacturing method and the other using Laser powder bed fusion (PBF-LB). The joining of dissimilar alloys possess a significant challenge due to the potential formation of intermetallic phases and defects at the interface. These defects could result in interfaces with inadequate mechanical properties for their intended applications. Optimization of process parameters and process conditions might help overcome these challenges and produce strong and defect-free interfaces when producing hybrid structures. This study investigated the interface region between PBF-LB-produced AlSi10Mg and AA2139 AM alloy powders and AA2017, AA5083 and AA7075 substrates. The influence of parameters including laser power, scan speed, hatch spacing, layer thickness and substrate roughness have been studied. Depending on the combination of processing parameters used, the interface region exhibits various defects, such as cracks, inconsistent depths in the interface region, and lack of fusion. Metallographic analyses using optical and electron microscopy have been employed to investigate the microstructure, defects and extent of mixing of alloys. These investigations help in comprehending the intermixing patterns and the potential formation of intermetallic compounds and defects at the interface. Additionally, to investigate the influence of substrate roughness and printing parameters on the hardness of the interface, a microhardness test has also been performed.

KEYWORDS: Laser powder bed fusion, Hybrid-lightweight components, Dissimilar alloys, Surface roughness, Interface

PROCESS/MICROSTRUCTURES/PROPERTIES OF ADDITIVELY MANUFACTURED METALS AT LLNL

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ABSTRACT

At LLNL, laser powder-bed-fusion (L-PBF) is the predominant additive manufacturing (AM) technique to produce complex components and obtain materials with enhanced properties. Rapid thermomechanical cycles during L-PBF retain non-equilibrium microstructures in as-fabricated metallic alloys, typically resulting in improved properties. These microstructures are complex, and the effect of rapid solidification is material dependent. However, before L-PBF parts can be certified and used in their as-processed state, a fundamental understanding of the relation between microstructures and properties is crucial.

Here, an overview of several ongoing efforts at LLNL on characterizing L-PBF metals to understand, control, and eventually improve their mechanical and corrosion properties will be presented. We will first discuss L-PBF titanium alloys, showing the challenges of transitioning from martensitic Ti-6Al-4V to a β metastable Ti-5Al-5V-5Mo-3Cr to reduce part cracking by improving ductility. Next, we present ongoing work on combining L-PBF and multi-principal component alloys to produce high strength, high ductility materials. Lastly, we show results using L-PBF 316L stainless steels (316LSS) as a case study and present our progress on understanding deformation mechanisms under uniaxial tension, and pitting initiation during aqueous corrosion. Starting with an introduction of the multi-scale microstructural features present in the as-fabricated and annealed materials, the simulation/experiment integration frameworks we developed to fully comprehend LPBF 316LSS properties will be presented.

This work was performed under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344.

KEY WORDS: additive manufacturing, alloy design, laser powder bed fusion, titanium, high entropy alloys

COMPUTER SIMULATIONS AND IN-PROCESS MONITORING FOR FABRICATION OF FE-BASED ALLOYS SINGLE CRYSTALS BY LASER POWDER BED FUSION

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ABSTRACT

Powder bed fusion (PBF), which is the major metal additive manufacturing (AM) method, has attracted increasing attention not only for the ability to produce parts with a high degree of freedom in shapes but also for the ability to control the microstructure part by part within individual objects. Recently, fabrications of materials with controlled crystal orientation texture by PBF with specially designed scanning strategies have been reported [1-3]. To establish a more universal and robust method applicable to various materials, the relationships among the process parameters, solidification conditions, and resultant texture are to be clarified with the aid of computer simulation and in-process monitoring. Here we demonstrate the computer simulation and in-process monitoring to reveal the solidification conditions under irradiation of scanning laser in the PBF process for the fabrication of single crystals of Fe-based alloys (316L stainless steel, Fe-Cr-Co alloy) by way of example.

Laser irradiation experiments on bulk samples were carried out for 316L stainless steel and Fe-Cr-Co alloy, and the melt pools formed under various irradiation conditions were observed. Then, computational thermal-fluid dynamics (CtFD) simulation was performed to analyze the solidification conditions of each point of the melt pool. The parameters for CtFD simulation, such as the laser absorption rate, were optimized by fitting the simulation results to the laser irradiation experiments. Based on the obtained solidification conditions and the melt pool size data, process parameters for PBF-LB were optimized, and single crystals of 316L stainless steel were fabricated using the μ-Helix strategy with narrow scanning intervals [4]. Besides, in-process monitoring was carried out to get rapid building qualification. The intensities of visible light detected by two photodiodes on and off the laser beam axis were mapped with the laser irradiation position by the melt pool monitoring (MPM) system. The correlation between the intensity distribution and the crystal orientation was examined. This study provides not only a possible approach to modeling the crystal growth in PBF-LB but also scientifically useful knowledge from the analysis of the physical model simulation of AM process.

KEY WORDS: Laser powder bed fusion, single crystal, simulation, process monitoring, μ-Helix.

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INFLUENCE OF LEAD/FOLLOWER DUAL-LASER STRATEGIES ON THE MICROSTRUCTURE OF FeNi20 PRODUCED BY LPBF

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ABSTRACT

FeNi20 is an iron alloy with 15 to 25% nickel. It is used as a master alloy to produce low-temperature, corrosion- and heat-resistant steels. It also has excellent magnetic and electrical properties which can change depending on the obtained LPBF microstructure.
The high cooling rates that occur during LPBF processing influence not only the microstructure but also cause residual stresses that have a negative impact on the toughness and average life of the printed part/material. Additively manufactured components generally require subsequent heat treatment in order to relieve the stress which significantly increase the time and cost involved in the process. This additional process step, however, is often associated with a further distortion of the components. An alternative to this route is using the intrinsic heat treatment which is already part of the layer-wise manufacturing process.
Using dual-laser strategies, the temperature profile can be influenced and thus change the microstructure. Tailoring the melt-pool size in this way may make possible to influence the material's properties in a targeted manner; for example, microstructure can be adapted locally to obtain areas with higher hardness or areas with increased ductility at points of high strain.
The aim of this investigation is to enhance the intrinsic heat treatment with the use of a second laser, thus generating an in-situ thermal treatment. One of the lasers acts as the main laser (*lead*) and the second as a *follower*, which implies that its position and speed is fixed by the position and speed of the lead laser. Applying dual-laser strategies requires careful position calibration of both lasers to achieve optimal process conditions.
The process parameters of the *lead* have been established through single-laser parameter optimisation to obtain pore-free structures. For the *follower* laser, the laser parameters were varied between 10% and 65% of the energy input of the *lead* laser, varying both power and diameter of the laser focus.
This *lead-follow* laser strategy allows both lasers to travel simultaneously or with a determined time offset. The influence of short (10^{-3} s) and long (0.5 s) time offsets, corresponding to distances of approx. 0.7 mm and 350 mm between *lead* and *follower*, respectively, have been also studied.

The resulting effect of the dual-laser strategies on FeNi20 material was analysed using OM and SEM, XRD stress measurements as well as through the assessment of the mechanical properties.

KEY WORDS: Laser Powder Bed Fusion, dual-laser, FeNi20, intrinsic heat treatment

Effect of chemical microsegregation on the hot cracking sensitivity of nickel-based superalloys manufactured by L-PBF

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ABSTRACT

Nickel-based superalloys such as Inconel 738 and René 77 are widely used in the aeronautic industry to ensure the mechanical properties of parts at very high temperatures. Safran aims to increase the engine temperature and reduce its weight. Additive manufacture processes such as laser powder bed fusion (L-PBF) permit topological optimization enabling lighter complex geometry. However, the high cooling rate during solidification of L-PBF process leads to hot cracking in non-weldable nickel-based superalloys such as Inconel 738 and René 77. Segregation of certain elements during solidification is often reported as potential cause of hot cracking. However, most studies in the literature are carried out on parts that have undergone several thermal cycles. It is thus difficult to discriminate chemical heterogeneities due to the solidification from the one due to solid-state diffusion. To tackle this problem, the present work focuses on microsegregation on single tracks performed by L-PBF. Single tracks of Inconel 738 and René 77 were performed on different sets of parameters resulting in different solidification conditions and different crack densities in massive sample. The resulting microstructures were observed by transmission electron microscopy (TEM) analyses on focused ion beam (FIB) specimens. Regardless of the solidification conditions, dendrites of γ-phase with interdendritic carbides and alumina precipitates were observed, although no γ' precipitates were detected. Segregation profiles have been determined by STEM-EDX analyses based on an adapted reconstruction protocol. A dependency of the titanium segregation on the solidification conditions was highlighted. Atom probe tomography (APT) analyses showed a higher concentration of boron, silicon, and zirconium at grains boundaries. Finally, other factors impacting the hot cracking sensitivity, namely the grain structure and the thermal gradients, were investigated. Based on these results, the mechanisms governing the hot cracking in the L-PBF process are discussed.

KEYWORDS:
Additive manufacturing
Nickel-based superalloys
Hot cracking
Microsegregation
Transmission electron microscopy

INVESTIGATING PHASE EVOLUTION DURING ADDITIVE MANUFACTURING OF TI6AL4V VIA OPERANDO SYNCHROTRON X-RAY POWDER DIFFRACTION

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ABSTRACT

During metal additive manufacturing (AM), the interaction between a feedstock and a heat source generates a melt-pool that solidifies within a few milliseconds. Subsequent layer addition subjects the solidified material to thermal cycling in the solid-state until the end of the process. This thermal cycling can trigger micro mechanisms that result in microstructure evolution during the AM process. In the specific case of phase transforming materials such as Ti-6Al-4V, solid-state thermal cycling (SSTC) could lead to the formation of a gradient of phases along the building direction.

The aim of this study is to understand the evolution of the fractions of different phases (α/α', α'' and β) that may occur during laser metal deposition (LMD) of Ti-6Al-4V, from the moment the molten material is deposited until the end of building. To that end, we have performed *operando* synchrotron X-ray diffraction experiments during LMD of Ti-6Al-4V and used the Rietveld refinement technique to extract phase fractions. The experiments were carried out at the ID31 beamline of the European Synchrotron Radiation Facility (ESRF, France). A miniature LMD machine specially designed for synchrotron experiments [1] was used. In this talk, the evolution of the phase fractions as a function of time and number of added layers will be presented. In addition, evolution of other statistical measures such as the lattice strain will also be presented.

KEY WORDS: Synchrotron X-ray diffraction, Operando, Intrinsic heat treatment, Directed energy deposition.

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DOI: https://dx.doi.org/10.2139/ssrn.4367212

MANGANESE-ALLOYED STEELS IN ADDITIVE MANUFACTURING – PROSPECTS AND CHALLENGES

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ABSTRACT

Standard materials such as Ti-6Al-4V and stainless steels (e.g. AISI 316L) are mainly used in additive manufacturing (AM). Thus, these materials have been in focus of numerous scientific studies. From data available it is obvious that numerous challenges prevail, damage tolerance being one of the key issues and roadblock toward envisaged applications, respectively. From conventionally processed alloys it is known that the exploitation of additional elementary deformation mechanisms can significantly increase damage tolerance. In this regard, twinning induced and transformation induced plasticity (TWIP/TRIP) have been widely studied. However, studies reporting on the characteristics of AM-processed TWIP/TRIP steels are still rare [1,2].

In the present study, assessment of microstructure evolution and structural integrity is conducted in order to qualify parts made from TWIP/TRIP steel pre-alloyed powders. Using the two most common AM processes, i.e., electron beam- and laser-based powder bed fusion (PBF-EB/M and PBF-LB/M), appropriate process windows have been elaborated. Microstructure evolution, chemical composition as well as mechanical properties were analyzed. Results show that TWIP/TRIP steels could be used in numerous envisaged applications, even in as-built condition without any post-process treatment. Remaining challenges will be presented and discussed.

KEY WORDS: Microstructure, structural integrity, twinning, martensitic transformation, alloy design.

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DEVELOPMENT AND PROCESSING OF THE 316LSI-INCONEL718 MULTI-MATERIAL BY LASER METAL DEPOSITION WIRE-BASED TECHNOLOGY

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ABSTRACT

The feasibility of the 316LSi-IN718 multi-material processing by double wire Laser Metal Deposition (DW-LMD) has been investigated in this work. The approach of multi-material developed by Additive Manufacturing (AM) results in the possibility of manufacturing complex geometries with a customized design. This, together with the combination of different properties by selected materials, can lead to a final component of high added value able to be applied in many different sectors with required properties. In this work, the good properties of the stainless steel 316LSi, together with the excellent mechanical properties of the nickel-based superalloy Inconel 718, turns this multi-material suitable for different applications even at high temperatures and corrosive environments.

In the first stage, the process parameters for both 316LSi and IN718 single materials have been studied within the wire-based LMD technology. Different combinations of the main LMD process parameters (print speed, layer height, laser power) were studied. Secondly, the 316LSi-IN718 multi-material processing has been carried out with a set of parameters which offered a high level of density and better processability. No gradient transition was applied to the multi-material processing, thus direct contact between the different metals was obtained. Different build orientation strategies were followed to evaluate the material deposited direction on the final properties of the multi-material.

Regarding material characterization, microstructural analysis was conducted by optical microscopy after cross-sectioning, mounting and surface preparation by standard metallographic techniques to evaluate the density level of the single and multi-materials developed. A statistical analysis of the defects was performed and the mean density value was obtained using ImageJ software. The mean value was presented after four images analyzed of each build direction (horizontal and vertical). High material densification values were obtained in the horizontal and vertical direction, 99.86 % and 99.70 %, respectively. The samples were etched to reveal the grain shape and size of each material, and the interfacial area between the two materials.

The mechanical behaviour was analyzed in both, 316LSi and IN718 single materials, as well as in the 316LSi-IN718 multi-material. Tensile tests showed higher ultimate tensile strength and yield strength on the materials obtained by the LMD-processed single materials compared to those conventionally manufactured (cast and wrought). Elongation was also higher in the case of the LMD processed single materials, and slightly higher when the material was built parallel to the direction of material deposition (horizontal). The effect of performing a specific heat treatment after processing the single IN718 material on the achieved properties was also studied. For mechanical testing, three 5 mm diameter x 32 mm length cylinder samples were machined and analyzed in a

universal INSTRON device under room temperature following the UNE-EN ISO 6892-1:2020B standard.

The effect of the heat treatment on the microstructure and mechanical behaviour of the 316LSi-IN718 multi-material was also evaluated. It has been demonstrated that in the case of the superalloy IN718 developed by LMD, a heat treatment for stress relief and ageing highly improved the mechanical properties. Therefore, this effect was also studied in the microstructure and mechanical behaviour of the 316LSi-IN718 multi-material by performing the heat treatment of stress relief and ageing under the same conditions.

KEY WORDS: Laser Metal Deposition (LMD) processing, wire metal-metal deposition, multimaterial, 316LSi/IN718, microstructure.

HIGH-POWER PROCESSING OF DENSE AND CRACK-FREE TUNGSTEN USING ELECTRON BEAM POWDER BED FUSION

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ABSTRACT

Tungsten finds many demanding applications thanks to its unique physical and chemical properties, such as high melting point, high density, high X-ray absorption, high tensile strength, etc. Due to the poor machinability of tungsten, there is an increasing interest to fabricate tungsten parts from powder, using additive manufacturing. However, Laser Powder Bed Fusion (L-PBF) has proven difficult due to the high ductile-to-brittle transition temperature of tungsten. Tungsten built with L-PBF is prone to cracking [1,2].

Electron Beam Powder Bed Fusion (E-PBF) has two distinct advantages useful for tungsten: elevated powder bed temperatures and a high vacuum environment preventing oxygen pickup [2,3]. In this study, we demonstrate crack-free tungsten processing above 1000°C and explore innovative E-PBF melting beyond the traditional hatch strategy. We show how microstructure, porosity and material properties are affected by various e-beam scanning patterns, and we discuss how to reach maximum build rate. Video material recorded in a Freemelt ONE system will be used for illustration.

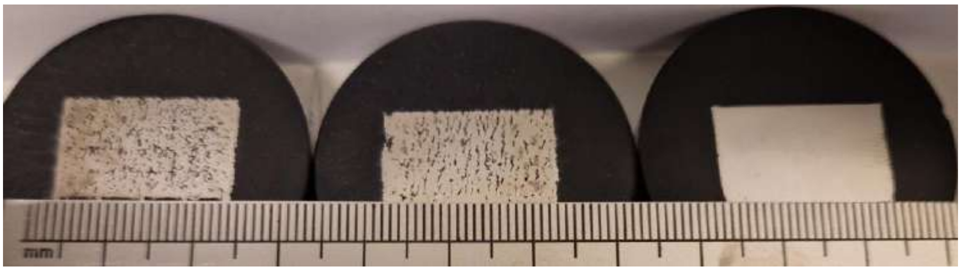

Figure 1: Tungsten cross-section specimens built in Freemelt ONE, showing random porosity (left), chimney porosity (middle), and full density (right).

KEY WORDS: Electron beam powder bed fusion, tungsten, beam scanning strategy, spot melting

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Integrated computational materials engineering (ICME) for tungsten rapid solidification: Towards understanding microcracking in additive manufacturing

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ABSTRACT

Tungsten is used as a plasma facing material for fusion reactors due to its high melting point, thermal conductivity, and low fuel retention. While additive manufacturing is a promising method to produce tungsten parts, it tends to produce microcracks. In this work, we perform a multiscale modeling analysis to explore the rapid solidification features of pure tungsten and certain tungsten-based binary alloys. We use a gaussian approximation potential MD and phase field crystal method to analyze rapid solidification defects, including point defects, dislocations, crystal orientation gradients, and potential microcavities. On continuum scale, we perform coupled phase field and crystal plasticity simulations to investigate microstructural (type II-III) residual stresses due to solidification shrinkage, and due to solid-state thermal contraction during cool-down. The simulation results are compared to bare plate single line scans. We discuss the role of ductile-to-brittle transition and oxide inclusions as sources of microcracking, and the effect of selected alloying elements on microcracking.

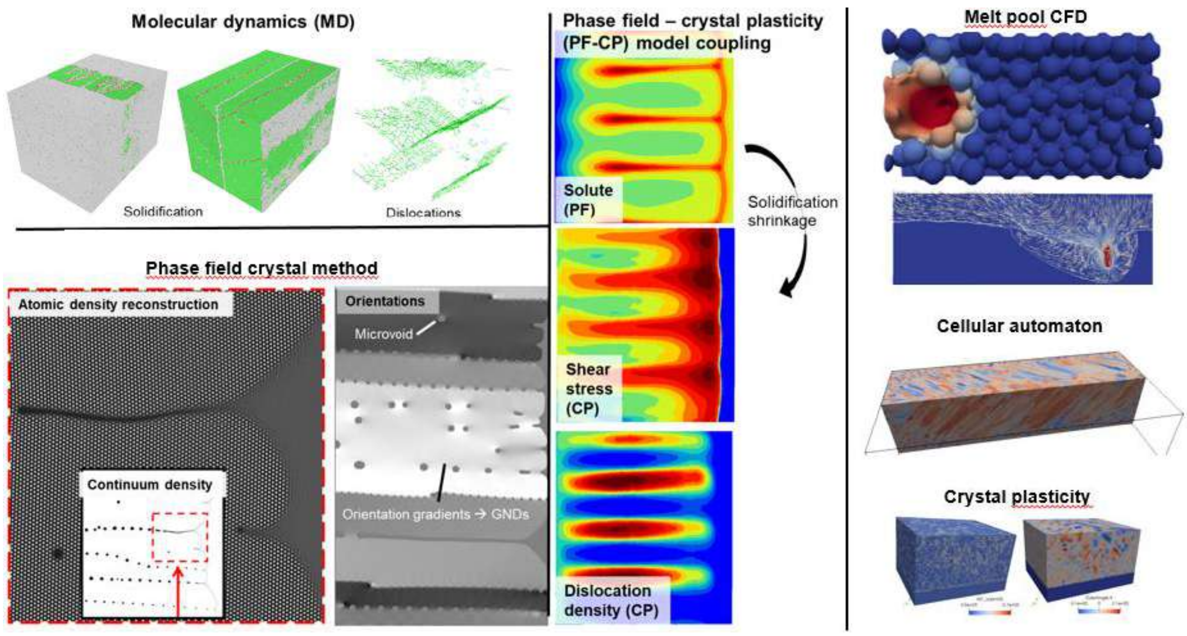

Figure 1. Multiscale modeling framework for solidification microstrucures.

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KEY WORDS: Rapid solidification kinetics, multiscale modeling, ICME, tungsten, refractories

LASER POWDER BED FUSION OF TI-BASED BULK METALLIC GLASS

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ABSTRACT

The development of novel materials for industrial applications of Additive Manufacturing (AM) is one of the most emerging areas of academic research in the recent years. Especially considering the comparably new fabrication process of laser powder bed fusion of metals (PBF-LB/M), the underlying unique processing principles, i.e. layer wise material application and large thermal gradients, attract research interest focused on process-material interactions [1]. These characteristics enable new potentials to fabricate advanced materials. The application of such tailored materials aims at combining favorable inherent properties with given process characteristics to optimize the resulting product quality. Especially the material class of bulk metallic glasses (BMGs) appears promising for PBF-LB/M [2,3]. The amorphous microstructure results in technological properties that often exceed the standards of crystalline materials. The fabrication is bound to high cooling rates, whereby the crystallization process is suppressed and a non-crystalline phase is established. The amorphous microstructure is connected to outstanding mechanical properties such as high hardness, strength and elasticity or corrosion resistance [3]. In terms of conventional manufacturing routes, BMGs are usually cast in small geometries, since fast cooling rates are needed to avoid crystallization and achieve vitrification [4]. In AM and especially PBF-LB/M, the cooling cycles are barely dependent on the part size or geometry. Recent research successfully applied the technique to process several glass forming alloys, especially Zr-based BMGs [5,6]. However, current alloy selection of BMGs-for PBF-LB/M is still limited. In this matter a recently developed sulfur bearing Ti-based alloy of the composition $Ti_{60}Zr_{15}Cu_{17}S_8$ is investigated in this research [7,8].
This composition offers a high yield strength to weight ratio which exceeds the established crystalline Ti6Al4V; with a ratio of 0,51 $\frac{MPa}{kg/m^3}$ for the Ti-based BMG alloy compared to 0,45 $\frac{MPa}{kg/m^3}$ for Ti6Al4V [7]. The absence of nickel and its biocompatibility makes it highly interesting for medical applications. However, with a critical casting thickness of 1 mm, technical applicability is limited [7]. Hence, the processability of the newly developed material class of titanium-based sulfur bearing bulk metallic glass (BMG) was investigated. The focus is set on the development of process parameters and the relation to pore formation and crystallization.
Initial experiments on cast material reveal that the thermal cycles during remelting in the PBF-LB/M machine suffices the required cooling rates to maintain their amorphous structure. First investigations on Ti-S powder reveal a general processability via PBF-LB/M. Challenges and advantages are

mapped considering up-scaling and eventually industrial application of the investigated Ti-based S-bearing BMG. Potential challenges are outlined and procedures to understand and overcome these are developed.

KEY WORDS: Additive Manufacturing, Bulk metallic glasses, Ti- based alloys for AM, Laser powder bed fusion

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Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

Cooling rates during laser powder bed fusion of $Cu_{47}Ti_{34}Zr_{11}Ni_8$ bulk metallic glass

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ABSTRACT

Additive manufacturing has attracted significant interest in demanding industries such as aviation, aerospace and medical. With growing requirements towards performance and durability, in these fields, advanced materials are desired.
In this matter, bulk metallic glasses (BMGs) are highly attractive for structural applications because of their high strengths within the range of 2-3 GPa and elastic limits above 2 % [1]. This property profile originates from the disordered atomic structure of their constitutional elements. However, the fabrication of BMGs necessitates rapid quenching, to prevent the atoms to arrange into a crystalline lattice. In common processing routes such as casting, this effectively limits size and complexity of structural parts. In the last decade, laser powder bed fusion of metals (PBF-LB/M) emerged as a technology to overcome these restrictions [2]. The transient laser-material interaction leads to cooling rates of up to 10^6 K/s [3,4]. Additionally, the incremental procedure decouples the local cooling rate from the overall part size, eliminating size and geometry restrictions for BMGs [5]. Albeit, despite the nominally large temperature gradients, (partial-) crystallization of BMGs is frequently observed during PBF-LB/M. In BMGs crystallization is often accompanied with the loss of their mechanical performance. Even compositions that promise a good glass forming ability tend to exhibit oxidic phases, which can be linked to the increased oxygen content present in the powder feedstock compared to laboratory casting [6]. Thus, increased energy densities during PBF-LB/M can lead to crystallization, while low energy densities are accompanied by lack of fusion and porosities. Only a small parameter window remains for amorphous and dense processing and quality assurance in complex geometries is challenging. Therefore, it becomes crucial to monitor and understand the thermal cycling during processing to analyze and control the thermal gradients.

In this matter, a high-speed ratio pyrometry set-up for the in-situ analysis of the glass-forming alloy $Cu_{47}Ti_{34}Zr_{11}Ni_8$ is applied during PBF-LB/M. The measurement allows an insight into the time-temperature regime of single laser tracks and the thermal cycling during consecutive exposure of a layer. The results show that, dependent on the applied exposure parameters, the thermal gradients can range between 10^4-10^6 K/s. While these should still be sufficient to ensure amorphous processing, the concatenation of several scan tracks can drastically increase the thermal load and foster crystallization. The findings contribute to a knowledge-based parameter development and provide first insights towards process monitoring that can prevent undesired crystallization in PBF-LB/M processed BMGs.

KEY WORDS: laser powder bed fusion, bulk metallic glasses, high-speed pyrometry, new materials.

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IMPROVING THE LASER POWDER BED FUSION PROCESSABILITY OF A METALLIC GLASS WITH REMELTING STRATEGIES

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ABSTRACT

Additive manufacturing of amorphous metallic alloys is promising to push the size and design limits associated with conventional arc melting and injection moulding. Laser powder bed fusion (LPBF) of metallic glasses is particularly challenging since manufacturing conditions must be found to minimise porosity without inducing crystallisation. This compromise is usually met within a narrow processing parameters window. In this context, the use of re-melting strategy can be interesting. The motivations for remelting cover promoting the amorphous phase and the chemical homogeneity within the layer-by-layer deposited material; while densification is also expected to be impacted. The present work investigates the implementation of several remelting strategies during the LPBF processing of a Zr-based metallic glass, *i.e.* various repetitions, rotation and/or beam energy. Additive manufacturing is carried out with an in-house developed miniature LPBF replicator. The system is designed for measurements at large scale facilities (Lhuissier et ***al.***, 2020) and allows in situ X-ray tomography analyses. Synchrotron X-ray scans at each production steps (*i.e.* after powder spreading, before and after powder melting and all remelting) reveal in situ the morphology of the deposited material and the surrounding powder bed, as well as the origin and evolution of defects. In the present work, it brings new insight on the impact of remelting and perspectives for rapid strategy optimisation. An example of samples produced with the LPBF replicator with and without single remelting is displayed in Figure 1. Conventional structural characterisation of the produced samples completes the study. The in situ tracking of transient and permanent defects highlights that the remelting procedure can be foreseen as a healing strategy, instead of being used systematically on every layer – at the expense of the productivity.

KEY WORDS: LPBF of amorphous metals; Zr-based grade; porosities; crystallization; laboratory and in situ synchrotron CT; defect healing strategy.

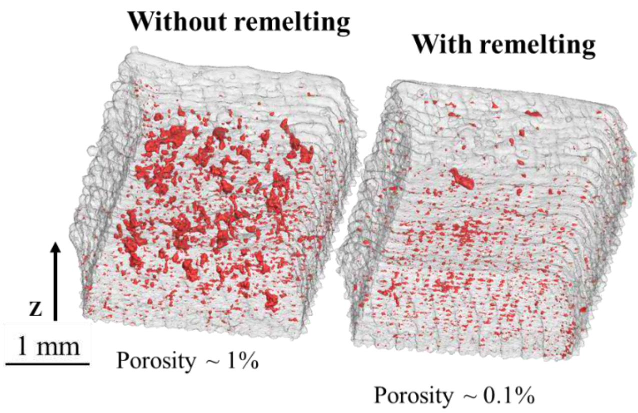

Figure 1: 3D X-ray microtomography observations of residual porosities produced with the in house L-PBF replicator without and with single remelting.

Lhuissier, P., Bataillon, X., Maestre, C., Sijobert, J., Cabrol, E., Bertrand, P., Boller, E., Rack, A., Blandin, J. J., Salvo, L., & Martin, G. (2020). In situ 3D X-ray microtomography of laser-based powder-bed fusion (L-PBF) - A feasibility study. *Additive Manufacturing*, *34*. https://doi.org/10.1016/j.addma.2020.10127

MULTISCALE MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION OF A NOVEL Al-1Fe-1Zr DESIGNED FOR AND PRODUCED BY LPBF

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ABSTRACT

The composition Al-1Fe-1Zr has been tailored for laser powder bed fusion (LPBF) to achieve high yield strength and conductivity through direct ageing at 400°C for 4h (Pauzon et al., 2022). This novel alloy takes advantage of the unique solidification conditions associated with the LPBF process, which are a high thermal gradient and solidification front velocity. In conventional Al ingot metallurgy, Fe is an element one must avoid since it tends to create coarse particles critical for the ductility. During LPBF, Fe and Zr are efficiently trapped in the solid solution, and direct ageing enables $L1_2$-Al_3Zr nanoprecipitation, contributing for up to more than 60% to the achieved yield strength. In the LPBF microstructure, the Fe particles are fine with a globular morphology in the as-built state and fine faceted Fe-rich intermetallics precipitate upon ageing. The multi-scale microstructural and mechanical characterization with SEM, TEM, EDS and Automated Crystal Orientation Mapping (ACOM) in the TEM as well as nanoindentation and in situ tensile tests in the SEM coupled with digital image correlation reveals the relation between the microstructural and local deformation heterogeneities in the as-built state. These new results permit us to propose a simple model for the alloy solidification and discuss the origin of melt pool boundaries, see model illustrated in Figure 1. These melt pool boundaries are associated with Fe depletion resulting from an early planar growth front of the solid/liquid interface. The evolution of these melt pool boundaries upon ageing is presented as well as their influence on the local strain distribution. With its good processability and wide range of industrial applications, this new grade, with Fe and Zr exhibiting low solubility at equilibrium and diffusivity in Al, achieves high conductivity (27 MS/m) and yield strength (330 MPa) following direct ageing at 400°C for 4h.

KEYWORDS: Additive manufacturing; Laser powder bed fusion; Alloy design; Aluminium alloys; Nanoindentation; In situ tensile test; Electrical conductivity.

Pauzon, C., Buttard, M., Després, A., Chehab, B., Blandin, J.-J., & Martin, G. (2022). A novel laser powder bed fusion Al-Fe-Zr alloy for superior strength-conductivity trade-off. *Scripta Materialia*, *219*(114878), 1–7. https://doi.org/10.1016/j.scriptamat.2022.114878

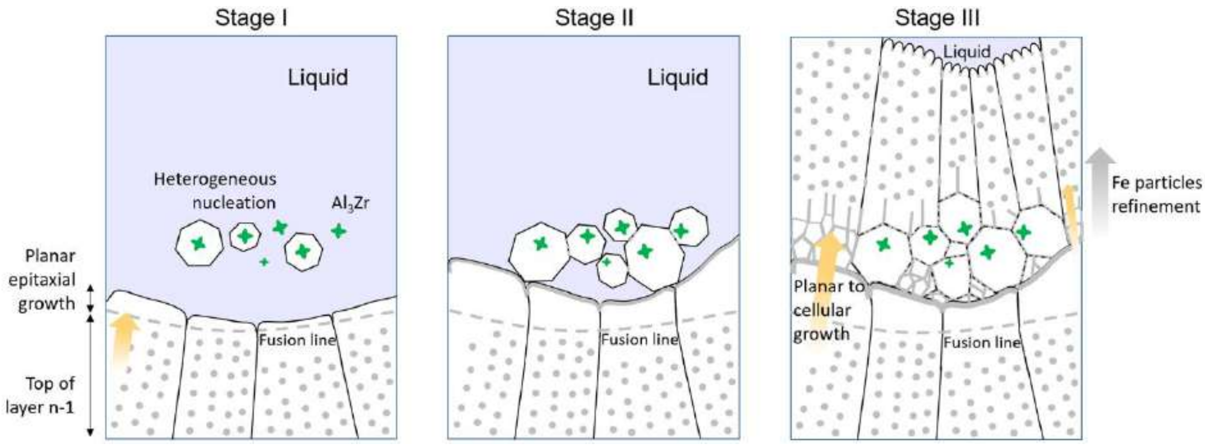

Figure 1: Solidification model upon LPBF for the Al-1Fe-1Zr alloy. Stage I: beginning of the epitaxial growth while Al nuclei are formed on primary Al_3Zr. Stage II: competition of the two growth mechanisms as the solidification front progresses. Stage III: columnar grain growth at lower solidification depth while the Fe rich particles refine from a continuous network to individual globular particles within the columnar grains.

Tailoring of microstructure and residual stress profiles in Laser Powder Bed Fusion (LPBF) via utilization of novel multi-laser scanning strategies

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ABSTRACT

Laser Powder Bed Fusion (LPBF) is by far the most widely utilized and researched method for metal AM. In the past years, the LPBF process has been validated for only a few alloys, the most relevant being 316L, AlSi10Mg, Ti6Al4V and Inconel718. However, the vast majority of more than 5,500 existing alloys cannot be additively manufactured. Though the mechanical properties of LPBF parts can be comparable or superior to the conventionally manufactured products, LPBF suffers from significant drawbacks including the accumulation of detrimental tensile residual stresses (TRS) as a result of shrinkage and high cooling rates during solidification, and the formation of a columnar grain structure resulting in high texture, directionality, and anisotropy in mechanical properties of the consolidated parts 1,2. The combined effect of TRS and columnar grain structure results in excessive stress concentration at the grain boundaries during and after the solidification process, leading to crack formation in several classes of steel, series 2, 6 and 7 Al-alloys and precipitation-strengthened Ni-based superalloys.

Formation of TRS upon solidification is highly dependent on the intrinsic properties of the material in question and the local thermal gradients at and around the melt pool solid-liquid boundary. The latter can be modified through alterations in the energy intensity distribution of the laser via novel laser beam combinations and tailored scanning strategies. The effects could go beyond the control over cooling rate towards regulating the temperature gradient (G) and solidification rate (R) at the solid-liquid boundary dictating the desired microstructure upon solidification.

To this end, novel and interdependent multi-laser scanning strategies were employed to evaluate the resultant synergy between microstructure and residual stresses. Scan strategies were designed based on both analytical and numerical thermal simulation of the process that quantify the effect of changes in the energy intensity distribution on the thermal gradients and cooling rates. The magnitude and orientation of the residual stress was measured via XRD on the top surface, combined with microstructural evaluation of the final parts.

KEY WORDS: multi-laser systems, microstructural design, residual stresses, beam shaping

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HIGH HARDNESS Ta DOPED EUTECTIC HIGH ENTROPY ALLOY BY WIRE ARC ADDITIVE MANUFACTURING

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ABSTRACT

High-entropy alloys (HEAs) are a relatively new class of materials that are based on multi component principle alloying elements approach forming supersaturated solid solution. Such alloys are composed of alloying elements in equal proportions. These materials have been found to have exceptional mechanical properties, such as high strength, ductility, corrosion and wear resistance, making them perspective for a variety of applications.

Combining WAAM with HEAs can offer a number of advantages. The most valuable is a cost-effective and efficient process for producing large-scale components. For the successful realization of the WAAM approach to HEAs manufacturing the mandatory part is the presence of filament with specific chemical composition (i.e. welding wire). In the case of soft HEAs (such as Canrtor), it is possible to manufacture solid wire or use multi-component wires cord. However, treating high-hardness alloy it becomes impossible to fabricate solid wire with appropriate composition. The solution to such a complex technological task is proposed in the current work [1].

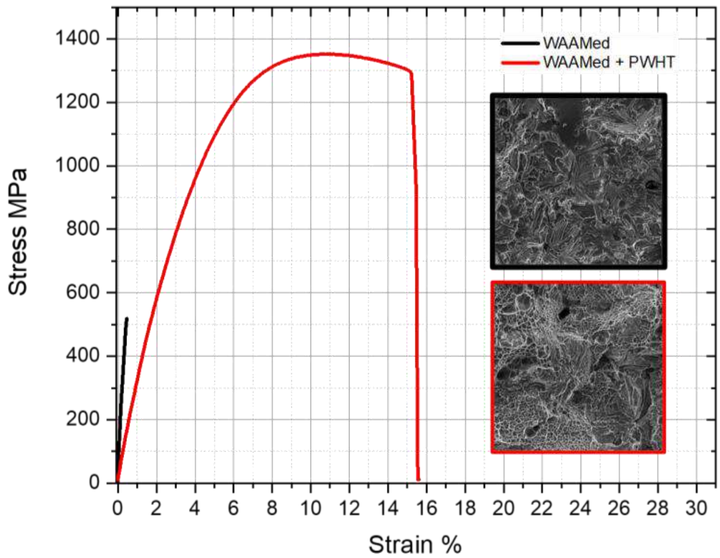

Figure 1. Mechanical properties of the WAAMed FeCoNiAl-Ta eutectic high entropy alloy.

The proposed method is based on gas metal arc welding (GMAW) with metal powder-cored wires (MPCW). The filling of the wire contains powder components in equal amounts relative to each other. Such an approach is beneficial compares with alternative methods of obtaining bulk alloy as melting in vacuum or argon-plasma melting, firstly due to the predominance in the molten volume of the workpiece. Further development of this approach is discussed on the example of a high hardness eutectic high entropy FeCoNiAl alloying system doped with Ta. The WAAMed alloy is characterized by almost zero plasticity, which is become prominent after the application of the special heat treatment procedure (Fig.1).

KEY WORDS: wire arc additive manufacturing, eutectic high entropy alloys, metal powder-cored wire, microstructure, properties.

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Assessing additive manufacturing processability of novel refractory high entropy alloys prior to powder manufacture

Over decades the popularity of additive manufacturing (AM) has increased, and many widely used alloys have been manufactured, adapted and studied in order to optimise their processability, resulting in high quality components. In more recent years, work has been done to design novel alloys specifically for AM which have optimised mechanical properties and microstructures due to the AM process. High entropy alloys (HEAs) are a class of alloys which have widely been shown to be capable of exhibiting stable microstructures and good mechanical properties. Many HEAs have also been manufactured by AM, showing excellent weldability and homogeneity.

When designing new alloys for AM, difficulties arise when there are many new alloy compositions which need to be screened for AM processability (as is often the case for HEAs in particular), which is time consuming and costly. On top of this, especially for refractory HEAs or alloys, bespoke powders can be difficult to manufacture with huge associated cost and lead times. Therefore, this work presents a simple processing map by which to assess alloy crack susceptibility in laser powder bed fusion (LPBF), for any novel alloy, prior to welding trials or powder manufacture. CALPHAD analysis is used along with Rosenthal based simulations to predict the alloy susceptibility to solidification and solid state cracking. These results are then compared with cracking behaviour seen in experimental weld tracks and LBPF for CoCrFeNi-based HEAs and with the cracking behaviour of some more commonly processed nickel or titanium based superalloys and steels. The method is then used to predict the AM processability of some novel refractory HEAs, one of which is then manufactured by LBPF and analysed.

Influence of processing regimes on the cracking morphology at the interface of 316L and a copper alloy in multi-material PBF-LB

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ABSTRACT

Laser based additive manufacturing (AM) processes, such as laser powder bed fusion (PBF-LB), offer a great degree of control over how materials are processed during manufacture. Adding the capability to seamlessly change materials within a single part will offer greater design opportunities. As such, desirable functional properties can be promoted in selective regions of a part. For example, integrating a copper alloy into a stainless-steel part in specific regions increases the thermal and electrical conductivity in the selected region of a high-strength, corrosion resistant part. This can improve upon the performance of current heat exchangers and tool moulds. However, the difference in thermal properties (melting temperature, CTE, etc.) of the two alloys makes this combination prone to cracking at the interface. The large solidification range present in the Fe-Cu binary phase diagram (**Figure 1a)**) combined with the high cooling rates associated with PBF-LB and the difference in thermal contraction during cooling between both alloys promotes the formation of solidification cracking. In addition, the large immiscibility gap (shown in **Figure 1a)** and **Figure 1b)**) and the absence of intermetallic compounds which form (**Figure 1a)**) make this combination prone to liquid metal embrittlement, which develops solidification cracks [1]. This type of cracking begins in the mushy zone, near the end of the solidification range, in which thermal strains tear apart the remaining liquid film [2].
In this talk, the effect of processing regimes at the interface of a 316L-Cu alloy structure produced by PBF-LB is discussed, with the aim of developing guidelines for a crack-free interface. Building 316L stainless steel on to a wrought CuCrZr substrate shows the propensity of cracking on the steel side of the interface (**Figure 1b)**). Altering the behaviour of the laser such that the cooling rate is reduced is shown to prevent the presence of cracking, reflected by **Figure 2**. However, some process strategies reduce the amount of mixing of the alloys at the interface (regimes presented in **Figure 2a)** and **Figure 2b)**). The results of this study show the influence the thermal history of the melt pool has on the cracking at the interface of 316L and a copper alloy, and how cracking can be eliminated using carefully prescribed process parameters. The same principle is applied to dual-metal printing using an Aerosint dual recoater unit combined with a multi-laser (400W + 1000W) AconityMIDI+ machine.
This work provides base guidelines that can be followed to mitigate cracks from developing at the interface of 316L steel and a copper alloy using PBF-LB. A breakthrough which will provide component designers the opportunity to create multimaterial parts in a single build while tuning the desired mechanical and physical properties in specific locations of an PBF-LB produced part.

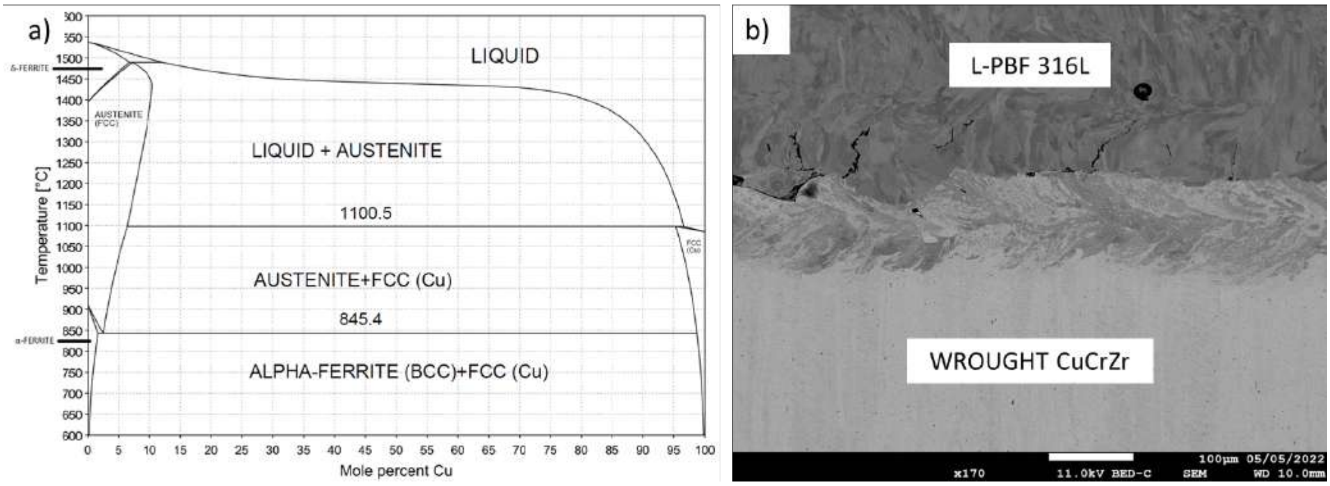

Figure 1 a) iron-copper binary phase diagram created using Thermo-Calc, b) SEM micrograph of the interface of 316L printed onto CuCrZr using L-PBF, showing cracks on the steel side of the interface

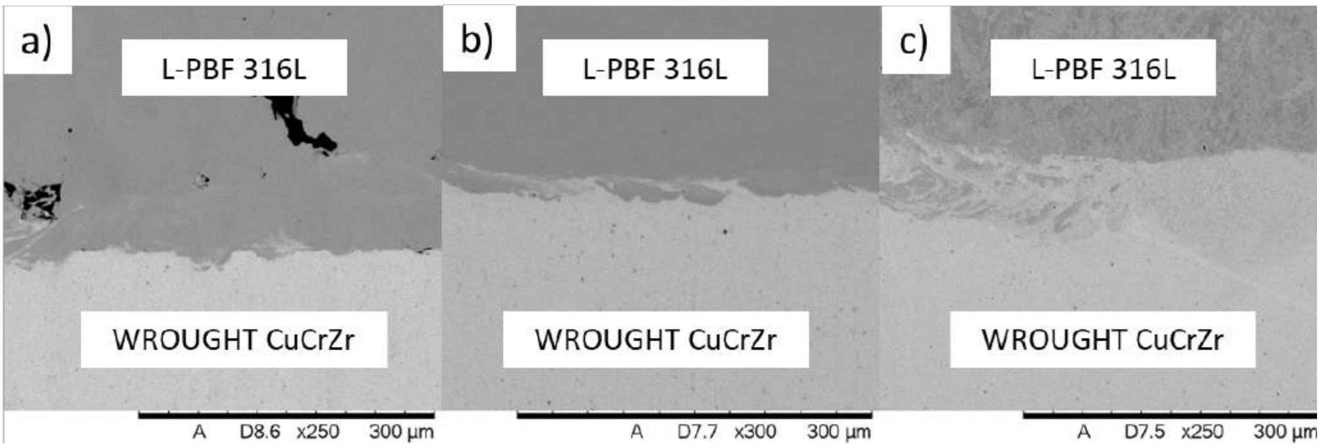

Figure 2 SEM micrographs of the effect of different processing regimes at the interface of 316L printed onto CuCrZr using a pulsed laser a) decreased exposure time, b) increased spot size, c) Decreased point distance

KEY WORDS: Multi-metal PBF-LB structures, steel, copper, cracking

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IN-SITU DETECTION OF STOCHASTIC SPATTER-DRIVEN LACK OF FUSION IN LASER POWDER BED FUSION

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ABSTRACT

The low productivity and the presence of defects in parts manufactured by laser powder bed fusion (LPBF) are two of the main issues that challenging the application of these technologies as reliable manufacturing methods in a broader range of industries. The build rates of laser powder can be greatly improved by the use of larger nominal layer thicknesses, thanks to the linear relationship between this process parameter and productivity [1]. However, when the process limits are pushed towards conditions that allow for higher productivity, the integrity of the manufactured parts might be compromised, including due to the formation of internal defects defects [2]. A potential solution to combine higher productivity with satisfactory reliability is employing in-process monitoring targeting defect detection. In this study, defects formed due to the redeposition of spatter particles on the powder bed are detected with the aid of optical tomography (OT) in-situ monitoring. The detections are validated ex-situ via metallographic analysis and X-ray computed tomography (XCT).

Optical tomography images were registered layerwise during the manufacturing of Hastelloy X specimens produced with varying layer thicknesses and optimized process parameters that yield material virtually free from systematic defects. The OT images were analysed to detect spatters landing on the powder bed, and deposition patterns were identified. There is a significant effect of the nominal layer thickness on the quantity and distribution of redeposited spatters, as observed in **Figure 1** A-C. Spatters preferentially land in the adjacencies of the gas outlet and, as the layer thickness increases, a larger number spatters is detected across a larger portion of the build area. Metallographic analysis showed that large and abundant lack of fusion defects are observed in specimens highly affected by spatter redeposition, while the specimens with where no detections were made did not contain lack of fusion [2] (**Figure 1** D-G). Both specimens illustrated were manufactured with identical, optimized process parameters.

Three of the smallest specimens in each build were analysed in detail by mapping their internal defect content via X-ray computed tomography and comparing the locations of the lack of fusion defects identified with spatter detections in OT images. A clear correspondence between defects observed in XCT volume slices and spatter detections in OT images is seen (**Figure 2**). Quantitative analysis revealed that 79% of lack of fusion defects were detected through OT, and the detection was particularly successful for large defects [3]. Thus, it is demonstrated the applicability of optical tomography in-situ monitoring for indirect detection of stochastic lack of fusion, whose presence is inferred from spatter redeposits on the powder bed.

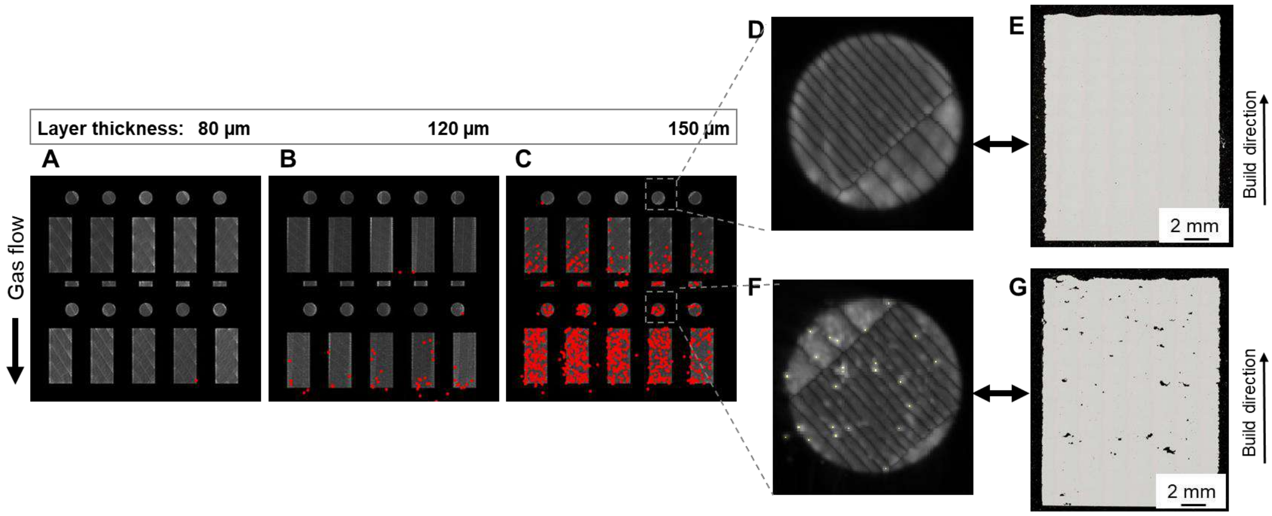

Figure 1: Detections of redeposited spatters (in red) in builds with layer thickness 80 µm (A), 120 µm (B) and 150 µm (C). Specimens where no detections were made (D) contained no lack of fusion (E), while specimens where abundant detections were present (F) contained multiple large lack of fusión (G).

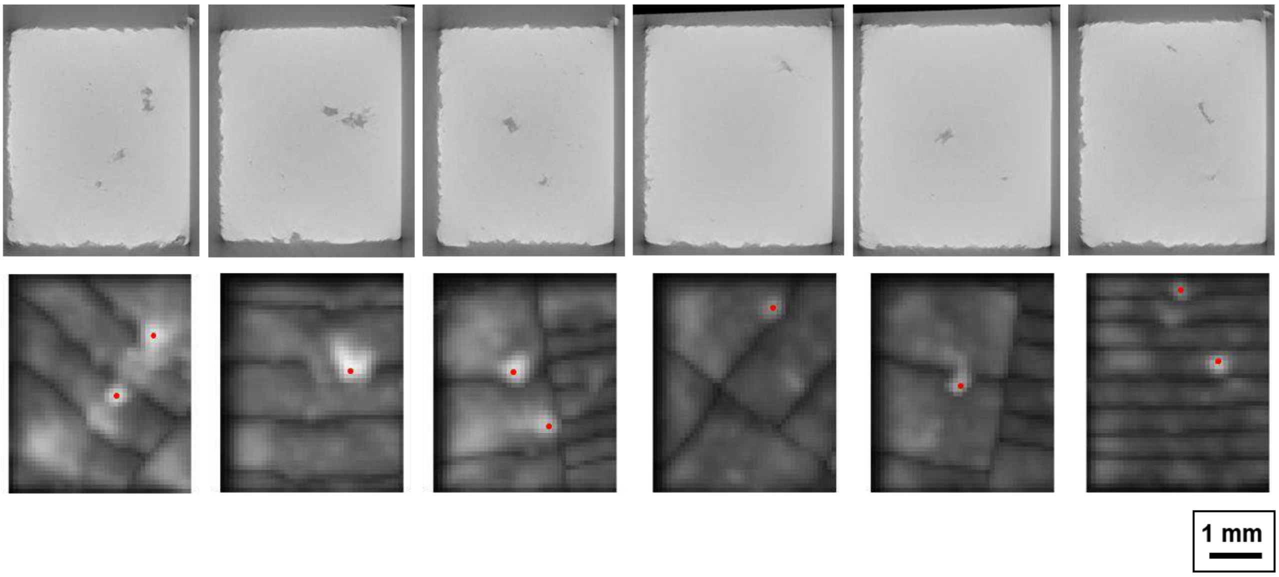

Figure 2: Visual match between defects in XCT slices (top) and corresponding OT images overlaid with detections (bottom).

KEY WORDS: Laser powder bed fusion; productivity; spatter; in-situ monitoring; defect detection; optical tomography; X-ray computed tomography; Hastelloy X

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The development of ultrafine grain structure in a novel additively manufactured titanium alloy via high-temperature microscopy

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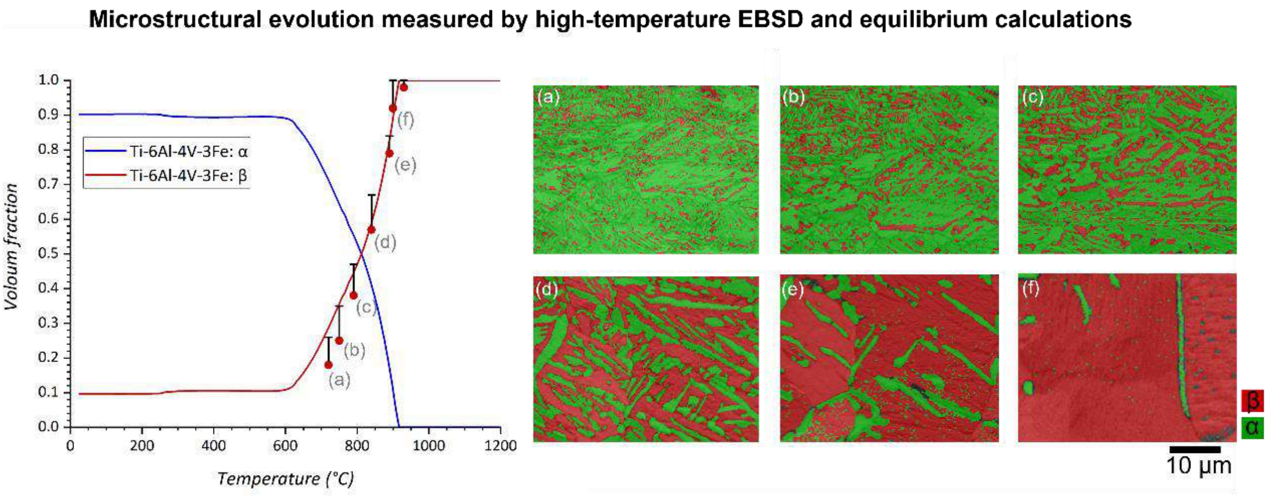
Abstract

Microstructures obtained from rapid solidification dominated by acicular α' martensitic phase, such as in the case of α+β titanum alloys fabricated by laser powder-bed fusion (PBF-LB), are known to suffer from reduced ductility and low toughness. The decomposition of such metastable microstructures into ultrafine α+β lamellar structures is highly desirable. Nevertheless, controlled decomposition remains fundamentally based on trial and error. Taking Ti-6Al-4V as an example, studies have indicated that *in situ* martensitic decomposition varies depending on the PBF-LB specific energy input and might take place in a wide temperature range (650 to 800 °C [1, 2, 3]). In most PBF-LB manufacturing conditions, there will be always regions of the build where the metastable phase (e.g. α′ martensite) decomposition is incomplete and the thermal profiles is difficult to control at part level where complex geometries lead to inevitable temperature profile deviations and spatial microstructure variations. Post-process heat treatments might lead, instead, to undesirable coarsening of the grain structure and softening. In this work, we elucidate the fundamental mechanisms that lead to the formation of a ultrafine lamellar structure in a novel α+β titanium alloy. As decomposition strictly depends on the nature of the metastable phases and the diffusional kinetics characteristic of the alloy, we purposely adapt the constitution of Ti-6Al-4V by additions of Fe, a known potent β stabiliser of high intrinsic solid diffusivity. We then study the response of the metastable phases formed in the material to heat treatment by using a combination of high-temperature XRD diffraction and orientation microscopy. The high-temperature techniques employed in this work allow us to elucidate the fundamental mechanisms associated to the microstructure evolution of the proposed alloy. We can detect the range of temperatures where homogeneous decomposition of the mestastable β phase takes place and the influence of the early partitioning of Fe (which has a markedly higher diffusivity than V and Al at moderate temperatures, i.e. 450 to 700 °C) to explain the nucleation and growth of laminar structures during heat treatment. With this information, we delineate a facile metallurgical pathway to achieve a ultrafine grain structure and demonstrate its benefits by performing tensile testing reaching extraordinary strength (yield ∼1050 MPa, UTS ∼1100 MPa) and ductility (elongation at break of ∼13.5%). The presented approach is machine-agnostic and offers a novel alloy design strategy for development of high-strength alloys in additive manufacturing.

Graphic abstract



Keywords

Additive manufacturing, Laser powder-bed fusion, Ti alloys, Ti-6Al-4V

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High-Speed X-Ray Diffraction Study of Solidification Mode in Powder Bed Fusion of Hot-Work Tool Steel

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ABSTRACT

Powder Bed Fusion (PBF) is a manufacturing process for producing complex tool geometries with improved performance. However, the high thermal gradients and solidification velocities during PBF can impact the solidification mode, which in turn affects the microstructure and performance of the manufactured components. In this study, we used synchrotron-based, high-speed X-ray diffraction setups to investigate the impact of thermal gradients and solidification velocities on the solidification mode of a hot-work tool steel.

Our results show that primary δ-ferrite is observed at a lower cooling rate, while at a higher cooling rate, δ-ferrite is suppressed, and primary austenite is observed. We linked the thermal conditions during the experiments to a solidification model based on the dendrite growth model by Kurz-Giovanola-Trivedi (KGT), and our modelling results predict the experimental observations.

This work demonstrates how in-situ XRD measurements can be used to understand the microstructure evolution and validate computational thermodynamics and kinetics models, enabling the development of alloys and process parameters for additive manufacturing.

KEY WORDS: Solidification in AM, Synchrotron X-ray diffraction, Dendrite growth model, Computational thermodynamics, Hot-work Tool Steel

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Monitoring of cracking in nickel superalloys during Laser powder bed fusion process with acoustic emission and operando X-ray radiography

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ABSTRACT

Nickel-based super alloys strengthened by γ'-precipitation such as CM247LC are highly sought-after for high-temperature applications which require excellent creep, corrosion, and oxidation resistance without loss in mechanical properties [1]. The application of additive manufacturing (AM) methods for producing CM247LC-based components offers the ability to develop lightweight and intricate parts at reduced cost and decreased material waste. However, the material composition and complex thermal history associated with the laser-based powder bed fusion (LPBF) process exacerbates the materials' susceptibility to solidification cracking [2-5]. This property labels CM247LC as a 'hard-to-process' material [6]. Understanding the solidification cracking mechanism is important to develop further crack healing/prevention strategies to overcome this issue and improve processibility.

Online process monitoring has received great interest in recent years as it is seen as an ideal non-destructive approach to improve AM part quality and repeatability [7-9]. In-situ sensorization enables understanding of several physical phenomena occurring during laser-matter interaction, including the detection of process anomalies and formulating closed-loop control methods.

This contribution presents a real-time LPBF process monitoring method that combines in-situ high-speed synchrotron X-ray imaging and structure-borne acoustic emission (AE) to detect and localize cracking during the process. X-ray radiographs were used as ground truth for the

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characterization of the acquired AE signals. Our results reveal the formation and propagation of cracks under different processing conditions. They show that cracks can be efficiently tracked using AE. The analysis of the structure-borne AE signals in the frequency domain showed that solidification cracking processes could be clearly distinguished from the process emissions. It showed that cracking processes were dominant around specific frequency ranges. Overall, this research contributes to the understanding of solidification crack formation during LPBF from the perspective of AE. It demonstrates the potential of AE-based real-time in situ solidification crack detection to improve the quality and reliability of γ'-strengthened nickel-based superalloy components.

KEYWORDS: Additive manufacturing; CM247LC; Laser-based powder bed fusion; Nickel super alloy; Process monitoring; Acoustic emission.

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RELATIONSHIP BETWEEN PROCESS PARAMETERS AND MATERIAL PROPERTIES OF AN ALLUMINIUM ALLOY CUSTOMIZED FOR ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM) can be employed in a meaningful and economical manner particularly for complex and highly-integrated components that require numerous manufacturing steps or cannot even be realized with conventional production methods. One of the use-cases that has gained attention recently are heat exchangers due to the goal of using hydrogen as fuel for future civilian aircraft designs. Heat exchangers can benefit especially from the possibilities that Laser-based Powder Bed Fusion (PBF/LB or LPBF) enables, but suitable materials with high thermal conductivity as well as good mechanical and corrosion properties that simultaneously satisfy the requirement of good processability are still lacking today for different thermal cases in consideration. DLR investigates the feasibility of different heat exchanger concepts that, for instance, rely on bleed air from different stages of a hydrogen-based turbine engine.

The first thermal use-case employs the heat provided by bleed air from a compression section, which in turn points to aluminium alloys as optimal choice for the heat exchangers. Therefore, the PBF/LB processing routes and materials properties of potentially suitable novel alloys such as Constellium Aheadd® CP1 are being developed and optimized at DLR. Process windows aiming at very fine structure resolutions and high surface qualities as well as complementary ones for high productivity have been determined. The resulting as-built microstructures were characterized and optimized with a peak-aging heat treatment for high thermal conductivity. The formation and growth of precipitates including Al_3Zr and Al_xFe_y, e.g., at grain boundaries, was analysed. The mechanical performance and heat conductivity were assessed in the different conditions. Currently, the possibilities and limitations of printing specific structures relevant for heat exchanger design tailored to AM are being studied. The process developments will be employed in the future for the development and manufacturing of heat exchangers for hydrogen using hot air from the compressor section of turbine engine.

KEY WORDS: Laser powder bed fusion (LPBF), Constellium Aheadd® CP1, microstructure, materials properties, heat exchanger

Al-Ce Alloys for Selective Laser Melting

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Rapid solidification during AM processing typically results in fine-grained microstructures and associated enhanced strengths compared to their coarse-grained counterparts synthesized by traditional casting processes. Common casting alloys (e.g., Al-Si) are most often used in Al AM, however, the mechanical properties are limited compared to high-performance wrought alloys. This highlights the need for new AM alloys that exhibit both good printability (e.g., no hot cracking) and excellent mechanical properties over a wide temperature range . Aluminum-cerium based alloys are a promising system for Selective Laser Melting (SLM) based on their processing flexibility and high thermal stability. The low mobility of Ce in liquid Al during printing results in an ultra-fine (< 500 nm) dispersion of intermetallic particles in an Al-rich matrix. These Ce-containing intermetallics are highly resistant to thermal coarsening during printing and in service. Moreover, the alloys do not rely on post-processing heat treatments to impart strength, which significantly increases manufacturing efficiency. Here, we discuss using high throughput synthesis and characterization to develop new Al-Ce alloys for SLM that exhibit good processing flexibility and high strengths at elevated temperatures. The controlling strengthening mechanisms of the alloys are discussed.

[1] Prepared by LLNL under Contract DE-AC52-07NA27344 and sponsored by the Critical Materials Institute, an Energy Innovation Hub funded by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy and Advanced Materials & Manufacturing Technology Office.

EXPLORING VAST ALLOY COMPOSITION SPACE: FROM CALPHAD DATABASE DEVELOPMENT TO ALLOY OPTIMIZATION

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ABSTRACT

Calphad modeling plays a foundational role in mapping the Materials Genome and powering materials design, but high-quality multicomponent Calphad databases are still difficult to develop. The rise of computing power and software tools have made DFT calculations increasingly accessible, but these approaches have not yet been widely adopted by Calphad modeling experts.

First, this presentation will demonstrate our systematic use of first-principles calculations and empirical models to rapidly generate Calphad databases. Finite temperature formation energies for solid phases are computed by high-throughput DFT. Liquid mixing energies are estimated using semi-empirical models. Using the ESPEI software package (https://espei.org), these thermodynamic properties are used to automatically generate Calphad model parameters for a 10-component refractory high entropy alloy (RHEA) system without relying on any experimental data. The database has excellent qualitative agreement with known phase diagrams, validating this approach for obtaining reasonable estimates for Calphad model parameters.

RHEAs–encompassing refractory multi-principal element and complex concentrated alloys–are gaining attention as structural materials due to their promising high-temperature properties. The enormous composition-space design offered by the intrinsic nature of HEAs (combinatorics) can be seen as a blessing: so many new possibilities!; and a curse: how to find a needle in a haystack? For non-equiatomic alloys with more than a few components, methods investigating a grid of compositions fail sooner or later depending on how fine the grid is.

Second, we will present a method of efficient searching for novel alloys that combines (1) highly optimized Black-Box Optimization (BBO) multi-stage investigation of individual alloy systems using Calphad modeling and surrogate models for targeting properties with (2) on-the-fly decisions on systems to investigate and resources to allocate to each. The developed toolset runs parallel across systems, allowing rapid calculations on high-performance computers (HPCs), and is agnostic of the surrogate models, thus can be quickly re-used to target any properties. Here, we demonstrate targeting high yield strength at elevated temperatures in 9-component refractory systems.

Finally, as many Calphad users and alloy design specialists do not have easy access to HPCs, The Alloy Optimization Software (TAOS) – an easy-to-use automated alloy optimization software that runs on stand-alone computer – will be presented with HEAs optimization as a case study. In a nutshell, TAOS is the front-end (GUI) of a sophisticated tool that can handle high-dimension alloys, unconstrained and constrained optimization of extremely complex and non-smooth functions, and leverage the Calphad method and databases via commercial software compatibility (Thermo-Calc

through either TC-Python or TQ-Interface) and open source software integration (PyCalphad: https://pycalphad.org). HEA design examples highlighting objective functions (solidification range, solidification cracking criteria, etc.) and constraints on phase stability (solid solutions, ordering, miscibility gap, Laves phases, etc.) relevant to additive manufacturing will be presented.

Prepared by LLNL under Contract DE-AC52-07NA27344. Work was partly supported by the Laboratory Directed Research and Development (LDRD) program under project tracking code 22-SI-007.

KEY WORDS: CALPHAD, Database development, Alloy optimization, Software development, High entropy alloys, Machine learning.

Experimental Quantification of Inward Marangoni Convection and Its Impact on Keyhole Threshold in Laser Powder Bed Fusion

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ABSTRACT

Laser metal additive manufacturing (AM) has the potential to revolutionize the production of complex geometries with high precision across various industrial applications. However, optimizing the reliability of the process requires a detailed understanding of the complex physical phenomena during the process. While numerous efforts have been made to investigate the melt pool dynamics and defects formation mechanisms in unstable keyhole mode using *in-situ* measurements [1,2], the melt pool behaviors in the regimes with relatively fewer porosities, i.e., conduction mode and stable keyhole mode, have not been fully explored experimentally. Besides, both experiments and simulations have shown that the direction of Marangoni convection in the melt pool can impact significantly the melt pool shape [3,4], but no *in-situ* investigations of laser AM have been carried out regarding the inward Marangoni convection, which can be induced by a slight increase of sulfur content in stainless steels within a few tens of ppm [5]. In this study, we investigated the melt pool dynamics of laser powder bed fusion (LPBF) with SS316L using *in-situ* synchrotron X-ray imaging with tungsten particles as tracers. The spatial distribution of the fluid flow in the melt pool has been quantified with a resolution of ~10 µm through automatically tracing all moving particles in the melt pool. The results identified the interplay between laser power and scanning speed on melt flow velocities and revealed a significant impact of the inward Marangoni convections on the conduction-keyhole threshold, offering a new degree of freedom to broaden the pore-free process window of the laser-based AM. These findings contribute to a more comprehensive understanding of the melt pool dynamics during laser metal AM and provide valuable references for calibrating the high-fidelity computational models.

We performed *operando* synchrotron X-ray imaging experiments of LPBF across conduction mode to keyhole mode using the miniaturized LPBF device (Mini-LPBF) [6] on the beamline TOMCAT at Paul Scherrer Institute (PSI). Through automatically tracing all the tungsten particles that are well dispersed in the melt pool, we quantified the fluid velocities and accelerations in the melt pool for different laser parameter combinations. Our results show that the interaction between laser power and scanning speed plays an important role in the fluid velocities and accelerations of the Marangoni convection, even when the same normalized enthalpy is applied.

Furthermore, we observed a linear relationship between the melt pool size and the normalized enthalpy. Based on this relationship, the effective absorptivity of the powder bed in conduction mode and keyhole mode were calibrated separately, rendering precise values of the normalized enthalpy.

This study highlights the importance of understanding the inward Marangoni convection in laser-based AM and its impact on the keyhole mode threshold. Our results provide valuable understanding and references for the mechanistic modeling of melt pool dynamics during the AM process and offer insights for extending the pore-free processing window through alloy design to control the melt flow directions.

KEYWORDS: Laser powder bed fusion, In-situ synchrotron X-ray imaging, Particle tracing, Inward Marangoni convection, Keyhole threshold

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CHARACTERISATION OF LASER-POWDER BED FUSION CO-FREE Fe2Ni2MnCr HIGH ENTROPY ALLOYS

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ABSTRACT

High Entropy Alloys (HEAs) have gained significant attention in the scientific community over the last two decades. They can display a favourable combination of properties such as thermal stability, corrosion and oxidation resistance, and notable mechanical properties. Therefore, HEAs have been identified as a promising alternative for industrial applications to some traditional structural alloys, like austenitic stainless steels and Ni-base superalloys, especially for high temperatures conditions and harsh environments.

A large amount of FCC-HEAs containing cobalt has been studied and reported in the literature, but Co is considered a critical metal. As a result, part of the research in the HEAs community is nowadays the development of Co-free HEAs, trying to obtain similar microstructural stability while maintaining their beneficial properties.

In this study, a Co-free FCC HEA of the Fe_2Ni_2CrMn family processed through Laser Powder Bed Fusion (LPBF) has been designed to maximise its FCC stability at high temperatures and to avoid the formation of other detrimental phases for mechanical properties, such as the sigma phase. Besides, the influence of small amounts of copper and molybdenum have also been investigated to enhance its mechanical properties and to study their influence on the FCC microstructural stability.

The alloys have been characterised initially with Electron probe micro analysis (EPMA) and scanning electron microscopy (SEM) to study the elemental distribution. The results revealed different segregation patterns for the Cu and Mn elements depending on the printing parameters. For some conditions, segregation occurs at the grain boundaries (Figure 1(a)) and cell boundaries (Figure 2(a)) while, in others, such segregation is associate to the melt pools (Figure 1(b)) and not clearly at cell boundaries (Figure 2(b)). In order to understand these results, Transmission Electron Microscopy (TEM) measurements were performed upon the cellular structure to have a deeper understanding of the elemental distribution of unveil the behaviour of the elements at the nanoscale.

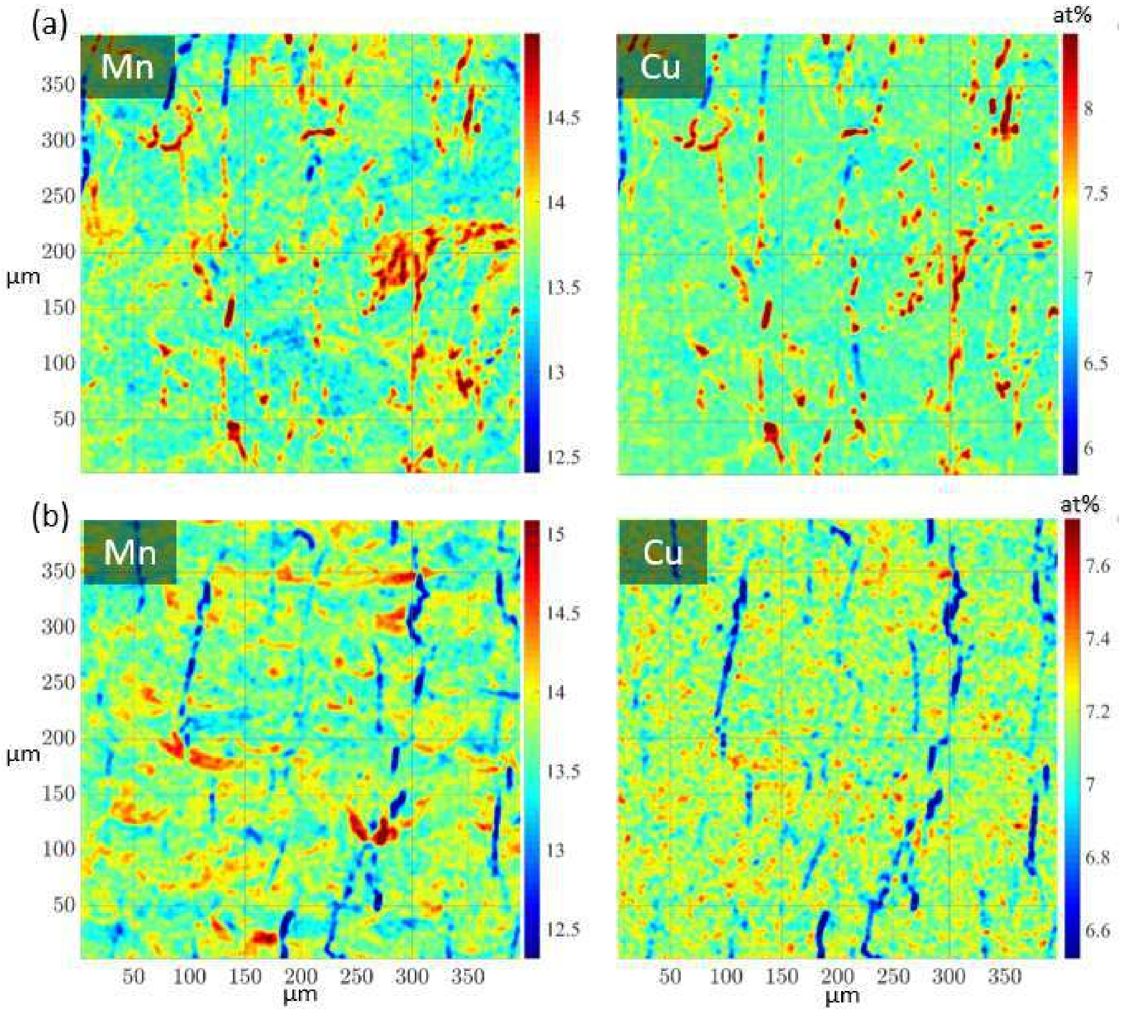

Figure 1: The different segregation patterns observed with EPMA (a) associate to the grain boundaries and (b) associate to the melt pools.

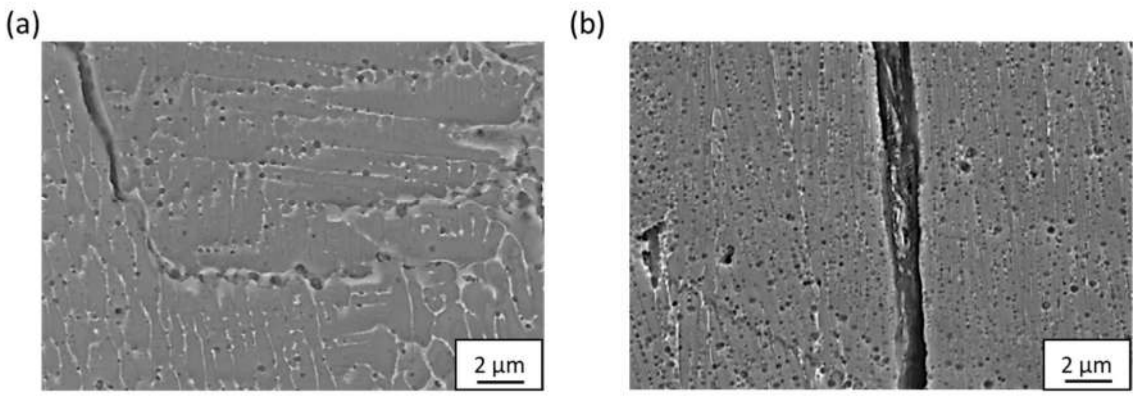

Figure 2: Secondary electron micrographs of etched microstructure of the samples that revealed segregation (a) associate to the grain boundaries and (b) associate to the melt pools.

KEY WORDS: High Entropy Alloys, Laser Powder Bed Fusion, segregation, Electron probe micro analyser, Transmission electron microscopy

Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

High-throughput exploration of alloys for additive manufacturing using experimental and machine learning approaches

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ABSTRACT

The development of novel alloys that are specifically tailored for additive manufacturing (AM) is one of the current major challenges of the AM material science research community. However, the existing approaches can be further made efficient in exploring the vast material and process design space in AM.

In the present work, we applied extreme high-speed laser material deposition (EHLA) to rapidly screen a wide range of chemical compositions and processing conditions within a single specimen. Combined high-throughput sample production and alloy characterization were used to explore the microstructure evolution and mechanical properties of additively manufactured advanced high strength steel. In-situ alloying of a base alloy (an austenitic steel) with pure Al in the range of 0-8 wt.% and flexible adjustment of the volumetric energy input enabled high-throughput sample production consisting of 20 individual chemistry-EHLA parameter combinations. These conditions were characterized using large-area EBSD analysis combined with EDS and spherical micro indentation stress-strain protocols. The significant influence of Al content and processing conditions on the behaviour of the investigated metastable base alloy allowed for efficient exploration of the respective mechanical properties. The derived process-structure-properties relationships are discussed based on the underlying physical mechanisms. The experimentally identified microstructure-property (SP) relationship was generalized using a machine learning (ML) approach. With this selected approach, the data-driven SP relationship can be described in terms of its uncertainty. In addition, the applicability of the methodology is critically evaluated.

KEY WORDS: Alloy design for AM, High-throughput screening, Machine learning, Steels for AM

MICROSTRUCTURE TAILORING OF IN738 USING DUAL-LASER LPBF STRATEGIES

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ABSTRACT

As layer-based manufacturing process, laser-based powder bed fusion (LPBF) offers increased degrees of freedom for component designs. These design opportunities are especially advantageous for components used for high temperature applications which leverage the possibility of integrating complex cooling channels. Materials of interest for such applications include gamma prime strengthened nickel-based superalloys like IN738. The coherent strengthening phase gamma prime increases the material's strength at high temperatures. However, as-LPBF IN738 does not display any gamma prime particles as the high cooling rates during the manufacturing process supress phase formation. Gamma prime formation therefore occurs during subsequent heat treatment which is applied to the entire component. For optimized, local gamma prime formation, this heat treatment would require careful, design-dependent controlling which would be time consuming, expensive, and restrict component-design optimization potential.

The aim of this study is to generate gamma prime formation in as-LPBF IN738 with the potential of achieving multi-modal size distributions in subsequently heat-treated material. The application of dual-laser scanning strategies using a *lead* and a *follower* laser to shape the temperature profile of the melt pool extends the time of the material at temperatures >850°C. The extended time is aimed to initiate gamma prime formation during manufacturing, thus combining increased design freedom with microstructural optimization.

Dual-laser strategies are explored whereby a second laser follows a designated *lead* laser. The *lead* laser determines both hatch distance and scan speed which remain the same during the process while laser power and laser beam diameter can be independently altered for both lasers. The dual-laser LPBF strategies are based on single laser parameters which result in consolidated IN738 material with minimal porosity and cracking. For the study, cubic material samples (5x5x5 mm^3) are divided into horizontal sections of 1 mm which are manufactured using single- and dual-laser strategies alternately for direct comparison of the resulting material characteristics. After manufacturing, samples are prepared metallographically and analysed using optical microscopy and SEM on etched samples using Marble's reagent to remove the strengthening phase. Additionally, hardness measurements are performed to investigate expected hardening due to the formation of the gamma prime phase. Finally, samples are aged at 850°C for various times and analysed using SEM to investigate multi-modal size distributions of gamma prime particles.

KEY WORDS: LPBF, nickel-based superalloys, microstructure tailoring, phase formation, dual-laser strategies.

POWDER BED FUSION BY LASER AND ELECTRON BEAM OF A MAGNETOCALORIC NI-MN-SN HEUSLER ALLOY

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ABSTRACT

A promising group of magnetocaloric alloys are Ni-Mn-X Heusler alloys with X = In, Sn (or Ga, Al). Especially ferromagnetic alloys of the type $Ni_{50}Mn_{50-y}X_y$ are of particular interest with regard to solid-state refrigeration, exploiting the high potential of the magnetocaloric effect (MCE) [1]. Alloyed with Ga, In, Sn or Sb, the ferromagnetic alloys undergo a coupled spin-lattice martensitic transformation (MT) and generate thermal energy in response to the application of external stimuli, e.g., magnetic fields or pressure [2,3]. Amongst others, $Ni_{50}Mn_{50-y}Sn_y$ has come into focus because of large magnetic entropy changes, and desirable Curie temperatures close to room temperature combined with comparatively good mechanical properties. At the same time, the elements of this alloy type are widely available. Additive manufacturing (AM) is a versatile way to consolidate near-net-shape geometries from powder materials while enabling unique microstructures.

Typical X_2YZ Heusler alloys crystallize in a fully ordered structure of $L2_1$-type while increased Y content promotes a $L2_1$-B2-type disordered structure [4]. This makes AM by powder bed fusion (PBF) a feasible considered approach [5], the latest successful demonstration of which by choosing laser radiation as an energy source (PBF-LB) is reported by W. Sun et al. in [6] and K. Sun et al. in [7]. Solids with dimensions of several ten millimeters with a composition of $Ni_{45}Mn_{44}Sn_{11}$ (at.-%) have been built; still, intergranular cracking due to anisotropic volume change during phase transformation remained an issue limiting the structural integrity.

Aiming at prospectively stepping towards the production of high-performance magnetocaloric parts, powder bed fusion with both photons (PBF-LB) and electrons (PBF-EB) of a magnetocaloric approx. 47.2Ni-39.2Mn-13.0Sn (at.-%) alloy was experimentally studied in order to comparatively investigate the material in terms of processing (Fig.1), microstructure and MCE.

The feasibility to produce crack free samples by PBF-EB was successfully demonstrated. EDX measurements revealed evaporation of approx. 1.9 (PBF-EB) to 2.2 (PBF-LB) in at.-%, respectively. After annealing at 900°C, both materials showed homogeneous recrystallization of the epitaxial grain structure with an average grain size of 70-100 µm (Fig. 2). SEM imaging and XRD patterns indicated almost fully martensitic microstructures in annealed state. No reflections of secondary phases ($MnSn_2$, MnNi or oxide) have been detected. Under the external field change of 1 T, a magnetic entropy change of $\Delta S_{max} = 0.24$ J/kg K is achieved for heat treated PBF-EB material at 308 K compared to 0.21 J/kg K at 328 K of the respective PBF-LB sample.

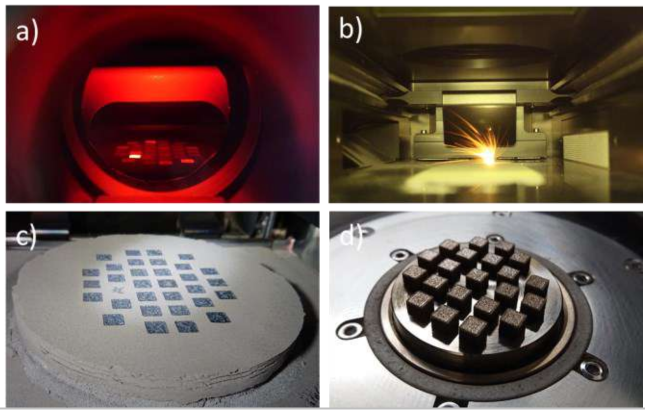

Fig. 1: Processing (a,b) and photographs (c,d) of PBF-EB (a,c) and PBF-LB (b,d) Ni-Mn-Sn samples

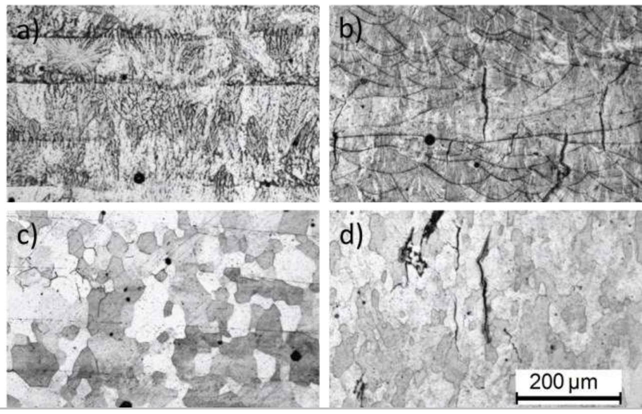

Fig. 2: Microstructure of PBF-EB (a,c) and PBF-LB (b,d) Ni-Mn-Sn samples, as-built (a,b) and heat treated (c,d)

Fundings from the DFG (Deutsche Forschungsgemeinschaft) via the CRC/TRR 270 (Project-ID 405553726), GO 2566/10-1-(Project-ID 445127149) and INST 218/90-1 (Project-ID 510085108) are gratefully acknowledged. The authors would like to thank Dr. David Koch (TU Darmstadt) for performing XRD measurements on very short notice and his readiness for discussion. The support of Juha Lagerbom (VTT) in producing and analyzing the powder material is highly acknowledged.

KEY WORDS: Advances in processing, electron beam and laser powder bed fusion, microstructure and phase transformations, Heusler alloys, functional properties.

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Alloys for Additive Manufacturing Symposium – AAMS 2023
Madrid, 27-29 September 2023

Efficient simulation-based creation of a metamodel for conduction mode melting in laser powder bed fusion processing

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ABSTRACT

Laser powder bed fusion (LPBF) is one of the most commonly used additive manufacturing techniques to create near net-shape metal parts. To this day, however, most optimization techniques rely on the trial-and-error approach and do not provide additional insight into the interplay between laser parameters and the process responses. To further promote the understanding of the LPBF process and ultimately circumvent the time and resource demanding trial-and-error approach altogether, researchers and practitioners recently directed significant efforts toward the numerical modeling of LPBF [1,2]. In line with these efforts, we present a state-of-the-art finite element (FE) modeling approach that accounts for the most important solid-state physics of the process. The model is used to resolve the temperature field within the vicinity of the laser-material interaction zone. The solution is then calculated for varying laser power, laser velocity, and initial temperature. Resultingly, the characteristic melt pool responses (width, depth, length) can be expressed as a function of the input parameters (laser power, laser velocity, initial temperature). A design of experiments (DoE) approach is utilized to determine the minimum number of simulations necessary to find an adequate metamodel for this relation. The results indicate that as little as 15 simulations are sufficient to capture the vast majority of the variability in the melt pool responses (R^2-scores > 0.95) within a wide range of the input factors. More than that, a direct byproduct of this method are easy to interpret coefficients that express the sensitivity of the responses with respect to the input factors. The validity of this approach is demonstrated on two of the most common alloys within the LPBF community, namely 316L stainless steel and Ti-6Al-4V [3,4]. Etched cross-sections of 316L samples, printed at room temperature, are used to experimentally verify that the simulations adequately represent the actual LPBF process. 20 different process parameter combinations were investigated with up to 12 observations per process parameter combination to establish a trustworthy mean value.

To summarize, a design of experiments approach was utilized on experimentally verified finite element simulations to determine the minimum number of simulations necessary to establish a metamodel that can fully describe the melt pool responses (width, depth, length) as a function of the input factors (laser power, laser velocity, initial temperature) for conduction mode laser powder bed fusion processing. It can be concluded that as little as 15 simulations are sufficient to establish such a metamodel and quantify the sensitivity of the melt pool sizes with respect to the aforementioned input parameters. These findings allow researchers and practitioners to solely focus on necessary sampling points and will improve general efficiency when exploring the conduction mode melting regime in laser powder bed fusion.

KEYWORDS: Laser powder bed fusion, finite element modeling, design of experiments, melt pool size, metamodel, conduction mode melting

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ICOSAHEDRAL SHORT-RANGE ORDER: A DESIGN STRATEGY FOR DEVELOPING ALLOYS IN ADDITIVE MANUFACTURING

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ABSTRACT

Through a multi-scale microstructural study of a novel Al-alloy designed for and fabricated via L-PBF, we identified several key features demonstrating the presence of Icosahedral Short-Range Order in the liquid during additive manufacturing. The consequences of icosahedral-based local ordering on the nucleation and growth mechanisms are discussed. Two different nucleation mechanisms requiring the presence of ISRO are identified: ISRO-mediated nucleation and icosahedral quasi-crystal (iQC)-mediated nucleation. The effect of ISRO on the classical epitaxial growth of the FCC-Al on the metastable primary Al_3Zr precipitates acting as a nucleating agent is also highlighted. The variety and efficiency of those nucleation mechanisms to refine grain size in additively manufactured Al-alloys are evaluated. The presence of twin dendrites with unexpected growth directions, often considered as defects in traditional cast products, is here seen as an efficient way to break down the morphological and crystallographic texture anisotropy of AM microstructures. The consequences of the presence of ISRO in the melt on the viscosity and diffusivity of solutes are also discussed. We conclude that alloy design strategies aiming to promote ISRO in the liquid during additive manufacturing of engineering alloys should be considered as a serious and promising route towards optimized properties.

KEY WORDS: design strategy, liquid ordering, solute trapping, nucleation, growth, primary phases.

Maxence Buttard, Guilhem Martin, Xavier Bataillon, Gilles Renou, Pierre Lhuissier, Julie Villanova, Béchir Chehab, Philippe Jarry, Jean-Jacques Blandin, Patricia Donnadieu, "*Towards an alloy design strategy by tuning liquid local ordering: What solidification of an Al-alloy designed for laser powder bed fusion teaches us*", Additive Manufacturing, 2023

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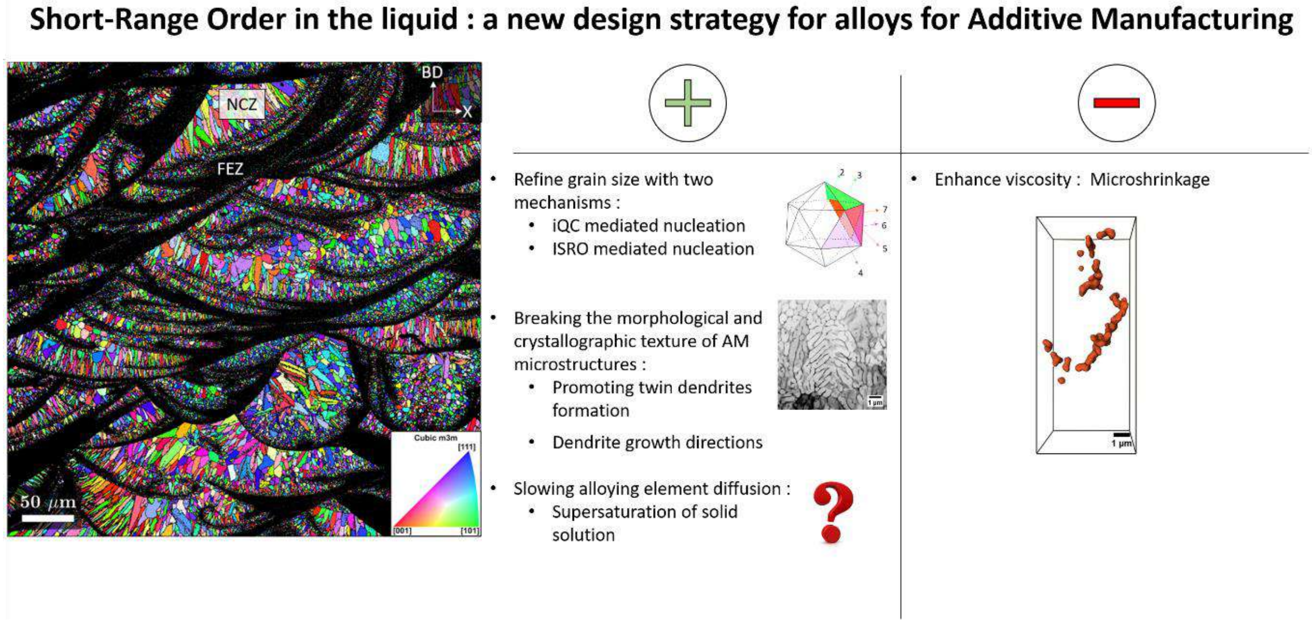
Graphical Abstract



Experimental investigation of the Properties of Hybrid Aluminium Alloys Manufactured using Wire-DED Plasma Arc Process

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Abstract: Wire-DED Plasma Arc (W-DED-PArc) has emerged as a promising Additive Manufacturing technology for fabricating high-performance and large volume metal parts. However, there is a lack of reports on Aluminium alloys using this technology. Additionally, producing multi-material components remains one of the challenges due to the interfacial properties, intermetallic phases, and compatibility of the different alloys to be joined together. The current study investigated the effect of different substrate alloys (2017, 5038, and 7075) during single-layer and multi-layer depositions of AlSi10Mg alloy using W-DED-PArc. The microstructure and mechanical properties of the interface were evaluated through optical microscopy, scanning electron microscopy, and hardness tests. Additionally, porosity analysis was carried out. The results showed that the build-up of AlSi10Mg alloy on all substrate alloys was successful with a well defined mixture zone and good interfacial bonding between the build-up and substrate. However, the microstructure and mechanical properties of the deposited layers varied depending on the substrate alloy. Furthermore, the hardness profiles across the build-up were found to be similar for the 2017 and 7075, while the 5083 exhibited a different behaviour due to the weldability and the chemical composition difference. In conclusion, this study provides valuable insights into the effect of different substrate alloys on the build-up and mechanical properties of AlSi10Mg alloy using W-DED-PArc.

Keywords: Additive Manufacturing, Directed Energy Deposition, Plasma Arc, Hybrid Materials, Aluminium Alloys.

Extraordinary combination of strength and ductility in an additively manufactured Fe-based medium entropy alloy through the in-situ formed nanoprecipitate

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ABSTRACT

In the present work, the mechanical properties of Fe-based medium entropy alloy printed by laser-based direct energy deposition (DED) method have been investigated in room and cryogenic environments. Besides, the impact of in situ precipitation, formed during DED, on the mechanical property was inspected. Therefore, the as-print sample has a dual-phase heterogeneous microstructure of austenite and martensite decorated by cellular structures and nano-precipitates. The corresponding MEA revealed acceptable ultimate tensile properties and total elongation and exceptional cryogenic mechanical properties, as compared to the present additive manufactured HEAs/MEAs. The improved tensile properties of the corresponding additive manufactured MEA, in comparison with the present literature, are due to the co-activation of solid solution strengthening, dislocation-mediated plasticity, hetero-deformation-induced strengthening, deformation-induced martensitic phase transformation, and precipitation strengthening. The present results can expand the possibilities for developing ferrous MEAs/HEAs to overcome the strength and toughness trade-off in severe conditions.

KEY WORDS: Additive manufacturing; High entropy alloys; In situ precipitation; Hetero-deformation-induced strengthening; Mechanical properties.

ULTRASONIC ATOMIZATION AND L-DED APPLICATION OF A CUSTOM TOOL STEEL

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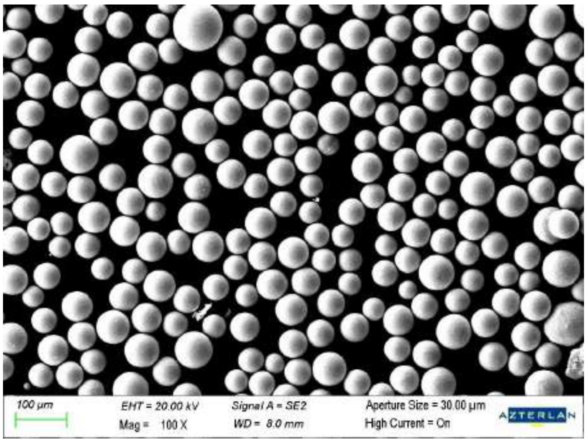
ABSTRACT

The main goal of this work is to manufacture and test a custom L-DED powder for improving wear resistance of forming tools after laser cladding application in the required areas. The wear of tool steels continues to be a great concern to the forming technologies, because of increasing die maintenance costs and scrap rates due to the severe tribological stresses and the strict tolerance limits of these type of components [1]. Hardness is commonly used in industrial practice for wear related material selection [2]. Nevertheless, making the whole dies with enhanced properties tool steels which have excellent wear resistance has the disadvantage of increasing costs. So, here, to overcome these limitations, the Laser Direct Energy Deposition (L-DED) manufacturing technology gains strength and seems to be a potential solution to be applied over a common tool steel substrate.

The main objective is to develop a custom powder to be applied by L-DED with enhanced hardness aided by the formation of different hard carbides. Target chemical composition for the powder was cast in a small pilot furnace of 50 kg at Azterlan, several keel blocks were cast and bars of Ø 8 mm were machined. The Cr content was ~5.5 wt. %, and the sum of the other promotor of carbides, X content was ~5 wt. %. These bars were then atomized by 3D Lab Sp. z o. o. in the ATO Lab+ ultrasonic metal powder atomizer, using the 35 kHz module. Very spherical powder, typical of ultrasonic metal powder atomization was obtained (see Figure 1) being D10 = 42 µm, D50 = 51 µm and D90 = 62 µm. Table 1 shows that a significant Mn fading (~ 78 %) occurred in comparison with the bar chemical composition analysed by ICP-OES and LECO, while the other elements were enriched accordingly. This powder was deposited by MESHIND, using a L-DED Trumpf TruLaserCell 3000 machine, in a single layer square sample with a thickness between 1.5-2.1 mm and good metallurgical bond with the substrate (Figure 2). Few pores were observed in the coating, being the biggest one of 0.2 mm. The Heat Affected Zone (HAZ) was small with a thickness between 0.5-1.2 mm. Besides, the dilution rate is small, the chemical composition of the coating is slightly enriched in Mn in comparison with the powder composition (see Table 1), while C is

reduced due to the dilution with the base 1.2344 steel. Several complex carbides are observed in the microstructure analysis, being the hardness of the coating 15 HRC higher than the substrate.



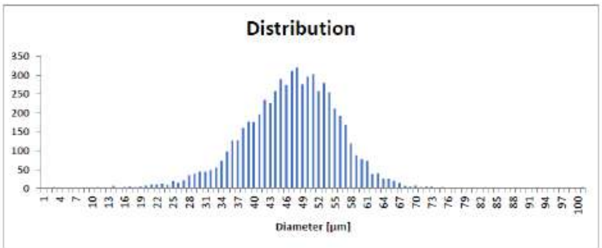


Figure 1. SEM image of the atomized powder (left) and Particle Size Distribution histogram (right).

Table 1. Chemical composition of the bar, powder and hard face coating in wt. %. X element is the sum of all carbide promoters apart from Cr.

	Chemical composition (wt. %)							
	C	Si	Mn	Ni	Cr	X	S	Fe
Bar	0.49	0.29	0.37	1.76	5.67	4.96	0.006	Bal.
Ultrasonic Powder	0.51	0.37	0.08	1.80	5.45	6.10	0.007	Bal.
L-DED Coating	0.38	0.42	0.13	1.81	5.31	5.45	0.007	Bal.

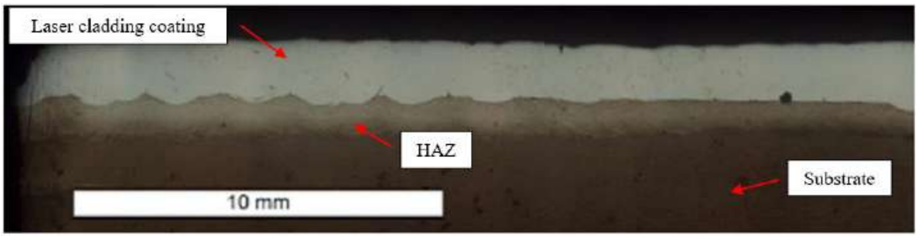


Figure 2. Cross section of the laser coating.

So as main conclusion, it has been proved that the proposed methodology is useful to manufacture cladded die, but it is necessary to increase Mn content during bar manufacturing to compensate the faded amount during the atomization process and thus achieve the desired content and chemical composition in the coating. The hardness of the clad in as-built state is 54 HRC and could be used without postprocessing treatments.

KEY WORDS: Die tool, atomization, manganese fading, laser cladding, surface strengthening.

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THE APPLICATION OF THE LPBF PROCESS IN MANUFACTURING PARTS FOR AUTOMOTIVE INDUSTRY

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ABSTRACT

The automotive branch is one of the key targets for the application of the Metal Additive Manufacturing (AM) technologies. Because of very high investment costs, and still relatively low productivity compared to high volume production, the use of AM is limited mainly to manufacturing parts for high-performance sport vehicles or hyper-cars. But like other inventions and new technologies, which were developed and tested under extremely high conditions, AM techniques also proved their reliability and material performance, which could be introduced in other fields of this industry. Centre for Advanced Manufacturing Technologies, operating at Wrocław University of Science and Technology, in his over 15-year experience works on over 30 different materials processed in AM technologies. Some recent projects covers evaluation of these techniques for fabricating parts for automotive industry for prototyping as well as replacing parts in low-volume modular car construction. This work presents how Laser Powder Bed Fusion (LPBF) process could be profitable in the new car development process. The project findings on the development of the full processing path of crash absorber prototypes made from a middle manganese steel powder, as well as the topology optimised parts made from aluminium alloy, will be presented to reduce its weight and increase stiffness.

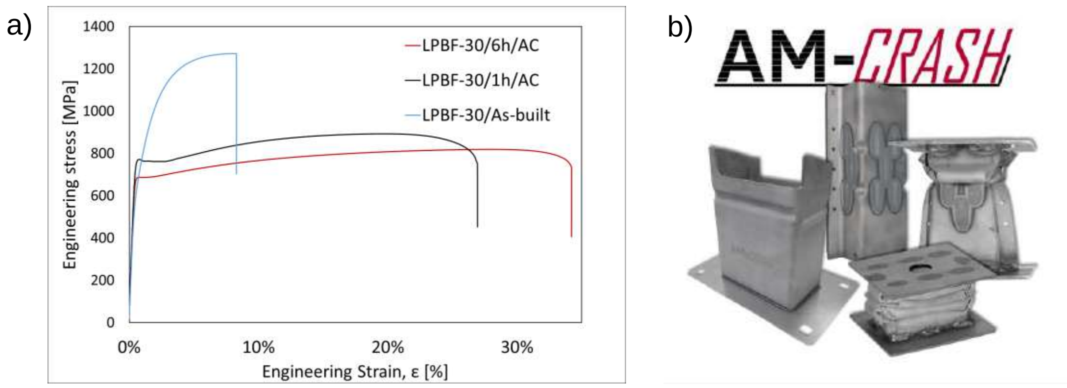

Fig. 1 a) Mechanical properties of Fe-0.15C-7.5Mn-1.8Al processed by LPBF system and at different HT states. b) image of evaluated crash-box demonstrators.

Deep drawing thanks to its low unit costs is a hard competitor to be replaced by AM. For prototyping purposes, AM technologies allow us to skip the expensive tooling preparation step, which could lead to saving time and money and thus shorten the development process. The limitation of the use of AM as replacement of deep drawn parts is a mismatch in the mechanical properties of a sheet material processed in traditional way and thin-walled 3d printed parts. The results obtained in the project **"AM-Crash"** show that the static and dynamic mechanical properties could be tailored thanks to the application of proper heat treatment (HT) (Fig. 1a) which aim to recover desired amount of austenite from the near to 100% nominal as-built martensitic structure [1]. Furthermore, developed and introduced local laser hardening zones could modify the deformation behaviour under applied loads – Fig. 1b [2].

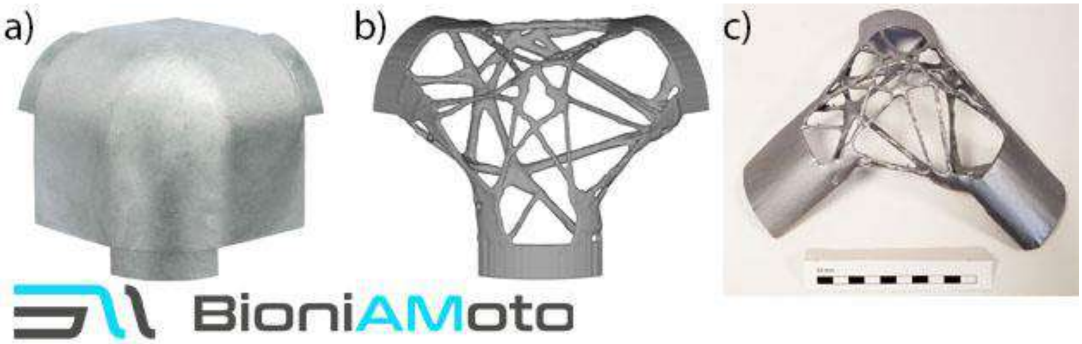

Fig. 2 Part example redesigned in order to reduce its weigth. a) Box corner part - Courtesy of ALU-SV CZ s.r.o., b) Part geometry designed with bionic optimization algoritm software, C) Part made from AlSi7Mg0.6 alloy by LPBF technique

Another conducted research **"BioniAMoto"** project led to achieve mass reduction in a construction of vehicles chassis, especially for that used in modular construction, like special vehicle bodies, like e.g. ambulances, vans or other special purpose vehicles. Such construction is made from extruded profiles joined together in nodes. Each modification of the construction changes the load distribution and requires a different frame design. Generative design tools, as well as topology optimisation algorithms, are commonly used to make parts in AM, strengthening the synergy effect and maximise achieved profits [3]. One of the example achieved in the projects shows that vehicle body box corner mass can be reduced by up to 63% from the initial 280 g to merely 102 g (Fig. 2).
Presented examples shows that AM technologies can be implemented in automotive industry in different ways. Each of them aims to reduction of vehicle performance or improve the economic of the car development process.

ACKNOWLEDGEMENTS
This work was supported by the Polish National Centre for Research and Development under the grant Bionic lightweight Additively Manufactured structural nodes for Automotive industry (Grant no. TECHMATSTRATEG-III/0044/2019-00) and "Additive Manufacturing Technologies for Crash loaded structural Components (AM-Crash)" M-ERA.NET 2 Cofund (Grant No. M-ERA.NET2/2018/1/ 2019). Financial support is gratefully acknowledged.

KEY WORDS: Design for Additive Manufacturing, Phase transformation, crashworthiness, LPBF, Topology optimization

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METALLIC POWDER MANUFACTURE FOR CONDITIONING CAST IRON AS AN AM SUBSTRATE

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ABSTRACT

The main purpose of this work is to design and develop a metallic powder to use it as a paint for cast iron moulds allowing subsequent L-DED deposition on the parts to increase corrosion resistance and/or wear resistance. Cast iron is widely used in the manufacturing of several components with complex geometry and cavities due to its good castability, low cost and excellent machinability. Currently, different technologies of surface modification are used to increase the wear and/or corrosion resistance, but there are still many problems such as limitation on coating thickness, high cost and complex equipment [1]. L-DED (Laser Direct Energy Deposition) has been proposed as a potential solution without substantially increasing the price. However, L-DED on cast iron components is a difficult and a complex process due to the risk of heterogeneous thermal and stress fields formation as result of the graphite and matrix properties, formation of pores for carbon dioxide produced during the laser beam radiation and the formation of hard and brittle phases due to the high cooling rate that may lead to crack formation [2].

An intermediate coating with Ni-rich powder is proposed. For that, a Ni-3Ti wire of Ø 1 mm has been atomized in the ATO Lab+ metal powder atomizer in Azterlan using the 35 kHz ultrasonic module and the following process parameters: argon flow 20 l/min, 70 % power pump, 100 A arc intensity and 80 % ultrasonic amplitude. Table 1 compares the chemical composition of both Ni-3Ti wire and powder. Apart from minor variations, the most important change was the fading of Mn (~38 %).

Table 1. Chemical composition of Ni-3Ti wire and ultrasonic powder (wt. %)

Ref.	Ni	Ti	C	S	O	N	Si	Mn	P	Cu	Al	Fe
Ni-Ti wire	96.1	3.02	0.017	<0.005	0.003	<0.002	0.38	0.42	<0.01	<0.08	0.05	<0.1
Ultrasonic Powder	96.1	3.13	<0.010	<0.005	0.054	0.004	0.41	0.26	<0.01	<0.08	0.05	<0.1

As it can be seen in Figure 1, the produced powder has an excellent sphericity with no satellites. Some dark spots are observed in some particles, identified as titanium by EDX analysis in a Scanning Electron Microscope (SEM).

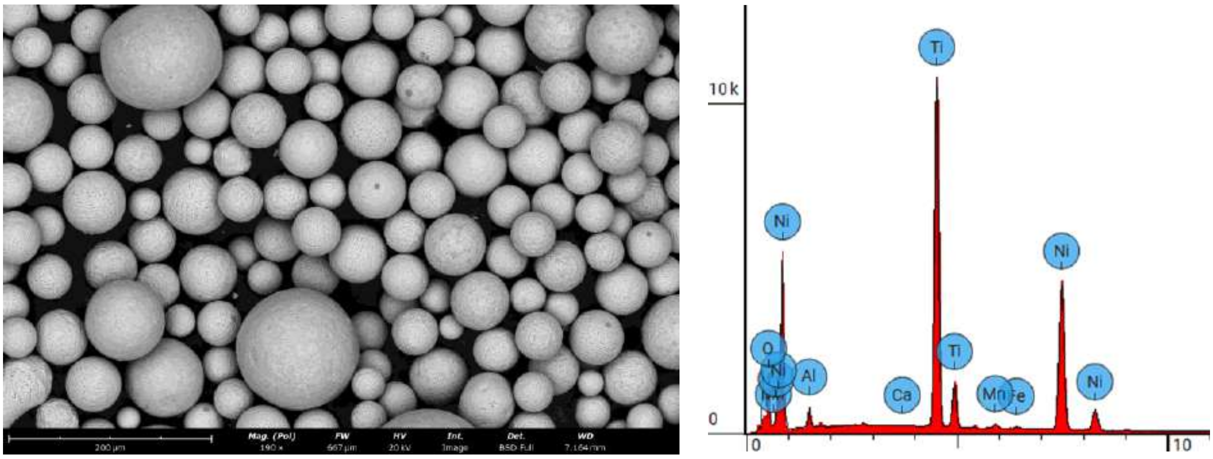
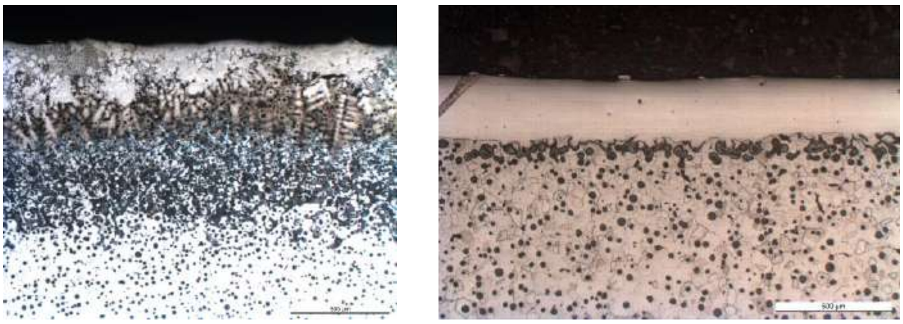


Figure 1. SEM image of the obtained powder and EDX of the dark spots.

The Ni-3Ti powder was mixed with a binder that was applied as a coat in the bottom part of a sand mold. Then, they were kept for 24 hours at room temperature to eliminate the moisture and get a solid coating. High silicon cast iron was melted in a medium-frequency furnace with a casting temperature ~1510-1520°C and poured into the sand mold avoiding direct pouring onto the coating. After demoulding, the surface was shoot blasted and L-DED single layer coat with Inconel 625 powder was deposited by MESHIND, using a L-DED Trumpf TruLaserCell 3000 machine. Figure 2a shows the microstructure of high Si cast iron coated with Ni-3Ti powder. There is a transition coating between cast iron and Ni coating. Figure 2b shows the microstructure after L-DED deposition. Note that no carbides are observed. Thus, it is possible to apply a hard coating over cast iron by introducing an intermediate diffusion layer of a powder base Ni-3Ti alloy.



a) b)

Figure 2. a) Resulting microstructure of the reaction of cast iron with the Ni coating; and b) resulting microstructure after L-DED deposition over the Ni coating.

KEY WORDS: L-DED, High Silicon cast iron, Surface modification, In-situ casting

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Investigating Multi-Material Laser Powder-Bed Fusion via Operando Synchrotron X-Ray Diffraction

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ABSTRACT

Laser powder-bed fusion (LPBF) of multi-material components is a rapidly growing field with a range of potential applications. To realize this potential, a comprehensive understanding of the phase evolution during the process, especially at the interfaces, is necessary. While even commercial alloys behave differently than their conventional counterparts under LPBF process conditions (high cooling rates, thermal cycling etc.), combination of multiple alloy systems puts forward a completely new challenge. Processability of a given alloy combination highly depends on understanding the solidification and phase transformation routes and their manipulation using the process parameters during LPBF.

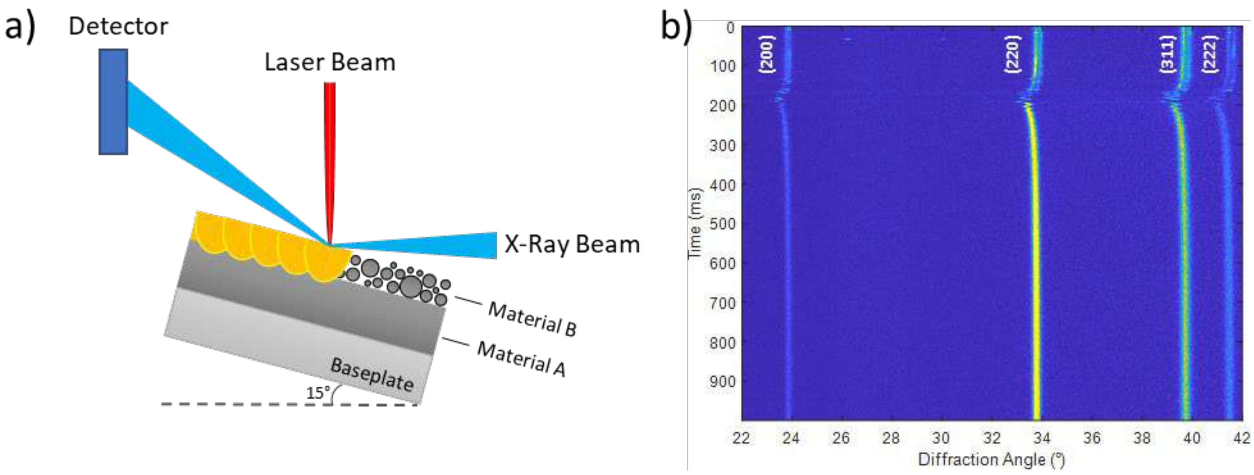

Figure 1. a) Experimental configuration and b) the evolution of the X-ray diffraction patterns over time.

This study investigates the phase evolution during multi-material laser powder-bed fusion of 316L stainless steel and CoCrMo medical alloy, with a focus on the interfacial regions. The materials were printed in different combinations and configurations (Figure 1a) and operando synchrotron X-ray diffraction measurements were conducted. X-ray diffraction patterns were collected at 20 kHz frequency to track the solidification behavior (Figure 1b) using Eiger1M detector and the miniature LPBF system (miniSLM) developed at the Paul Scherrer Institute (PSI) [1,2]. The patterns were collected over successive layers around the interfaces during melting and solidification. A single-phase FCC structure has been observed at the CoCrMo/316L interface. The alloying elements did not produce any detrimental intermetallics, nor were any defects such as cracks or large porosities as observed at the interface during post-mortem analyses. The sound interface shows the printability of this alloy combination using LPBF. Overall, the results provide a deeper understanding of the solidification behavior of multi-material combinations involving these alloys during LPBF and hold promise for the improvement and optimization of multi-material components in medical applications.

KEY WORDS: phase transformation, x-ray diffraction, stainless steel, cobalt chromium, medical alloy

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Using powder mixtures to develop high entropy alloys via in-situ alloying in PBF-LB/M and studying its phase evolution by annealing

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Manufacturing high entropy alloys (HEAs) using powder bed fusion-laser beam/Metal (PBF-LB/M) enables their production with minimal elemental segregation due to its inherently fast cooling rates resulting in excellent properties. So far, HEAs have been fabricated with fully pre-alloyed gas-atomized powders which makes it expensive and slower to explore new alloy compositions. In this work, for the first time, instead of pre-alloying, blended powders of CoCrF75, Ni625, Invar36, and pure Al powders were used as feedstock to develop a $CoCrFeNiMo_xAl_y$ HEA which consists of FCC phase in the metastable state. The process was optimized achieving relative densities greater than 99.8%. Moreover, the phase evolution from metastable FCC phase was studied by annealing at various times and temperatures with the help of thermocalc simulations. This method of mixing powders for PBF-LB/M enables rapid exploration of new HEAs and this work is expected to contribute to its successful application in the future.

DEVELOPMENT OF INNOVATIVE STRUCTURAL MATERIALS FROM HIGH ENTROPY ALLOYS OBTAINED BY A HYBRID POWDER/WIRE ADDITIVE MANUFACTURING PROCESS

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ABSTRACT

Conventional way of developing a new material was to select major elements to confer primary properties, and to use additional alloying elements to confer secondary properties. In 2004, Yeh and Cantor highlighted the possibility of developing alloys composed only of major elements [1-2], called High Entropy Alloys (HEA). HEA contain at least five elements whose proportions vary between 5 and 35% and form a solid solution.
These type of alloys, in the context of the development of new materials for molten salt reactors.

With the aim of producing innovative materials, additive manufacturing is an interesting process. It enables the production of complex and reproducible parts while avoiding the need for welding. However, there are some drawbacks to consider. Powder laser additive manufacturing is highly material-intensive and not very cost-effective. On the other hand, wire laser additive manufacturing is very economical but lacks flexibility in terms of composition complexity.

In this work, the hybridization of the additive manufacturing process of powder technology (Direct Laser Deposition) and wire technology (Wire Laser Additive Manufacturing) was chosen. The coupling of Direct Laser Deposition and Wire Laser Additive Manufacturing processes will allow combining the advantages of each of them, the high yield of material deposition brought by the wire technology and the flexibility of chemical composition brought by the powder technology, while minimising their respective disadvantages.

Thus, in a first step, compositions of interest with the desired microstructural characteristics are targeted by a preliminary step of thermodynamic calculations using the CALPHAD method. Then, the same alloy is produced by two different additive manufacturing techniques: Direct laser powder deposition technology, which is very commonly used, and the hybrid powder/wire laser innovative process.

In a second step, their microstructures are characterised by scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD).

After characterization of these alloys, their corrosion resistance is being tested in salt molten environment. A corrosion mechanism taking into account the microstructural differences will be presented.

KEY WORDS: Design of new alloy, Multicomponent alloys, Hybrid processes, Powder/Wire Additive Manufacturing, Powder Additive Manufacturing, CALPHAD approach

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Tailored deformation behavior of stainless steels produced with L-PBF

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ABSTRACT

Apart from the profound advantage of producing complex geometries, laser-powder bed fusion (L-PBF) provides the possibility of manipulating microstructures and crystallographic textures. By combining the texture manipulation capabilities of L-PBF with the strong orientation dependence of the transformation induced plasticity (TRIP) and the twinning induced plasticity (TWIP) effects [1,2], it is possible to realize L-PBFed components with superior mechanical properties compared to their wrought counterparts. The nature of the crystallographic texture is closely related to the morphology of the melt pool, which forms during the laser scanning. Specifically, it has been found that shallow melt pools promote the formation of <100> crystallographic texture along the building direction (BD), while deeper melt pools promote the formation of <110> crystallographic texture along the BD [3].
Finding the optimum interplay of process parameters is challenging and requires a series of parametric investigations which are typically used to extract empirical and qualitative trends. During our efforts to manipulate the crystallographic texture in austenitic stainless steels produced with L-PBF, neutron diffraction appeared to be a high throughput method to quantitively assess the crystallographic orientation along the building direction in a series of test samples. The combination of the process parameters and quantitative texture characterization is used as input into regression trees analysis that is able to reveal trends and pathways in the process spectrum. Regression trees is a common data mining technique that aims to predict the value of a certain dependent variable (texture), based on the input of several independent variables (process parameters). Based on the output of the regression trees analysis, we design a site-specifically texture-tailored 316L stainless steel part. The sample is then subjected to bending deformation and exhibits superior mechanical properties, compared to the counterparts having the exact same process parameters but different, non-tailored, crystallographic textures. The present investigation highlights that L-PBF can be

exploited for realizing complex geometries with site-specifically tailored microstructures and enhanced mechanical properties.

KEY WORDS: crystallographic texture, site-specific design, deformation twinning

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Innovative superalloy powders designed for AM and for high temperature use in turbine applications

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ABSTRACT

Turbine industry needs to reach higher expectations to fitful the decarbonization requirements. This will impact many sectors where these parts are used as aeronautics, spatial or energy. A shared target is to consume less energy or to consume better thanks to the increase of thermal and propulsive efficiency, the light weighing and the use of new energies such as hydrogen. The combination of the design freedom offered by Additive Manufacturing (AM) process and high strength and high temperature material opens many new opportunities in turbine and engine applications to develop lighter and higher performing components for critical applications. While superalloys such as Ni718 have been successfully used to build complex parts in AM, applications requiring higher service temperatures necessitate the development of alloys with increased capability. However, the performance has been limited until now in particular for parts used at higher temperatures as the legacy cast alloys such as Ni939, Ni738 or CM247 are prone to cracking during Layer Powder Bed Fusion (LPBF), hence limiting the use of AM technology. At Aubert&Duval, we have been working on our Stellar® superalloys offer with new products: ABD®-alloy (partnership with Alloyed) and AD730® for these demanding applications. These products are specially developed for AM processes: free from crack during LPBF process or during heat treatment along with enhanced temperature capability. Designed to be free of solidification, liquidation and strain-age cracks, our innovative superalloys showcase exceptional printability for 40% γ'-phase strengthened alloys. Their development was supported either by thermodynamic modelling in combination with composition-dependent models to predict the engineering properties and manufacturability of millions of compositions simultaneously to isolate a truly optimized alloy composition for a given set of material requirements. But also, by understanding the influence of minor elements on the hot cracking susceptibility. This work presents materials performances and case studies.

KEY WORDS: Additive manufacturing, Ni-based superalloy, ABD®-alloy, AD730®, alloy design, engines.

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A new class of high-strength aluminium alloy for additive manufacturing

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ABSTRACT

Laser Powder Bed Fusion (LPBF) is a popular method in additive manufacturing due to its ability to produce intricate designs with optimized geometries and fine features. Despite recent developments in aluminium alloys specifically designed for LPBF, creating high-performance alloys for large components at an industrial scale remains a significant challenge. This study aimed to investigate and develop a high-strength aluminium alloy suitable for LPBF while taking into consideration industrial-scale production constraints. The alloy needed to be processable at large-scale AM platforms and have a high production rate and low cost.

New candidate alloys were designed using Alloyed's proprietary software platform, Alloy by Design (ABD®). A wide alloy design space with millions of possible alloy composites was defined. Candidate alloys that met the model's criteria for printability, strength, elongation, and macro-crack were then isolated through a filtering process.

Electrodes of the designed alloys were cast using the gravity casting method, and optical emission spectroscopy (OES) was used to confirm the target composition. The electrodes were then atomized

using the Electrode Induction Gas Atomization (EIGA) process. The powders produced were spherical with a particle size distribution (PSD) range of 20-63 µm, which is suitable for LPBF. A Renishaw 500Q AM machine was employed to manufacture the AM specimens. Toast rack geometries were designed using Rhino, and optimal laser processing parameters were developed. Over 99.9% optical density was achieved in printed alloys in the as-built condition. Microstructural characterization, including optical microscopy and SEM, showed a fine and equiaxed microstructure in the printed material.

Tensile bar geometries were manufactured using the best processing parameters, and heat treatment parameters were developed by conducting heat treatment at various temperatures guided by thermodynamic data. Tensile results indicate 310 MPa yield strength and 23% elongation in the as-built condition and 520 MPa yield strength and 10% elongation after heat treatment. The excellent balance of strength and elongation is attributed to minimal defects and the right balance of solid-solution, dispersoid, and precipitate mechanisms in the microstructure.

In conclusion, this study successfully developed a high-strength aluminium alloy suitable for LPBF at an industrial scale. The use of Alloy by Design (ABD®) software and EIGA process allowed for the creation of candidate alloys with desired properties, and the Renishaw 500Q AM machine produced specimens with over 99.9% optical density. The resulting microstructure of the printed material showed fine and equiaxed grains, while heat treatment improved the yield strength and elongation of the alloy. The new class of high-strength aluminium alloy developed in this study has the potential to enhance the performance of components produced through LPBF and contribute to the advancement of additive manufacturing technology. New candidate alloys for the LPBF process were designed using Alloyed's proprietary software platform - Alloy by Design (ABD®). A wide alloy design space with millions of possible alloy composites was first defined. Subsequently, candidate alloys that could meet model's criteria for printability, strength, elongation, macro-crack was isolated using a filtering process.

KEY WORDS: Alloy development, additive manufacturing, microstructural control by design, AM parameter development

Numerical modeling for oxide particles evolution in AISI316L during the additive manufacturing process

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ABSTRACT

Additive manufacturing (AM) has been received great attention as a new solution to solve the challenges conventional manufacturing has faced. The process has shown the advantage in design freedom and functional integration, the potential of AM was not fully realized. A good example is oxide dispersion strengthened (ODS) material. In terms of cost and flexibility, AM could be advantageous over the conventional ODS fabrication methods. However, the lack of understanding of the oxide particle evolution process in the melt pool has retarded the research progresses. Therefore, in this study, oxide particle evolution in the AM process was numerically and physically modeled to elucidate the evolution process and suggest effective ways to enhance the ODS effect. The current model coupled the Kampmann and Wagner numerical model with the estimated temperature profile, solidification calculation, and thermodynamic databases. The calculated results from the model well-matched the experimental data obtained from both directed energy deposition and powder bed fusion process using an austenitic stainless steel powder. According to the calculation, most of the oxide particles were nucleated during the solidification. The oxygen concentration in the melt pool reached up to 0.6 - 0.7 weight percent for a moment. The interfacial energy between Si-Mn-Cr-O oxide and the melt pool was predicted to have 0.4 - 0.5 N/m. Finally, the way to maximize the dispersion strengthening effect in the AM material was discussed.

KEYWORDS

Additive manufacturing, Oxide, Dispersion strengthening, Nucleation and growth, Simulation.

IMPACT OF POWDER PROPERTIES AND POWDER REUSE ON ADDITIVE MANUFACTURING OF COPPER

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ABSTRACT

There is an increased need in complex-shaped components characterised by high geometrical complexity and possessing high thermal and electrical conductivity, caused by significant growth of electrification and increasing complexity of energy harvesting and distribution systems, high-powder electronics, etc. This creates a breeding ground for additive manufacturing of copper, where number of AM technologies as e.g. powder bed fusion technologies as powder bed fusion – laser beam (PBF-LB) and powder bed fusion – electron beam (PBF-EB) and binder jetting (BJT), allowing to produce copper components with complex geometries, full density and high conductivity. However, even though copper is characterized by low thermodynamic stability of its oxide, copper powder is very sensitive to handling and pick-up of trace elements, that is especially crucial for electrical conductivity. This will have very different implication to both, material densification during AM processing as well as final properties.
Initial state of the powder surface chemistry and its changes during number of reuse cycles as well as impact of processing conditions are studied by means of scanning electron microscopy, X-ray photoelectron spectroscopy and Auger electron spectroscopy. Results indicate that even though there are a lot of similarities between powder-based metal AM technologies, there is significant difference in impact of the initial powder surface chemistry on densification and final properties as well as powder reuse and degradation. Generic model of the powder degradation in dependence on initial powder properties and AM process characteristics is elaborated. Effect of the reused powder on the defect formation during AM processing and its impact on material properties is discussed.

KEY WORDS: Powder for AM, powder reuse, powder degradation, powder bed fusion – laser beam (PBF-LB), powder bed fusion – electron beam (PBF-EB), binder jetting (BJT).

IMPORTANCE OF POWDER MANUFACTURING AND PROPERTIES ON SUCESSFUL MATERIAL DESIGN FOR AM: CASE OF NI-BASE SUPERALLOYS

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ABSTRACT

Metal powder constitutes the most common feedstock used in metal additive manufacturing (AM), including the most utilized processes for AM fabrication of components for advanced high-temperature applications using advanced Ni-base superalloys, as powder bed fusion (laser beam PBF-LB, and electron beam - PBF-EB). Considering significantly different conditions during component manufacturing by AM with the specific reference to local and directional melting and high cooling rates, tailoring or even totally new design of materials for metal AM is required to assure robust AM processing and defect-free high-performance AM materials. However, very often material design for AM is overlooking importance of powder manufacturing and resulting powder properties. Typically, powder is controlled when it comes to its morphology and bulk chemical composition, whereas impact of surface chemistry and chemical state of the micro-alloying elements is typically overlooked. This is especially important in case of multi-component high-alloyed systems, consisting of oxygen-sensitive elements or elements with high-sensitivity to sublimation.
At the same time, metal powder can be produced by the variety of methods, characterized by different productivity and cost, where variety of powder properties can be obtained for the same alloy system. Further on, metal powder is exposed to the processing conditions that are determined by process parameters and hardware solution and hence differ significantly between different AM technologies. Understanding the impact of powder atomisation and handling as well as the change in powder properties during AM processing in dependence on AM technology and alloy composition and its impact on final properties of the component is a must to ensure successful industrial implementation of powder-based metal AM.

This talk provides insight into importance of B and Zr alloying in case of advanced Ni-base superalloys on the example of In738 [1,2]. Powder manufacturing and AM processing of this superalloy were successfully developed by tailored alloy design, powder atomisation and PBF-LB process development, allowing the manufacture of components free from micro-cracks but containing important grain boundary strengthening elements. High temperature tensile testing in the range of 750°C to 1000°C and creep testing for up to 2000 hrs proved excellent mechanical properties of the modified alloy.

KEY WORDS: powder for AM, powder surface chemistry, In738, powder degradation.

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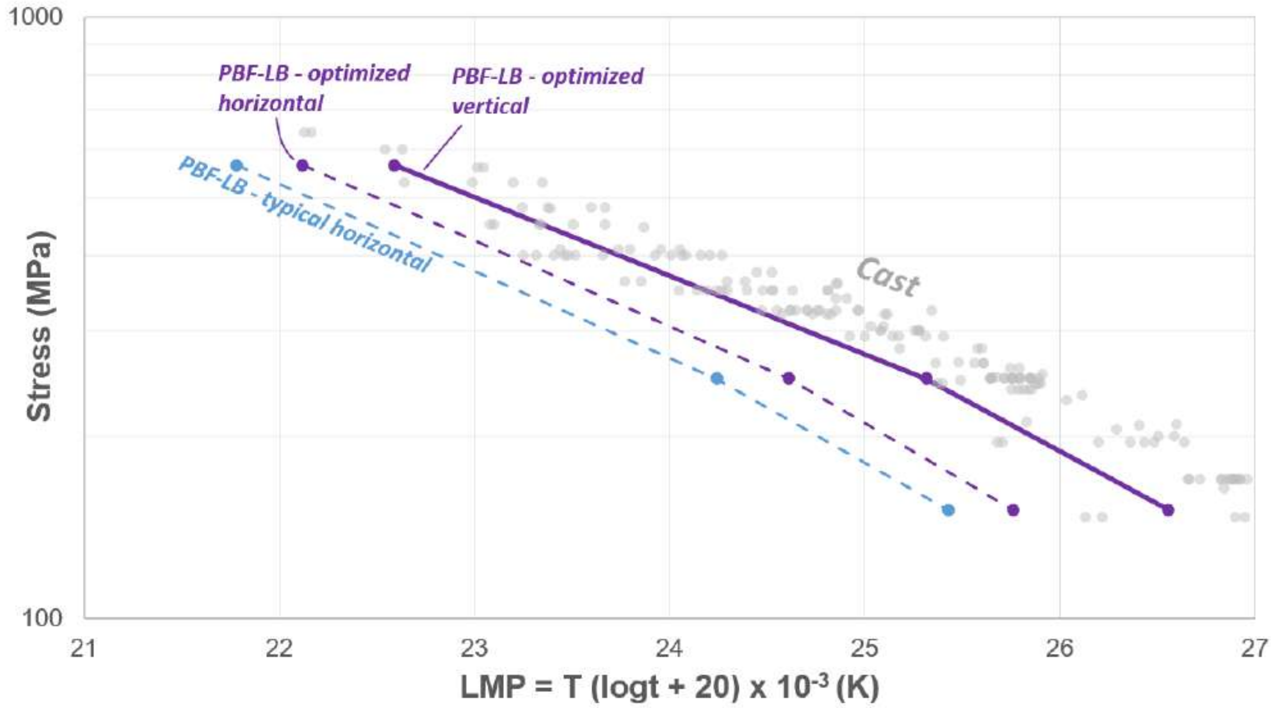

Figure: Creep performance of PBF-LB optimized IN738 compared to typical-PBF-LB IN738 as well as cast IN738, compared on Larsson-Miller parameter vs Applied Stress plot

Microstructure evolution and mechanical properties of a fully functionally gradient composite structure fabricated using friction stir additive manufacturing (FSAM)

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ABSTRACT

The study discusses the use of friction stir additive manufacturing (FSAM) technique to fabricate functionally graded composite structures using different grades of aluminium alloys, namely AA1050, AA5083-O, AA6061-T6, and AA7075-T6. The FSAM technique allows the creation of defect-free gradient composite structures with graded strength, microstructure, and microhardness by stacking successive layers of aluminium sheets. The different grades of aluminium alloys used have unique strengths, ductility, and microhardness. The FSAM build undergoes varying degrees of strain, strain rate, and temperature along the build depth due to the reheating and re-stirring effect of successive build passes. The top region of the FSAM build has the highest strength and microhardness because of the dominance of AA7075 in these regions. Optical microscopy (OM) and field emission scanning electron microscopy (FE-SEM) equipped with electron-backscattered diffraction (EBSD) analysis was used to examine the presence of microstructure gradient along the build depth. To understand the local strength-ductility behaviour, a miniature tensile testing technique was employed at the top, middle, and bottom regions of the FSAM build. The study found that the presence of precipitate-hardened alloys at the top regions of the build led to a drop in strength and microhardness, possibly due to precipitate coarsening and dissolution. Texture evolution in all regions suggested the presence of sufficient strain gradient and recrystallization behaviour. The major shear texture components B/$\overline{B}$ and C were noted from the pole figures (PF), and recrystallization textures (cube, p, and goss) were noticeable from orientation distribution function (ODF) plots of all regions. Overall, the study demonstrated the potential of the FSAM technique to create complex gradient composite structures with varied microstructure and mechanical properties.

KEYWORDS: Friction stir additive manufacturing, Functionally gradient material, EBSD analysis, Texture evolution, Microstructure.

UNDERSTANDING CRACKING DURING ELECTRON BEAM POWDER BED FUSION OF NI-BASE SUPERALLOYS

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ABSTRACT

To this date, most alloys processed by additive manufacturing (AM) have been initially developed for forging or investment casting. Contrary to these processes, the material undergoes multiple fast heating and cooling cycles during AM. This poses a problem, especially for alloys considered non-weldable such as Ni-base superalloys, which are prone to cracking. As AM-built superalloy parts may offer superior mechanical properties compared to cast ones, there is great interest in developing crack-free Ni-base superalloys.

In general, alloys with a high fraction of γ′ phase, which is crucial for high-temperature performance, are difficult to process by AM. New alloys with better manufacturability have been developed by reducing the γ′ solvus temperature [1]. Cracking has also been mitigated by adapting the scanning strategy or raising the processing temperature [2, 3]. Electron beam powder bed fusion (PBF-EB) is particularly well suited for high-temperature processing. However, no consistent strategy for designing or defect-free processing Ni-base superalloys with a high γ′ phase fraction has yet been established.

In this work, we attempt to understand the interdependence of processing strategies and alloy composition to identify the material and process parameters responsible for cracking. Therefore, we simulated the thermally induced stresses during the electron beam melting of the commercial alloys CMSX-4, a notoriously difficult to process superalloy, and IN718, a widely used Ni-base alloy with much better processability, at several beam powers and scanning speeds. The thermo-mechanical simulations were carried out using a custom finite element framework adapted to highly detailed AM process simulations. Additionally, CALPHAD calculations of the solidification process were performed to determine the temperature ranges in which these alloys are vulnerable to hot cracking.

Based on these simulations and comparison with experimentally determined crack densities in CMSX-4 [2], we aim to understand better the conditions under which cracks form in high-γ′ superalloys.

Hot cracking is associated with high strains in a temperature range where a low liquid fraction is present [4]. Due to difficult liquid feeding, cracks can open if dendrites are pulled apart far enough. The maximum simulated horizontal strain in the vulnerable temperature range (90 % to 99 % solid fraction) is shown in Figure 1. CMSX-4 experiences a far higher maximum strain than IN718 due to a higher coefficient of thermal expansion. Furthermore, the high-strain region reaches far into the heat-affected zone below the melt pool due to plastic deformation at high temperatures. The elastic strain energy density, i.e., the energy available to open cracks, is also higher in CMSX-4.

These findings may explain why superalloys with a high γ′ phase fraction are more susceptible to cracking than low-γ′ alloys. Based on these analyses, we attempt to derive alloy development and processing strategies for mitigating cracking during PBF-EB.

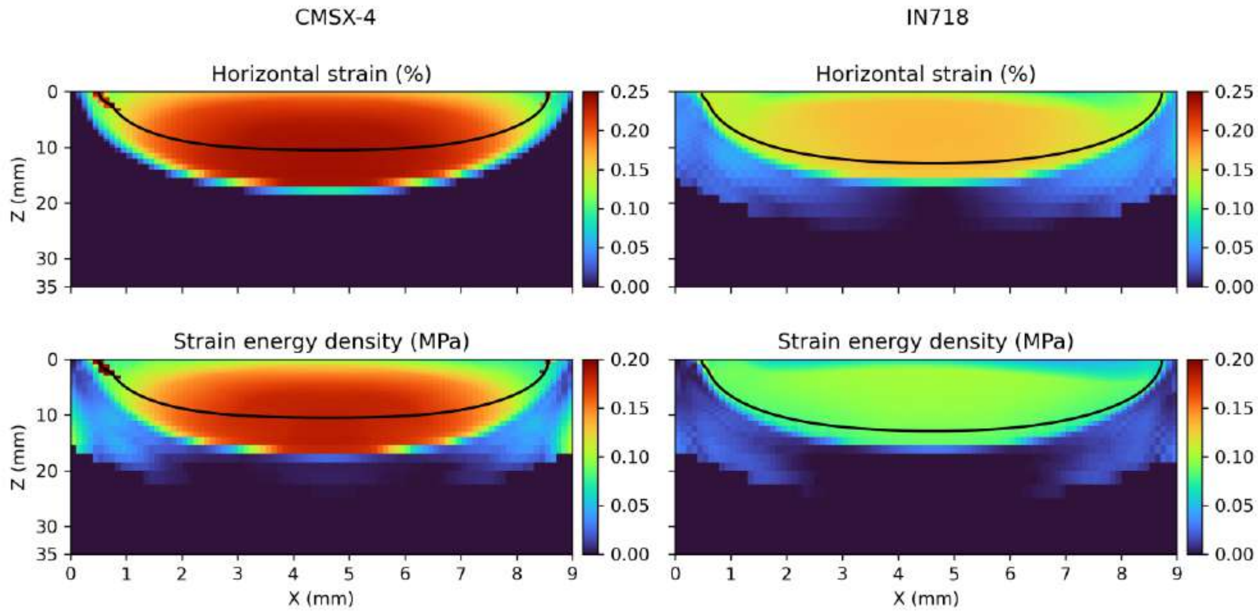

Figure 1: Results of thermo-mechanical simulations for 827 W beam power and 1568 mm/s scanning speed: maximum horizontal strains and elastic strain energy densities in the vulnerable temperature range for CMSX-4 and IN718. The extent of the melt pool is outlined in black.

KEY WORDS: Superalloys, Hot cracking, Thermomechanical simulation.

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Improvement of mirostructure and mechanical properties enhancement of CMT-WAAM deposited IN625 assisted by friction stir processing

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ABSTRACT

A novel study of friction stir processing (FSP) on additively deposited Inconel 625 was examined and tested in this study. The microstructure, phase composition and mechanical properties of as-deposited bead and FSP on bead were analysed. The use of FSP in this study resulted in a reduction in porosity and refinement of the microstructure of the fabricated builds. The microstructure of the components was characterized using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis. The results showed that FSP led to a significant reduction in porosity, with a corresponding improvement in the mechanical properties of the components. The microstructure of the components was also refined, which improved the overall strength of the material. Very high heat input and severe element segregation during the CMT-WAAM degrades its mechanical performance, therefore it is then followed by FSP on the deposited layers to enhance the mechanical properties. The as deposited additive bead shows the presence of intermetallic phases such as laves phase, NbC and MC carbides in the gamma-nickel matrix. It was found that the introduction of FSP can effectively eliminate the pores, Nb and Mo rich dendritic and eutectic network were severely broken up, leading to a remarkable enhancement in ductility and mechanical performance. Grain refinement, ultra fine precipitate and more dislocation density are the reasons behind the enhanced mechanical properties. The microhardness after FSP on additive beads found to be improved by 70% and tensile strength after FSP in the longitudinal direction is found to be improved by 73.46% and in the transverse direction by 27.9% compare to as-deposited bead. EBSD analysis shows, the grain size of 2592 µm in the as-deposited bead is refined to 2.44 µm in the processed additive bead. HRTEM analysis of the as-deposited bead and processed additive beads confirmed that dispersed fine scale granular precipitates residing in the γ matrix of Inconel 625 additive bead was converted to ultra fine precipitate through FSP on bead and these smaller precipitates obstruct the dislocation motion and dislocation pile-up occur around these precipitates and hence strengthen the mechanical properties of the as deposited bead. The results suggest that FSP could be used to improve the quality and reliability of IN625 alloy components for a wide range of applications.

KEY WORDS: Wire arc additive manufacturing (WAAM), Friction stir processing, Mechanical characterization, Hybrid technique.

Microstructure and property design of silver nanoparticle-modified permanent magnet powder treated via laser powder bed fusion

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ABSTRACT

Permanent magnets are used in various applications such as electric power generation, electro-mobility, and robotics. However, the high cost of rare-earth elements in permanent magnets, their supply, and their availability represent critical factors, and novel technologies that avoid or minimize the use of such scarce elements must be developed. Powder bed fusion using a laser beam (PBF-LB) is an established additive manufacturing technology. It has great potential to produce permanent magnets of complex shapes under material resource-efficient conditions, reducing the amount of rare earth elements. However, PBF-LB of rare-earth element-based permanent magnets typically results in low coercivity. To overcome this issue, we modify the surface of a permanent magnetic feedstock material with surfactant-free low melting point Ag nanoparticles allowing the PBF-LB-based production of permanent magnets with nano-sized $Nd_2Fe_{14}B$ and α-Fe.

KEY WORDS: permanent magnet, microstructure, nano additivation, laser ablation in liquids, silver nanoparticles

LASER-BASED POWDER-BED FUSION (L-PBF) OF Cu-25Cr COMPOSITES - INSIGHTS GAINED FROM SYNCHROTRON X-RAY COMPUTED MICROTOMOGRAPHY

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ABSTRACT

The design of composite-like microstructures through additive manufacturing based-process has been of increasing interest for alloys with tailored properties. Different strategies have been studied to obtain such microstructures, especially for powder-bed fusion processes. In-situ alloying, powder mixtures, solidification and precipitation have been shown to be promising strategies to yield the designed composite microstructures. Elemental powder mixtures have been an interesting strategy to produce such microstructures overcoming issues related to pre-alloying atomization and being able to obtain a graded composition. Cu-Cr-based alloys with Cr content from 5 to 50 wt.% are widely used for electrical and thermal management applications because of their excellent combination of mechanical properties, thermal, and electrical conductivity. Because of the limited solubility of Cr in Cu, these alloys can be considered as Metal-Metal composites. Additionally, due to the presence of a metastable miscibility gap when solidifying under out-of-equilibrium conditions, unique and fine microstructures can be obtained, which are not possible through conventional manufacturing techniques, such as solid-state sintering and vacuum casting. Therefore, powder-bed fusion additive manufacturing is a promising technique for the microstructural design of Cu-Cr-based alloys with tailored properties [1, 2]. In this study, we investigate the melting and mixing conditions of a Cu-25Cr (25wt%Cr) alloy via in-situ synchrotron X-ray computed microtomography during L-PBF [3] using elemental Cu and Cr spherical powders. Two powder mixtures were employed with different Cu/Cr size ratios: i) 80/80 µm and ii) 80/40 µm. Samples were built using different energy inputs. The laser power was kept constant at 400W, and the laser speed varied from 200 to 600 mm/s. Throughout the building process, XCT scans were acquired before and after the processing of each layer. The reconstructed images allow the investigation of the powder bed layer before melting and the built volume with a resolution of 2µm. Thanks to the difference in x-ray absorption between Cu and Cr, the homogeneity and the mixing can be directly evaluated from the reconstructed images. To complement the XCT results, metallurgical characterizations were carried out using scanning electron microscopy. Results show that to maximize the melting conditions at 400W and dense layers, lower speeds are preferable. The two powder mixings i) and ii) are analyzed and compared. Images from the powder bed show signs of denudation in both cases, however, more pronounced for the 80/80 mixture. The metallurgical characterization shows very fine Cr particles embedded in the Cu matrix with spherical morphology, a microstructure typically obtained in rapid solidification processes that reaches the Cu-Cr miscibility gap. For powder mixing i), more heterogeneous microstructures are

observed, with unmelted and partially melted Cr particles. The microstructure of the powder mixing ii) shows better mixing and homogeneity.

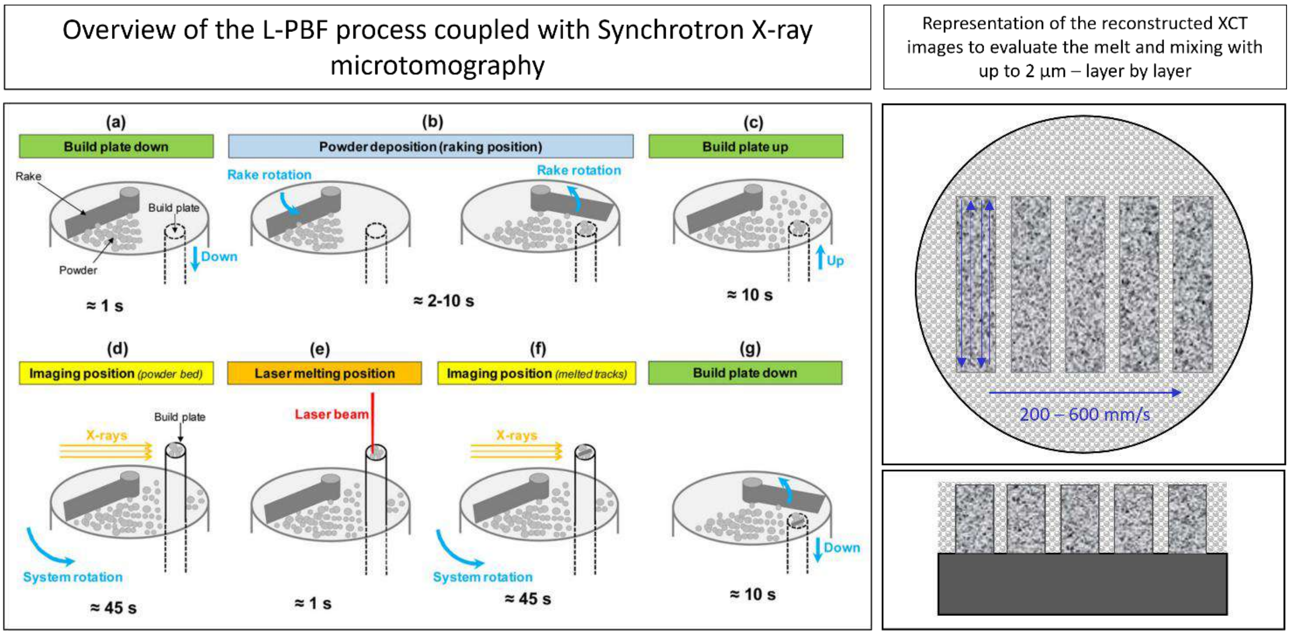

Figure 1: Left - Overview of a build sequence. (a) Build plate down (layer thickness). (b) Rake position: the rake is rotated to deposit powder on top of the build plate. (c) Build plate raised to the imaging position. (d) 3D X-ray imaging to characterize the powder bed. (e) Laser beam melting. (f) 3D X-ray imaging to characterize molten tracks embedded in the powder bed. (g) Build plate lowered for subsequent layer addition. Full characterization required roughly 2 min (time for each step is estimated and indicated. Right – Representation of the reconstructed XCT images before and after melting layer by layer. (Adapted from [3]).

KEY WORDS: Cu-Cr alloys, L-PBF, Synchrotron X-ray microtomography, Composites, In-situ.

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The development of Nb-Si core-shell powders for Laser-based Powder Bed Fusion

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ABSTRACT

Aircraft engine materials are constantly evolving to meet new requirements. One example is the goal of increasing engine efficiency. This can be achieved by increasing the turbine inlet temperature. As the turbine inlet temperature is increased, the materials used need to be able to withstand higher temperatures. The use of alloys based on the group of refractory metal silicides is a promising approach. A potential alloy could be based on Nb and Si which form Nb-Si precipitates within a Nb matrix. Such a Nb-Si alloy exhibits a high level of strength and good creep behavior at high temperatures. By using this alloy the maximum possible the turbine inlet temperature could be increased to 1350 °C, which is 200 °C above the current limit of Ni-based alloys [1]. However, due to the high melting point and the reactivity of the melt, Nb-Si alloys are hard to process by fine casting [2]. Therefore, laser-based powder bed fusion (PBF/LB or LPBF) can be a suitable processing route for the production of Nb-Si parts since the prevailing temperatures exceed those of conventional processing techniques.

In this work, a Nb-Si core-shell powder was additively manufactured by LPBF. The powder was manufactured by coating a pure Nb core with Si (by pack-cementation). This manufacturing route was chosen because of the aforementioned challenges in processing intermetallic Nb-Si (alloy) and since pure Nb is prone to oxidation, which occurs at high process temperatures even in extremely good gas atmospheres. Therefore, Nb powder is coated with Si in order to increase the oxidation resistance allowing for longer reuse in LPBF. Although the first built samples still exhibited a crack network and porosity, general trends can be associated with the building parameters. The microstructure consists mainly of intermetallic phases which explained the brittle behavior even at 1000 °C built platform temperature. Thus, further development of the core-shell powder and LPBF parameters are necessary. However, the results are promising and provide a good foundation for the future production of dense parts from Nb-Si Core-shell powders by LPBF.

KEY WORDS: Nb-Si, core-shell powder, Powder bed fusion/Laser-based (PBF/LB), intermetallic phases, silicides, high temperature alloy

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INFLUENCE OF DISLOCATION DENSITY AND RESIDUAL STRESSES ON RECRYSTALLIZATION IN LPBF 316L STEEL THROUGH NEUTRON DIFFRACTION

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ABSTRACT

This study examines various Laser Powder Bed Fusion (LPBF) process parameters and construction strategies for controlling the formation of residual stresses and increasing the dislocation content in 316L steel. The objective is to improve the driving force for recrystallization phenomena. Each layer undergoes multiple thermal cycles during the LPBF process, resulting in alternating compressive and tensile strains [1]. Large thermal gradients are produced in the bulk by the highly localized heat source. Since residual stresses arise when the material expands upon heating/melting and contracts upon cooling, the laser passage will produce a residual tensile stress surrounded by residual compressive stress [2]. In order to evaluate the influence of key process parameters for favoring recrystallization upon heat treatment, we use neutron diffraction [3].

In a first step, we have monitored the occurrence of recrystallization through laser-based heat treatments (LHTs), on highly deformed 316L steel sheets, by combining the experiments with in situ X-Ray diffraction. Extending to LPBF 316L samples, the low recrystallization driving forces required to identify the ideal process parameters, producing the highest stresses and dislocation content. Ex-situ neutron diffraction measurements were used for that purpose, looking at multiple scanning strategies and extreme laser powers and scanning speeds.
As the samples were detached from the baseplate after LPBF processing, this study lacks the understanding of the evolution of stress states during the build. However it provides grounds on understanding the effect of stored dislocation density and residual stresses on the kinetics of recrystallization in LPBF 316L stainless steel, upon subsequent heat treatment.
In a final step, the impact of various LPBF processing conditions on dislocation density and residual stresses was evaluated *in situ* by fabricating specimens in a downsized LPBF device modified for use at the neutron beamline. Different magnitudes of stress fields were generated during the manufacturing process to observe the transitions between tensile and compressive stresses. Continuous measurements of dislocation density in the in-plane direction revealed the influence of each stress state on the recrystallization capabilities through subsequent laser heat treatments on the specific layer, immediately validating its ability to promote recrystallization.

KEY WORDS: Recrystallization, 316L steel, Laser Powder Bed Fusion, in-situ monitoring, Neutron diffraction

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NOVEL ALTERNATIVE TO POWDER RECYCLING TO TACKLE POWDER DEGRADATION IN PBF-LB

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ABSTRACT

Reusing metal powders is key to ensuring process cost-efficiency and sustainability. It is therefore important to find ways to minimize the impact of reuse while maintaining as much as possible the initial powder properties to ensure process repeatability. Powder recycling becomes a promising option to reset the properties while using the raw materials avoiding the need of extracting the elemental materials. As shown in Figure 1 closing the cycle of production would be highly beneficial to the metal additive manufacturing (AM) industry. Much valuable waste is often discarded due to contamination such as oxygen pick up and condensate produced during the powder bed fusion – laser beam (PBF-LB) process.

In this study, waste collected from PBF-LB processes using SS316L and INC718 powders was melted using VIGA process to produce recycled powder, as shown in Figure 2. The waste consisted of support structures, failed parts, powder disqualified due to degradation and bulky parts from conventional manufacturing to ensure an optimal melting in the crucible.

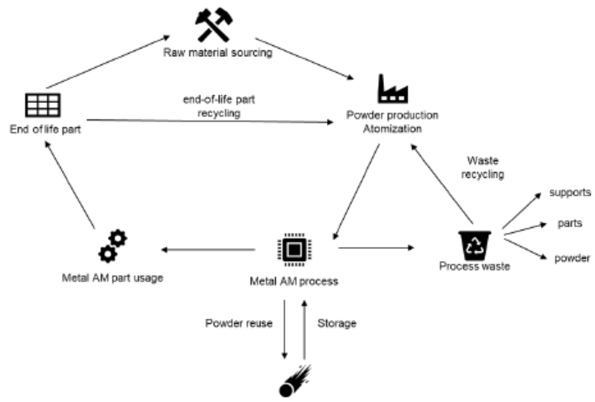

Figure 1. Concept for recycling the waste produced in metal AM processes

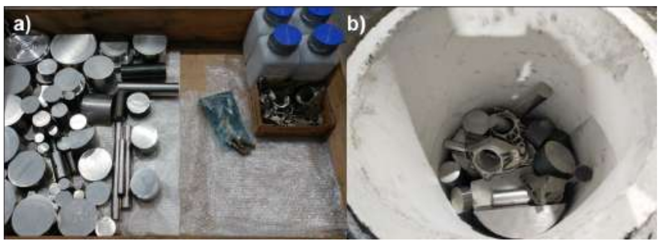

Figure 1. Waste material used to reatomize metal powders for PBF-LB (a), Crucible view with the metal parts to melt to produce new powder (b)

The resulting powder from recycling (re-atomization) used parts, with exhausted powder and process waste (support structures) is compared with reused and virgin powder in terms of morphology, chemical composition, rheological properties, and particle size distribution. As shown in Figure 3 the morphology of recycled powder in this case presents a more homogenous surface due to the atomization process used (VIGA) which was selected to obtain high purity powders. Figure 4 shows the different oxygen content values for the virgin, reused and recycled powders.

The results demonstrate that even for prolonged reuse of metal powders, recycling the (waste) material could offer a great alternative to applications where powder quality and traceability are key. The variations in morphology and chemical composition will have a greater influence in the powder rheology and spreadability which often vary when reusing powder in the laser powder bed fusion process.

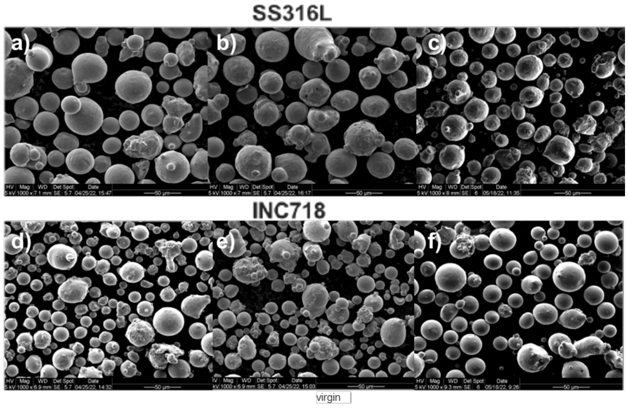

Figure 3. Morphology of (a) virgin, (b) reused, and (c) recycled powders of SS316L and INC718

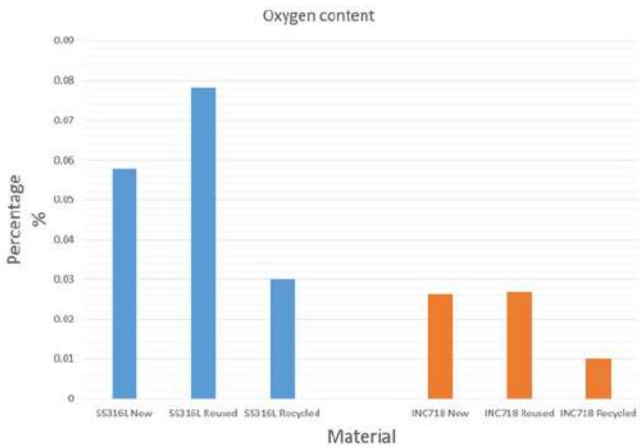

Figure 4. Oxygen content obtained from virgin, reused and recycled SS316L and INC718 powders

KEY WORDS: additive manufacturing, powder reuse, powder recycling, contamination, VIGA

Acknowledgments
The authors thank f3nice Srl (Milano, Italy) for providing the powder materials and Höganäs AB (Höganäs, Sweden) for the bulk composition measurements of the powder.

Funding
The work was performed in the framework of the project RECIRCLE (grant number: 2022-00829) and Centre for Additive Manufacturing-Metal (CAM2) hosted by Chalmers University of Technology, supported by VINNOVA (grant number: 2016-05175).

PBF-LB of a non-weldable Ni-base Superalloy: role of processing parameters on hot cracking

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Additive manufacturing of non-weldable CM247LC by powder bed fusion – laser beam of metals (PBF-LB) is challenging due to its high cracking susceptibility. The cracking mechanism can broadly be divided into hot cracking which occurs during the PBF-LB process and solid-state cracking which occurs during post-processing heat treatment. Hot cracking, in particular solidification cracking, occurs during the last stage of solidification within a solidifying melt pool and can also traverse across multiple melt pools along the build direction. On the other hand, solid-state cracking like strain age cracking occurs during the heat treatment. The residual stresses from the PBF-LB process and the γ′ formation stresses lead to strain age cracking. There are number of works on minimizing solidification cracking through alloy design and process parameter modification. However, less focus has been placed on reducing solid-state cracking (strain age cracking) by the development of process parameters to minimize residual stresses.

This study explores the role of laser processing parameters to produce dense parts with low porosity and crack density. The obtained results showed that the optimal processing window is obtained for parameters with low line energy density ($^{Power}/_{Speed}$ < 0.2 J/mm) and strong horizontal melt pool overlap (50 to 80%). The hatch spacing was lowered to minimize the porosity formation and to have satisfactory volumetric energy density $\left(^{Power}/_{Speed\ .\ Hatch.\ Layer\ thickness}\right)$. The minimal cracking has been found due to the shallower melt pools and the porosity is minimized by having stronger melt pool overlap. Scanning Electron Microscopy (SEM) revealed the presence of carbides (rich in Hf and Ta) and some oxides (rich in Hf, Ta and Al). It is not yet clear how the oxides contribute to the cracking as they have been found both in the crack vicinity and elsewhere in the microstructure without cracking. Electron Backscatter Diffraction (EBSD) analysis performed on selected process parameters reveals that grain morphology and texture obtained is also quite different for the parameter with minimal cracking. A strong <100> texture is present in almost all the analyzed parameters with the exception of certain parameters which did not have a strong texture. These were parameters which had a low line energy density and hatch spacings of 0.06 and 0.09 mm. On the other hand, process parameter used to process weldable superalloys such as IN-718 lead to much more higher cracking. This has shown that there is a wide scope for tuning the microstructure of non-weldable alloy such as CM247LC. And the strategies developed for other easy-to-weld alloys would most probably not work for CM247LC. X-Ray Diffraction was used to calculate the residual strains (and in turn residual stresses by using x-ray elastic constants) for 4 parameters with different volumetric energy densities (VED) ranging from 50 to 100 J/mm^3 with two parameters having similar VED but different processing parameters. The initial analysis showed that VED is proportional to the maximum residual stress. The parameters having similar VEDs had similar residual stress profile. This is an important analysis during the process development which can help in developing further parameters in the lower VED range in order to minimize strain age cracking during heat treatment.

It was found that CM247LC alloy can be processed with minimal cracking and porosity. However, the residual stresses in the as-built state is high which can be problematic during heat treatment. It is complex multi-scale problem and this work is the initial step in considering the residual stress from the initial design of experiment.

Controlling additive manufacturing defects in conductive alloys

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Abstract

The processing of conductive alloys is a well-known challenge in additive manufacturing. For these alloys, energy density is not a reliable way to find optimal laser parameters, as shown by Pranshanth et al [1]. Equal energy densities achieved with low and high laser powers produce different densities. In short, high laser powers are needed to ensure melting rather than warming, even in relatively low melting point alloys.

In this paper we show the further complications that come with producing complex shapes in conductive alloys. For instance, geometries with long hatches allow for cooling and so are even more prone to lack of fusion defects. Conversely, melting large areas means an accumulation of thermal energy that can cause overheating.

Using AlSi10Mg CubeSat mirrors as an example geometry it is shown that "traditional" approaches to hatching always produce defects. However, using novel approaches to hatching that account for the local geometry and the material properties, it is possible to achieve defect-free parts.

We also explore the appearance of unusual defects in conductive alloys. There are instances where defects form that have all the hallmarks of lack of fusion; large, irregular and non-spherical, but have occurred in the highest energy density samples.

Key words

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Manufacturing and producing nano-scale accurate surfaces in additive manufacturing

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Abstract

Surface roughness control in additive manufacturing is one of the most researched areas in additive manufacturing. However, there are some applications where the surface roughness requirements are so high that pursuing better surfaces is pointless. Mirrors and other optical surfaces for example require nanometre precision. The challenges here are to ensure the surfaces are defect free and that the microstructure is suitable for precision post processing.

Optical applications, for ground-based, air-based and space applications, are ideally suited for AM [1]. There are severe weight restrictions in these applications, even on the ground-based telescopes. The main hurdle so far has been the defects in the part that are detrimental to the surface.

Ideally these mirrors would operate in the IR, near-IR and visible spectrums. The exact requirements of these mirrors vary with each application, but typically roughness values on the order of nanometres is needed. Surfaces with Ra values of up to 7 nm have been reported in this work on AlSi10Mg mirrors.

This paper looks at two ways to eliminate defects and to achieve the best surface possible. Firstly, consideration of the geometry and the laser path to control the thermal conditions and minimise defect formation. Secondly, using a hot isostatic press (HIP) to absorb the voids into the bulk metal. The research into defects was carried out using XCT, tracking their initial formation and subsequent reduction when HIPed.

The highly accurate surfaces were achieved using single-point diamond turning (SPDT). The surfaces of multiple samples were analysed, in terms of form and roughness, with interferometry and Zernike analysis. The defects were also analysed after the SPDT process to investigate if the local pressures and deformations make any difference.

The HIPing process has also shown unintended consequences for the material. These changes to the grains and microstructure meant that HIPing might not be the best way to achieve the best surface finish. To answer this question though requires an understanding of all processes; AM, HIP and SPDT, as well as the material evolution throughout.

Key words

Additive manufacturing, process control, diamond turning, surface roughness, conductive alloys, porosity, defects, mirror fabrication

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Influence of powder bed fusion - laser beam parameters on microstructure and mechanical properties of a non-equiatomic metastable HEA

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ABSTRACT

Manufacturing high entropy alloys (HEAs) using additive manufacturing techniques such as powder bed fusion - laser beam (PBF-LB) helps in preventing the formation of detrimental phases, owing to high solidification rates compared to conventional casting. Rapid melting and solidification during the layer-by-layer printing could also result in martensitic transformation in metastable HEAs. This work focusses on the development of a novel pre-alloyed non-equiatomic HEA based on the CoCrFeNi grade. Detailed microstructural characterization and statistical analysis was performed to understand the influence of the PBF-LB parameters on the densification behaviour and microstructure of the metastable fcc-structured HEA in the as-printed state, with a particular focus on the resulting martensite. Based on a statistical analysis of the densification behaviour, two sets of parameters with significant difference in the laser power were chosen to further study the microstructure and mechanical properties. Optical microscopy and scanning electron microscopy on the as-printed samples revealed the presence of nanoscale banded features associated with highly defective substructures. Transmission Kikuchi diffraction indexed these bands as the hcp phase, indicating that an athermal martensitic transformation occurred during the printing process. Annealing of these alloys was performed at 800°C, 1000°C and 1200°C to understand the changes in the microstructure and the resulting mechanical behaviour. The different printing parameters did not reveal any notable difference in the mechanical properties, with both alloys showing the yield strength of ~560 MPa and the elongation to fracture of ~35% in the as-printed state. Post-mortem analysis of the as-printed tensile samples revealed nearly 50% of fcc transformed to hcp. Tensile tests on the heat-treated samples revealed different strain hardening rate as compared to the as-printed samples.

KEY WORDS: Phase transformations, High entropy alloys, Strain induced martensitic transformation.

Lattice strain evolution during monotonic and cyclic loading of SS316L manufactured by laser powder bed fusion simulated by crystal plasticity modelling and validated via in-situ neutron diffraction

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ABSTRACT

Additively manufactured (AM) 316L steel exhibits extraordinary high-yield strength. Extremely fine cells are being formed due to rapid cooling and dense dislocations which are responsible for the macroscopically high yield strength of AM316L. Analysis of the microstructure of AM316L has revealed deformation behaviour involving dislocation slip as well as deformation twinning. Cyclic loading tests show significant anisotropy exists between the tensile and compressive hardening behaviour, which may partly be due to the effects of deformation twinning/detwinning. Despite its numerous advantages, the use of laser powder bed fusion manufactured components in engineering applications is hindered by the lack of assurance of their structural integrity during operation. In this study, in-situ neutron diffraction experiments have been conducted aiming at examining micro-mechanism leading to the plastic anisotropy in AM316L under cyclic deformation and providing data for the crystal plasticity model validation (CP-FEM). Deformation (e.g. cyclic hardening, softening and saturation) response and the corresponding microstructural evolution of AM316L during cyclic loading at room temperature is investigated. In particular, the physical interpretation and the role of internal stresses are thoroughly evaluated in order to better comprehend the relationship between microstructural evolution and cyclic deformation response. A physically-based evolutionary constitutive model aiming at accurately representing the complex cyclic deformation response of the material to describe the change in microstructural condition and its relationship with internal stress variables is proposed. In addition, dislocation-dislocation and twinning interactions will be incorporated in the model to capture the plastic anisotropy.

KEY WORDS: LPBF 316L, Crystal plasticity, Neutron diffraction, Polycrystal deformation

Additive manufacturing of superalloy HAYNES® 282®: development of PBF-LB processing, post-AM heat treatment, and properties

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ABSTRACT

Improved design freedom in the manufacturing of high-performance materials has been the original driver of additive manufacturing (AM). However, material properties of most superalloys manufactured by Powder Bed Fusion Laser Beam (PBF-LB) have typically under-performed their cast or wrought counterparts until now [1].

Investigations into LPBF processing and post-processing of a γ' strengthened superalloy HAYNES® 282® were conducted to better understand resultant effects on high temperature creep and fatigue performance. Conventional 40 µm as well as high productivity 80 µm layer thickness process parameters were assessed, and resulting defect distributions were studied by X-Ray Computed Tomography. Heat treatments to reduce anisotropy with and without HIP were evaluated through microstructure analysis by scanning electron microscopy, and the resulting grain structures were analysed by electron backscattered diffraction. Mechanical performance was evaluated through tensile testing at ambient and elevated temperatures, as well as creep testing.

Robust PBF-LB processing to enable full-density defect-free components of HAYNES® 282® was developed [2]. The results also showed that improvement in productivity by use of 80 µm LPBF process parameters comes with a trade-off in porosity and mechanical performance. However, 80 µm parameters could still produce porosity volume fractions of less than 0,05%. Furthermore, microstructure analysis showed that through tailored heat treatment it was possible to achieve grain boundary microstructures of interlocking γ' and carbide phases. These microstructures closely resemble those of the wrought alloy, and are expected to contribute greatly to resilience of the alloy at high temperatures. Additionally, the tailored heat treatments utilized for the LPBF alloy were found to greatly reduce anisotropy in mechanical performance. These heat treatments also resulted in grain structures with large numbers and wide distributions of twin boundaries, resulting in comparable or even improved performance relative to the wrought form of the alloy. The steady state creep rate at 927ºC and 89 MPa for the LPBF manufactured alloy was an order of magnitude lower than for the wrought alloy. The results lead to the conclusion that tailored heat treatments are instrumental in achieving the high performance expected from superalloys and realizing the original promise of AM.

KEYWORDS: Additive manufacturing; laser powder bed fusion; productivity superalloys; high temperature.

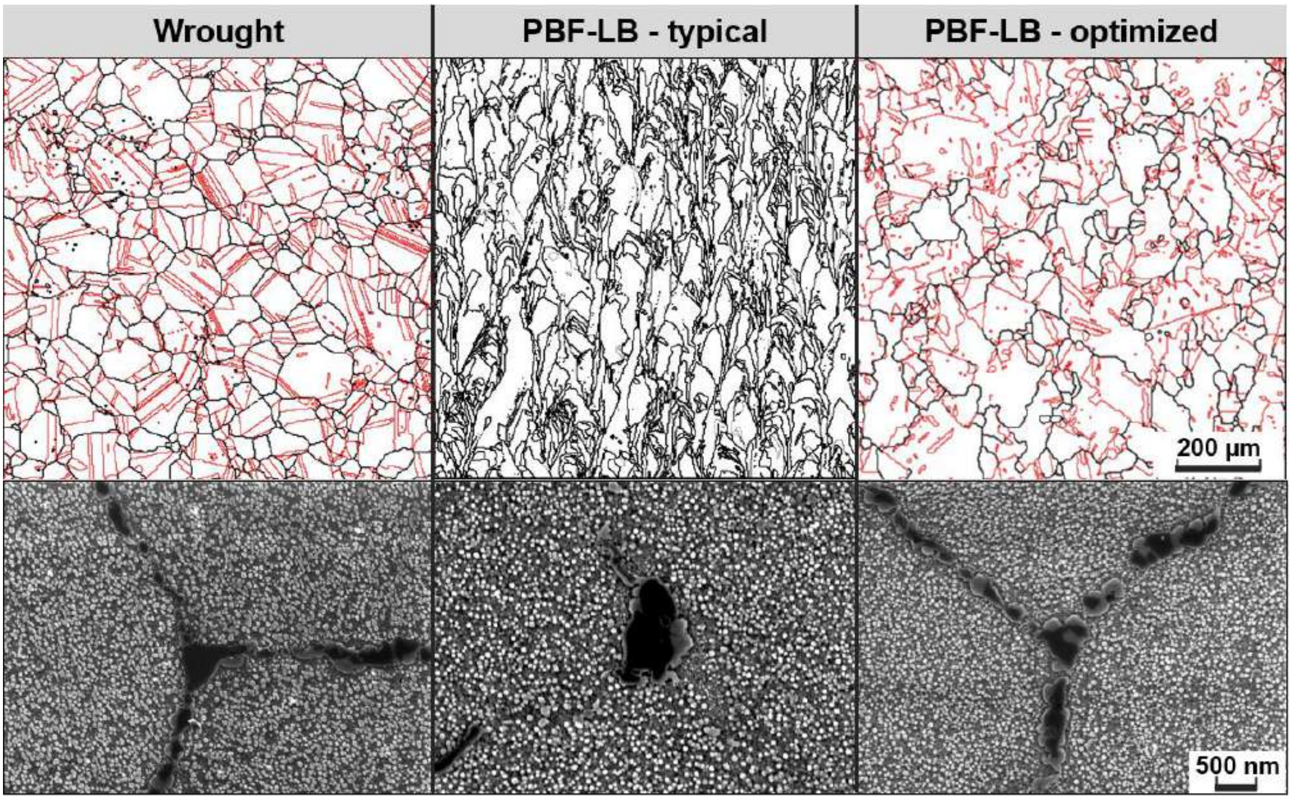

Figure: A comparison of grain structure and grain boundary microstructure developed in Haynes 282 superalloy: Left shows wrought material, center shows PBF-LB after typical heat treatment, right shows PBF-LB after optimized heat treatment

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Potential Strategy for the development of Pure Copper via powder bed fusion-electron beam (PBF-EB) for thermal and electrical applications

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ABSTRACT

Owing to the exceptional thermal and electrical conductivity properties of pure copper makes it a highly desirable material for a range of applications including electronics, heat exchangers and electric motor components. Additive manufacturing (AM) technology is best suited for developing components for cooling systems and heat exchangers due to the complexity in their geometry. Powder bed fusion-electron beam (PBF-EB) exhibits relatively low reflectivity for pure copper when compared to powder bed fusion-laser beam (PBF-LB). In addition to the density, microstructure of pure copper significantly influences on its conductivity. This study focusses on the thermal and electrical conductivities, and refinement of the microstructure using new processing strategies in PBF-EB such as point melt instead of hatch melt. Results demonstrates that the relative density of pure copper obtained is about 99.9%, while achieving twice the productivity when compared to hatch melt.

KEY WORDS: Additive manufacturing (AM), powder bed fusion-electron beam (PBF-EB), pure copper, point melt, thermal and electrical conductivities

MICROSTRUCTURAL DESIGN OF ADDITIVELY MANUFACTURED STAINLESS STEEL NITRONIC 60

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ABSTRACT

Laser powder bed fusion (L-PBF) is one of the most frequently employed additive manufacturing technique which offers a highly localized melting/solidification process during laser-powder interaction. The interaction can be altered during the fabrication by changing processing parameters, which unlocks the potential for the as-built microstructure manipulation. The L-PBF technique flexibility is an essential aspect exploited in this study aiming to obtain components with tuneable complex microstructure. For that purpose, the powder of stainless steel Nitronic 60 was used due to the higher content of manganese, a volatile element. By using various processing parameters, the manganese content can be decreased, offering a unique possibility to control phase fractions of austenite and ferrite in microstructure. Moreover, austenite forms a fine-grained structural component with random crystallography with embedded ferritic layers. Depending on the used scanning strategy, distinct crystallographic texture can be formed in ferrite. The presented study examined several microstructural variants fabricated by different processing parameters and scanning strategies in terms of microstructural characterization by SEM and TEM and also mechanical properties characterization by tensile testing and microhardness mapping.

KEY WORDS: processing parameters, microstructural manipulation, laser powder bed fusion, stainless steel, microstructural characterization.

EFFECT OF HEAT TREATMENT ON MARTENSITIC TRANSFORMATION IN L-PBF PROCESSED AUSTENITIC STAINLESS STEEL

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ABSTRACT

Post-process heat treatment is often applied in case of additively manufactured stainless steels, in order to relieve residual stresses and modify microstructure and resulting properties of manufactured parts. In as-built conditions, laser powder bed fusion (LPBF) process forms a characteristic microstructure with sub-micron cell structure containing walls with high dislocation density and significant chemical segregation. Application of any heat treatment substantially affects the original microstructure and modifies steel properties, with metastability included. The effect of the heat treatment application on the susceptibility to the deformation-induced phase transformation is therefore examined in present studies. Three sample series with different crystallographic textures (<001>, <011> and random orientation) in loading direction were manufactured by LPBF and subjected to the uniaxial tension and compression loading. The deformation-induced phase evolution was monitored using in-situ neutron diffraction and ferritoscope measurements. Results of in-situ experiments were supported by a thorough microstructural analysis of post-mortem specimens by EBSD and TEM.

It was found that in the as-built conditions, the γ to α’ transformation starts much earlier during the deformation compared with the series after heat treatment. This behavior can be attributed to the strong chemical segregation, causing local fluctuation of the stacking fault energy. Application of heat treatment resulted in the suppressing formation of the deformation-induced martensite up to the later stages of the deformation and also reduced the total volume fraction of α’ phase.

KEY WORDS: L-PBF, heat treatment, microstructure, austenitic stainless steel, martensitic transformation

Design for additive manufacturing of lattice structures with asymmetric tilt grain boundaries

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ABSTRACT

Design for the additive manufacturing makes it possible to build the complicated structures which are not easily formed with the conventional methods such as casting and machining. Recently, the crystal inspired additive manufacturing with highly damage tolerance has been reported. [1] The combinations of misoriented lattice structures with controlled interfaces are a promising design policy to build stress controlled light structural materials.

In this study, the lattice structures with periodic asymmetric tilt grain boundaries based on the coincidence site lattice were manufactured and their mechanical test have been investigated systemically. The model asymmetric tilt GB, [001](100)//(430) Σ5, was selected and its atomic structure in complex ceramics were investigated with the combination of bicrystal experiment and first principles calculation model.[2] It was found that bonding configurations in interfaces controls the initial stage during the compression test. It demonstrates the effect of interfaces on manufactured lattice structures as same as in real crystals.

KEY WORDS: crystal inspired DfAM(Design for Additive Manufacturing), lattice structure with asymmetric tilt GBs, interface modeling with CSL

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Role of manufacturing routes on microstructural features of CoNi-based high entropy superalloy

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Abstract

The emergence of Co- or CoNi-based superalloys in 2006 and high entropy alloys in 2004 have garnered immense attention from the materials community, as they offer the potential to design and develop high-temperature and high-strength alloys beyond the matured Ni-based superalloys. In this study, we utilized thermodynamical calculations, specifically the CALPHAD method, based on the lever rule, Gulliver-Scheil, and multicomponent phase diagram, to develop a CoNi-based high entropy superalloy (HESA). The accuracy of the CALPHAD method was verified through casting and heat treatment. Powder of the designed composition was then produced using gas atomization and consolidated using spark plasma sintering (SPS) and powder bed fusion – laser beam (PBF-LB). Advanced characterization techniques such as double-beam scanning electron microscopy equipped with electron backscatter diffraction (EBSD) and energy dispersive spectroscopy (EDS), density measurements, and micro-hardness testing were used to analyze the microstructure and physical and mechanical properties of the as-built alloys. Fully dense parts with relative density of greater than 99.9% obtained through SPS and PBF-LB and the results indicated that the microstructure of the as-built alloys is consistent with the predictions made by CALPHAD calculations, with a single-phase fcc structure and no secondary phases. However, in the case of the as-cast alloy, a small amount of beta phase (≈2.5%) was detected, which necessitated homogenization and subsequently led to abnormal grain growth after heat treatment.

Keywords: CoNi-based superalloys; thermodynamical calculations; high entropy alloys; spark plasma sintering, powder bed fusion – laser beam.

A unified treatment of alloy dependent material properties and process parameters for accurate solidification simulations for AM based on CALPHAD

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ABSTRACT

Composition of alloys and their viscosity, surface tension of liquid, thermal/electrical conductivity all as a function of temperature, are all important properties for modeling the AM process together with heat and heat capacity. While the treatment of heat and fluid flow is considered as state of the art in current FEM models, material properties are treated in a highly simplified manner. During the last few years new models to predict thermophysical material properties using the CALPHAD method have been developed and by adopting a unified treatment of both process parameters and alloy dependent thermophysical properties, there is the potential for more accurate solidification simulations for AM.

This presentation will describe how such an approach has been implemented into Thermo-Calc through an add-on module for Additive Manufacturing. This combined approach can be thought of as an example of ICME. Examples will be shown together with other ongoing/completed developments related to AM.

KEY WORDS: CALPHAD, Thermophysical properties, ICME, melt-pool, keyholing, precipitation.

ULTRAFAST LASER SURFACE PROCESSING OF ADDITIVELY MANUFACTURED IN718 SUPERALLOY

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ABSTRACT

IN718-based superalloy has excellent mechanical, thermal and chemical properties, which makes its usage inevitable in aerospace, nuclear, marine, and petrochemical industries. Although it possesses excellent properties to be directly utilized for the intended application, at times, different functional performances at the superficial levels are demanded other than what the bulk offer. The study of surface structuring has become a topic of interest for many researchers because of its broad range of applications, such as anti-icing, wettability control, anti-corrosion, aeronautical, and biomedical engineering applications.

Laser surface texturing is the most common method to generate micro/nano-textures resulting in remarkable super-hydrophobicity/super-hydrophilicity over the artificial surfaces. In the past, cast or conventional IN718 alloys have been surface-structured using nanosecond lasers for various applications. However, the initial surface chemistry, material composition, laser texturing features and their parameters, and laser processing parameters play a vital role in determining the adsorption behavior on a designed surface. Laser powder bed fusion (LPBF) has been one of the widely investigated domains of material development and manufacturing processes. The excellent processing capability of LPBF-based metal AM has been instrumental in fabricating aerospace-grade superalloys (e.g., titanium and nickel-based superalloys). However, the secondary laser processing of LPBF IN718 alloys is still not investigated in the context of surface structuring.

In the present study, we present metal printing of IN718 alloy on different laser parameters and its behavior at different laser surface structuring parameters. Different sets of periodic grooved patterns

have been produced on LPBF IN718 alloy surfaces with the help of an ultrafast laser. The morphology of the textured surfaces has been investigated over distinct regions over and inside the patterned grooves (Fig. 1) and correlated with the micro-nanomechanical properties.

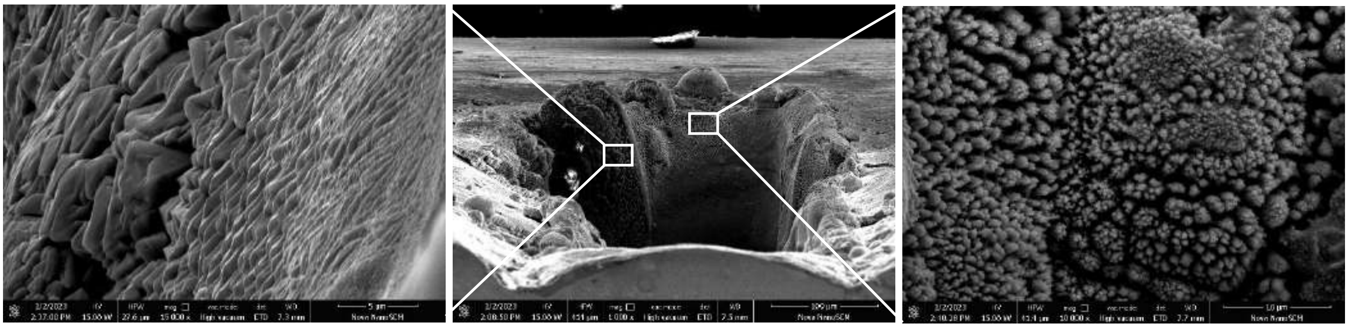

Fig. 1 Distinct zones after laser surface structuring over LPBF IN718 alloy surface

KEY WORDS: Laser structuring; Inconel 718; LPBF; Additive manufacturing (AM); Metal AM.

CORRELATION OF LOCAL THERMAL HISTORY OBSERVED VIA IN-SITU MONITORING WITH MICROSTRUCTURE AND PHASE TRANSFORMATIONS IN LASER POWDER BED FUSION OF NICKEL SUPERALLOYS

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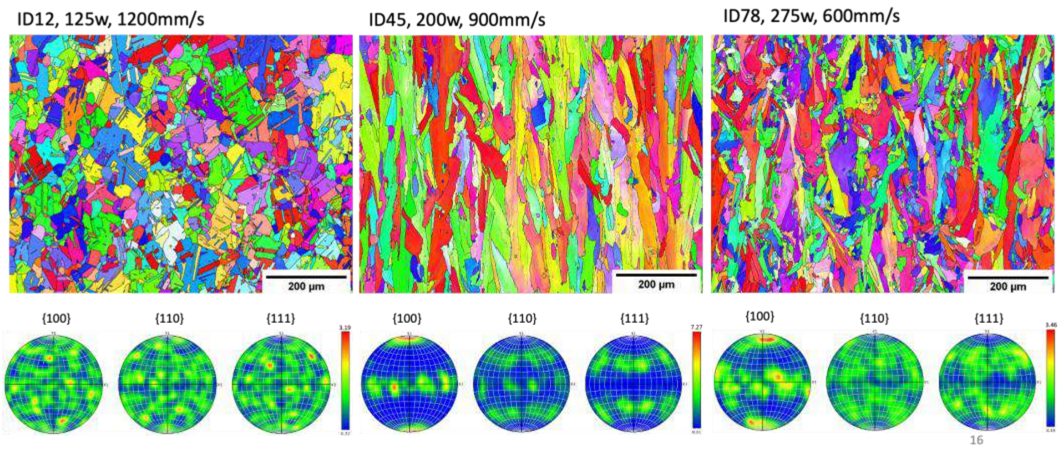
ABSTRACT

Additive manufacturing processes such as laser powder bed fusion produce material by localized melting of a powder feedstock layer by layer. The small meltpools and high energy density generate very different microstructures in nickel superalloys when compared to more traditional cast or wrought processing, including features such as cellular structures and epitaxial grain growth. The features of these microstructures vary depending on local thermal history, alloy chemistry and processing parameters. In this work in-situ monitoring of a laser powder bed fusion process is used to characterize the local thermal conditions throughout an AM build for alloys IN718 and Haynes 282, and this information is correlated to observations on the microstructural features of these alloys in the as-built condition. In IN718, the solidification conditions lead to cellular precipitate structures, with the cellular dendrite spacing ranging from approximately 350-800nm, with larger spacing correlated to higher power density parameters with lower cooling rate during solidification observed using long wave infrared in-situ monitoring. During subsequent heat treatment, the increased local concentration of elements including niobium and molybdenum in the interdendritic region leads to formation of Laves phase, with a larger dendrite spacing leading to an increased area fraction of observed particles. The presence of these Laves phase particles is observed to influence the recrystallization of the alloy, as alloys with fewer particles can be fully recrystallized while those with increased numbers of particles retain the directional epitaxial as-built grain structure, as shown in the figure below.



This difference recrystallization behavior is observed for relatively small differences in processing parameters and the resulting cooling rates, with all samples showing acceptable levels of porosity

and lacking any evidence of cracking. The observed level of variability is analogous to that expected in parts with complex geometries leading to differences in heat flow throughout the part. This work will show how in-situ monitoring can be used in conjunction with CALPHAD modeling to predict as-built microstructures and segregation in nickel superalloys. Observations will be shown for both IN718 and Haynes 282, with in-situ monitoring derived thermal histories for each alloy correlated with solidification microstructures, with the eventual goal of using this information for both alloy design and development of closed loop process control methodologies.

KEY WORDS: Phase transformations in AM-produced alloys, in-situ monitoring, nickel superalloys,

OPERANDO X-RAY DIFFRACTION AND IMAGING TO STUDY MICROSTRUCTURE EVOLUTION DURING LASER POWDER BED FUSION

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ABSTRACT

Laser-based powder bed fusion (LPBF) is one of the most versatile and widespread additive manufacturing techniques for processing metals. Despite decades of research in this very active scientific field, there are still many open questions regarding the relationship between process parameters and microstructural evolution. One successful pathway towards a better understanding of this relationship is the use of *in situ* techniques. For this purpose, we have developed a miniaturized laser powder bed fusion device that is compatible with synchrotron X-ray diffraction [1-3] and imaging [4] beamlines. In combination with fast X-ray detectors, this setup allows tracking the evolution of crystallographic phases, local temperature, cracks, pores, etc... during LBPF with time resolutions in the tens of microseconds range [4-8].

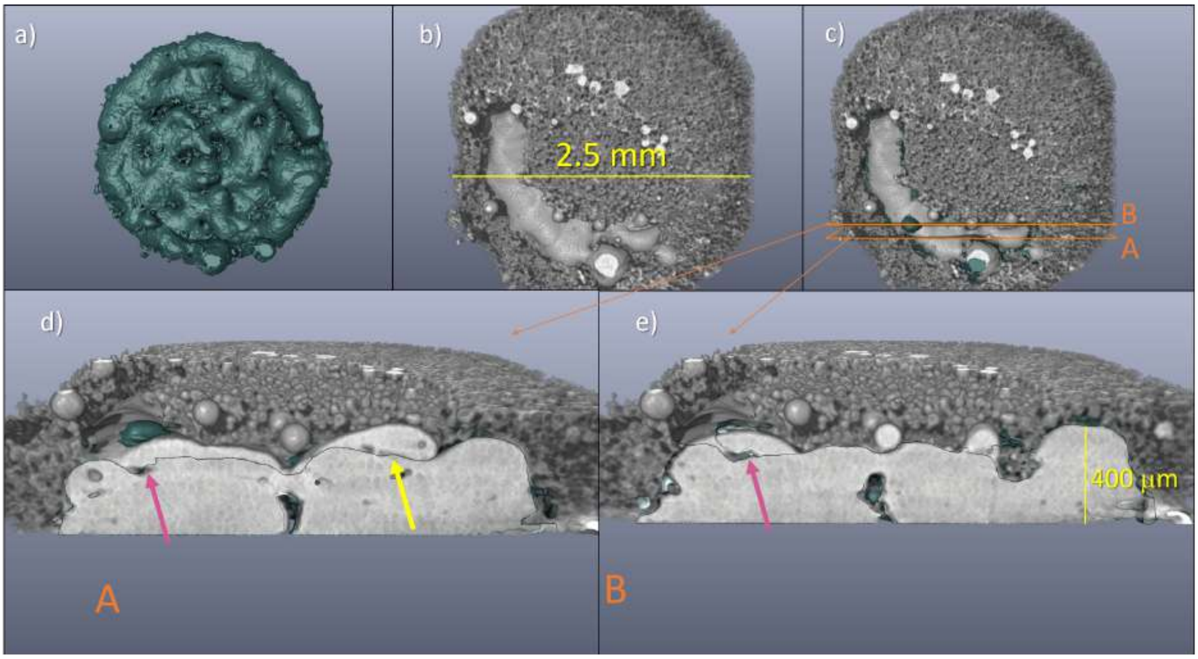

Fig. 1. 3D rendering of snapshots during LPBF of Al_2O_3 showing porosity caused by lack of fusion between consecutive layers due to poor wetting. a) surface generated after solidification of the previous layer, b) a volume rendering of a partially processed new layer. In c the planes A and B are indicating the cross sections shown in d and e. These images are a combination of the surface generated after solidification of the previous layer and a volume rendering of the sample after t = 0.75 s. Thus, the cross sections shown in d and e show the situation shortly after solidification of the material with a visible contour of the surface of the previous layer.

In this contribution, we will highlight recent developments and results obtained with this setup. In particular, we will demonstrate that *operando* X-ray diffraction allows tracking the phase evolution and local cooling rates in various metallic alloys. The outcome of such experiments can be directly compared with simulations that aim to describe the microstructure evolution during LPBF. Emphasis will be given to phase evolution at the phase boundaries in multi-materials and during site-specific microstructural engineering. Furthermore, we demonstrate the power of *in situ* X-ray radiography combined with optical and acoustic sensors and machine-learning algorithms. Finally, we report on the first *operando* X-ray tomography experiments during LPBF. This technique allows tracking, in 3D, the evolution of melt pool geometry, pores (Fig. 1) and cracks during LPBF. This will be demonstrated for the case of Al_2O_3 [9].

KEY WORDS: Operando X-ray diffraction, Radiography, Tomography, Laser Powder Bed Fusion, Multi-Materials, Ceramics

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Developing A Sustainable Aluminum Alloys Designed for Laser Powder Bed Fusion (LPBF) using In-Situ Alloying

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ABSTRACT

Some of the frontrunner Al-alloys for Laser Powder Bed Fusion (LPBF) rely on strategic and critical elements (e.g. Sc and Ag) as alloying elements, which affects both the cost of the powder and the sustainability of using these alloying additions. In this study, a strategy for designing new sustainable aluminum alloys for L-PBF was developed considering the abundance, the cost of the alloying elements, the solidification behaviour, and the desired mechanical properties, through in-situ alloying.

Thermo-Calc software was used to study the thermodynamic and solidification properties of several alloying compositions, with an aim to minimise the metallurgical defects such as cracks and voids by designing alloys with L-shaped solidification diagrams, where the maximum mole fraction of solid is less than 10%. The solidification range was also minimised to reduce the potential for cracks and voids. To test the robustness of the approach, in-situ alloying approach was used to fabricate Al-Ni blend of different Ni-contents. The LPBF parameters were optimised to achieve a high degree of homogeneity by effectively dissolving Ni element into the Al matrix, which reducing the presence of pores and cracks.

A series of LPBF experiments were conducted to assess the effectiveness of the approach, using binary Al-Ni alloys of different Ni-contents (5.7, 7.7, 9.7, 11.7 wt.%). The optimised alloys exhibited significantly improved mechanical properties, such as a high yield and ultimate tensile strength in the as-fabricated condition. The yield stress of the alloys increased from 170 MPa to 310 MPa by increasing the nickel (Ni) wt. % from 5.7% to 11.7%. LPBF samples for the alloys with different compositions showed no cracks. Since Ni has a limited solid solubility in Al, fine Al_3Ni intermetallics formed during the process, which contributed to the high strength of these alloys due to the rapid solidification associated with LPBF. A structure-property model was constructed to rationalise the impact of the different strengthening mechanisms (solid solution strengthening, grain boundary strengthening, and precipitation strengthening). The contribution of dislocation strengthening was estimated using annealing heat treatments.

The designed alloys exhibit excellent thermal stability at high temperatures (300˚C), making them highly suitable for demanding applications that require high-temperature performance. These alloys maintain their mechanical properties, such as strength, even when subjected to high temperatures, opening new possibilities in high-temperature applications, including aerospace and automotive industries.

Overall, the study demonstrates the ability of in-situ alloying in speeding up sustainable alloy design. Future work will move from binary to more sophisticated chemistries to enable the design of more complex Al-alloys from sustainable alloying elements.

KEY WORDS: Phase transformations in AM-produced alloys, sustainable alloys, alloy design, Al-alloys, mechanical properties.

DIRECTED ENERGY DEPOSITION OF HIGH-STRENGTH ALUMINIUM ALLOYS

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ABSTRACT

Powder-blown directed energy deposition (DED) is gaining interest in alloy design and multi-material fabrication thanks to the flexibility of composition modification during production. However, there are still challenges when producing novel alloys or aluminium alloys. The main challenges are related to the high reflectivity, high conductivity and high oxygen affinity of aluminium alloys. This combination of properties can cause back-reflection problems during DED and the need for very high laser powers in order to melt the deposited powder. As a result, only a few aluminium alloys have been successfully produced with DED as compared to the wider range of alloys developed for other additive manufacturing technologies, such as laser powder bed fusion.
In this work, the manufacturability of a high-strength aluminium alloy by DED was studied. First, the powder characterisation was carried out in order to evaluate the flowability and powder quality. Then, the process parameter optimisation was carried out. Different laser powers, travel speeds and mass flows were studied as well as techniques to reduce the back reflection. The standard optimisation procedures developed at the Royal Netherlands Aerospace Centre, which aim to produce the least amount of samples, were applied. The selection of parameters was performed based on the lowest porosity and roughness. After the parameter optimisation, the microstructure of the as-built parts was analysed using optical microscopy and scanning electron microscopy. In addition, the phase formation and grain structure were studied.
In the next steps of the work, different heat treatments will be analysed as well as the mechanical performance. The powder analysis, process optimisation, microstructure and mechanical performance will be compared to other high-strength aluminium alloys produced by laser powder bed fusion.
This research was carried out within the framework of GARTEUR, Action Group 36.

KEY WORDS: Directed energy deposition, high strength aluminium alloys, process optimisation, microstructure, powder characterisation

NON-EQUILIBRIUM DYNAMICS IN ADDITIVE MANUFACTURING THROUGH OPERANDO X-RAY STUDIES

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ABSTRACT

Although additive manufacturing (AM) has found application across many industries such as aerospace, automotive, and biomedical, the transient nature of the process makes it challenging to study the complex phenomena that occur during the fast solidification. Some in-situ monitoring techniques such as high-speed imaging and thermal imaging have been employed for quality control as well as to capture information about the melt pool such as surface temperature and melt pool stability. However, these methods can only probe the surface, and any sub-surface inspection must be done post-mortem. In contrast, synchrotron X-ray imaging and diffraction can penetrate through thick samples to give information about the melt pool and solidification mechanics, overcoming the shortcoming of optical and thermal imaging. Here, we give two examples of how synchrotron X-ray diffraction (XRD) studies can be coupled with post-mortem microstructural characterization techniques to reach a fundamental understanding of the complex relationship between process and microstructure in AM. In the first example, we explore the relationship between grain boundary roughness and solidification in stainless steels. In the second example we discuss thermo-mechanical deformation modes during solidification of Inconel 625 using synchrotron XRD.

Laboratory of Advanced Materials and Manufacturing (LAMM, Cornell University, Ithaca, NY) has developed a custom setup for operando monitoring of the AM process using high-energy synchrotron source (**Figure 1**). The details of the set up can be found in author's previous publication [1]. The setup was integrated into the Forming and Shaping Technology ID3A (FAST) beamline of the Cornell High Energy Synchrotron Source (CHESS) and used high-energy monochromatic hard x-rays with an energy of 61.332 keV and a wavelength of 0.2022 Å.

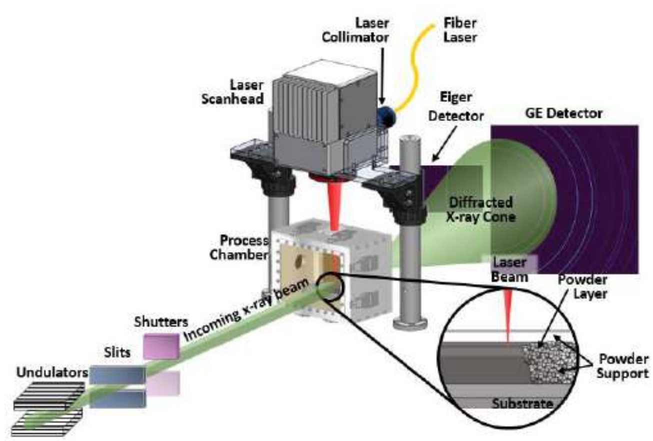

Figure 1. Schematic of custom AM setup integrated at Cornell High Energy Synchrotron Source (CHESS).

Using the setup, we gain insight into the relationship between composition, solidification pathway, and microstructure in two common stainless steels, 304L (SS304) and 316L (SS316) [2]. The printing process parameters used were a laser power of 200W, a scanning velocity of 6 mm/s, and a layer height of 2mm in an Argon atmosphere. The data acquired on the Eiger detector was integrated along the azimuth to produce 1-dimensional X-ray diffraction plots stacked against time (**Figure 2**). Figure 2a and 2b show results for SS304 and SS316 respectively, both materials showing peaks corresponding to the stable austenitic phase (marked by red circle). It is only in SS304 that we observe the emergence of peaks corresponding to a secondary phase, a metastable ferrite (marked by blue diamonds). This shows clear evidence of the contrasting solidification pathways that take place between the two materials at the same nominal processing conditions. Such difference in solidification pathway was shown to have a direct impact on grain boundary morphology.

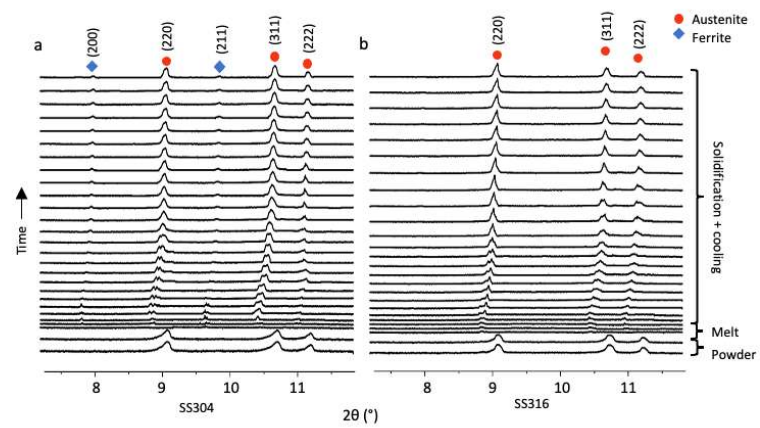

Figure 2. (a,b) stacked 1-dimensional X-ray diffraction (XRD) plots integrated along the azimuth for SS304 and SS316, respectively.

In the second example, we employ operando x-ray diffraction to study thermomechanical deformations such as torsion, bending, fragmentation, assimilation, oscillation, and interdendritic growth due to torsional and bending forces during AM of In625 [3]. Understanding such phenomena can aid the optimization of printing strategies to obtain specific microstructural features, including localized misorientations, dislocation substructure, and grain boundary character.

KEY WORDS: Solidification, operando x-ray diffraction, microstructure

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Integrated Multi-Scale Solutions for Accelerated Materials Development in Metal Additive Manufacturing

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ABSTRACT

While Additive Manufacturing is growing rapidly and moving towards industrial-grade production technology, the development and qualification of Additive Manufacturing materials remain time-consuming and costly challenges. In this talk, we will discuss an integrated multi-scale approach designed to accelerate AM materials and process development. Our approach combines smart DOE methods, high throughput materials testing and characterization, and process monitoring and control to enable rapid and efficient qualification of new AM materials and processes. Smart utilization of non-destructive testing (NDT) techniques, as well as an Integrated Computational Materials Engineering (ICME) approach, can significantly reduce the time and cost required for AM materials and process development and qualification. We will bring examples of Al, Cu, and Ni alloys recently developed at Morf3D.

KEY WORDS: Materials Design, Alloy Development, Process optimization, NDT, ICME, Smart DOE.

DESIGN OF HIGH THROUGHPUT TECHNIQUES FOR FUNCTIONAL ADDITIVELY MANUFACTURED MEDICAL DEVICES

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ABSTRACT

Since the early designs of medical devices, it has become apparent that implants should act as modulators of specific biological processes to ensure short- and long-term benefits[1]. Nevertheless, standard alloys used in orthopaedics have been repurposed from other industries (e.g. aerospace) as a consequence of their mechanical behaviour, corrosion resistance and biocompatibility. With increased life expectancy requiring longer service life of implantable devices and common alloying elements (e.g. aluminium or vanadium) demonstrated to negatively impact biological processes beyond cytotoxicity, it is clear that novel medical alloys should be developed to modulate clinical outcomes[2.] In this work, the difficulties of designing alloys for implantable devices will be contextualised, providing case studies focused on generating high throughput methods for their use in alloy development with especial attention on the advantages posed by metal additive manufacturing (AM) platforms.

When metallic elements are considered, there exist a plethora of materials with reported effects on biocompatibility, antimicrobial, angiogenic, osteogenic properties and/or their ability to modulate the innate and adaptive immune response[3.] Nevertheless, most effects been reported for single element compounds, reducing their direct correlation to complex alloys and calling for methods to rapidly evaluate biological properties. The first case study will showcase the development of high throughput techniques for both material processing and biological evaluation. The use of AM and novel Reduce Build Volume designs for Powder Bed fusion coupled with powder blending will be shown as a tool to enable the rapid evaluation of alloy systems for antimicrobial applications with conventional and AM Ti-Cu samples used to highlight their benefits over traditional casting. Microstructural variations were assessed through SEM imaging, X-ray diffraction and Vickers microhardness evaluation which were complemented with antimicrobial assays following ISO 22196 in model strains of *S. aureus* and *P. aeruginosa*. In addition, the power of powder compaction and HIP technologies will be harnessed to enable the rapid analysis of bacterial behaviour and antibiotic synergistic/antagonistic effects through the agar diffuse method and metabolic assays in model strains of Gram-positive and Gram-negative species to enable novel databases in the healthcare industry.

Besides combinations of different metallic elements, alloy design should consider the effect of microstructure and the manufacturing of complex alloys with significantly different processing parameters. Copper and Molybdenum are two elements that have shown promise to tackle antibiotic infection, nevertheless, their disparity in reflectivity or melting point has made their incorporation in titanium alloys a challenge from a manufacturing perspective. Herein, the use of AM, powder compaction and sintering will be used to demonstrate the possibility of providing novel alloys with highly different elemental properties and their use in multicomponent alloys. Through variations in composition and heat treatment, we successfully produced a blended powder of two dissimilar elements which can be used to manufacture SLM parts with reduced input energies (133J/m instead of 300J/m)[4]. Similarly, the effect of microstructural variations with antimicrobial properties and

murine osteoblastic, MC3T3, and macrophage, RAW 264.7, cell lines responses will be shown for the rapid optimisation of novel alloys.

KEY WORDS: Alloy development, AM processes, High-throughput evaluation, Antimicrobial and cell behavior.

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POWDER FUNCTIONALIZATION FOR IMPROVED PROCESSABILITY AND PERFORMANCE

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ABSTRACT

The Powder Bed Fusion - Laser Beam (PBF-LB) processability of certain metal powder grades, such as nickel superalloys, aluminum alloys, and pure copper, can pose significant challenges due to their susceptibility to solidification and liquation cracking, or high laser-reflectivity. The modification of the original chemical composition of powder by adding proper alloying elements is often necessary to produce dense, crack-free structural parts. But this isn't always a straightforward solution. In fact, such additions can cause gas atomization issues like nozzle clogging and the separation of solid phases from the molten metal. In addition, in some instances, only modification of particle surface properties is needed to improve powder processability, without significantly changing the overall chemical composition of the powder. Thus, a more innovative approach is needed. One such approach is powder functionalization, which involves decorating the surface of powder particles with thin coatings or discrete particle deposition. This strategy can improve powder processability by promoting the formation of fine microstructures, enhancing their flowability, or improving laser absorptivity.

In this work, we functionalized Al alloy and Cu powders using a variety of methods and then processed them through PBF-LB to produce cubes for microstructural and physical analyses, and bars for mechanical testing. For pure Cu powder, we used an electrodeposition technique and we properly treated it to facilitate diffusion of Cu atoms in the metal coating, which helped reduce surface absorptivity. We then performed microstructural analyses on the coated powder and as-built samples using several methods, including SEM, EDX, and EBSD. We also conducted eddy current tests to investigate the electrical conductivity of printed parts and compare it with that of cathodic

Cu. In a second case study, we used ceramic particles to decorate an Al-Cu-Mg alloy powder using various techniques, including electro-chemical and mechanical methods. The resulting powders were analysed and printed by PBF-LB. The alloy showed a crack-free microstructure characterized by fine equiaxed grains.

Overall, our study provides valuable insights into how surface features can improve powder processability, and hopefully, it will inspire further innovations in this exciting field.

KEYWORDS: coated metal powders; powder functionalization; PBF-LB; copper; aluminum alloy.

Novel powder feedstock towards microstructure engineering in Laser Powder Bed Fusion: a case study on Duplex/Super Duplex and austenitic stainless steel materials

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ABSTRACT

The present study focuses on the development and characterization of novel custom duplex (DSS) and super duplex alloys (SDSS) used as feedstock material in laser powder bed fusion (LPBF). Additive manufacturing of DSS and SDSS has been successfully demonstrated using LPBF in recent years, however, both alloys feature an almost fully ferritic microstructure in the as-build condition due to the fast cooling during the LPBF process. To overcome this challenge, various compositions of duplex and super duplex stainless steel alloys were formulated by blending with austenitic stainless steel 316L powder. The powder blend compositions were optimized through a systematic experimental design approach, aiming to achieve in-situ austenite formation which results in superior mechanical and corrosion resistance properties. Powder characteristics were investigated and process parameters such as laser power, scanning speed, and powder layer thickness were optimized to produce near fully dense parts and maintain the desired microstructure for each alloy. The manufactured specimens underwent a comprehensive nanoindentation (NI) characterization process to evaluate the nanomechanical response, evaluate the mechanical properties of separate constituent phases and provide information about their content and distribution within the system. The metallographic analysis revealed a two-phase microstructure of austenite and ferrite in the DSS and SDSS parts, with a uniform distribution of alloying elements. The findings from this study provide valuable insights into the powder mixing ratios for the development of custom duplex and super duplex stainless steel alloys that result in duplex microstructure in the as build condition and eliminate high temperature annealing as a post processing step. Our results demonstrate the importance of powder characterisation for the successful production of high-quality DSS and SDSS parts using LPBF. The optimisation of powder composition and particle size distribution can lead to better flowability, packing density, and overall improved melting behaviour of the powder, resulting in a more uniform microstructure and improved mechanical properties. The formation of austenite and ferrite phases was heavily influenced by the chemical composition that was adjusted by the amount of 316L powder added to the blends. The tailored alloy compositions and processing parameters contribute to the successful fabrication of components with enhanced mechanical properties and corrosion resistance. The results offer promising opportunities for the utilization of these custom alloys in demanding applications within the oil and gas, chemical, and marine industries, where superior performance in harsh environments is crucial.

KEY WORDS: duplex, super duplex, austenitic, stainless, nanoindentation, powder, mixture, characterisation, nanoindentation, modulus, hardness, LPBF

Envisioning Additive Manufacturing with X-ray

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ABSTRACT

Laser Additive Manufacturing (LAM), has the potential to revolutionize manufacturing processes. However, its wider industrialisation is currently inhibited by solidification cracking, residual stress and distortion, anisotropic microstructures and most importantly a large distribution of entrained defects. It is critical to establish a scientific understanding of how to control defect formation and thus optimise mechanical performance in LAM. At the European Synchrotron (ESRF), taking advantage of the recent Extremely Brilliant Source upgrade and the most advanced synchrotron material characterisation techniques, *in-situ* and *ex-situ* investigation have been used to establish a well-rounded picture of the LAM process. The outstanding photon flux density at ESRF can reach ultra-high temporal resolution at hard X-ray energies in combination with coherence levels which allow for imaging with high sensitivity. Combining fast synchrotron radiography (> 40 kHz) with an *in-situ* LAM rig, fast X-ray imaging enables the observation, in both real and reciprocal space, of the laser-matter interaction, defects formation, material phase transformations and microstructural features evolution. High angular resolution Dark Field X-ray Microscopy (DFXM) is used to quantify the resulting LAM microstructure including spatially resolved 3D grain maps, 3D distribution of strains, lattice misorientation and Geometrically Necessary Dislocations (GNDs). Microstructure development is explored via solidification sequence modelling, which is calibrated by *in-situ* synchrotron imaging of the manufacturing process. The results presented here provide new insights into the LAM process with relevance to microstructure and defects control in AM fabricated components. They provide information that can contribute directly to industrial practice while producing quantitative data to inform and validate physical models in support of digital twins.

KEY WORDS: Synchrotron X-ray, in situ imaging, defects control, alloy development

4D PRINTING OF METALLIC ALLOYS TOWARDS NOVEL SHAPE MORPHING MEDICAL DEVICES

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ABSTRACT

Additive manufacturing (AM) technologies have reinvented many areas of product development. In the medical field, the ability to promote patient personalization has become a key factor. AM technologies allow the manufacturing, based on medical images, of models for surgical planning, surgical guides and even, implants and porous scaffolds for tissue regeneration. However, many of these applications are static and do not allow a dynamic interaction, which would enable minimally invasive surgeries. or allow shape changes according to the healing process of the tissue. The use of "smart" medical devices, obtained through the emerging concept of "4D printing", capable of undergoing progressive metamorphosis according to surgical procedures, biological integration and/or healing processes, is still a dream, especially in metallic materials that offer substantial load bearing capabilities.

In this work, we investigate two different concepts that can be implemented in metallic alloys to develop smart shape-morphing metallic implants by AM: the use of active materials, such as shape memory alloys (SMA), capable to undergoing shape changes upon a thermal stimulus, or the use of different biodegradable metals in the same construct, so that the fast degradation of one of the metals triggers the shape change. In all these cases, laser powder bed laser fusion (LPBF) techniques might offer the degree of dimensional precision and manufacturing control required to achieve this goal, provided the metallurgical changes that take place during processing are well understood and that effective post-processing methods are developed to control the final surface condition, which is critical for many biomedical applications. Several examples will be presented on the effect of processing parameters on the chemical composition, microstructure and properties of several SMAs of the nitinol family, as well as Mg and Zn alloys of biomedical interest.

KEY WORDS: PBLF, 4D printing, Biodegradable metals, Shape Memory Alloys, Biomedical devices

Alloy Design for Additive Manufacturing of Shape Memory Alloys

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ABSTRACT

Additive Manufacturing (AM) has revolutionized metal component production, highlighting the need for suitable metal alloys. This presentation focuses on the alloy design procedure for additive manufacturing, with a specific emphasis on challenges in high temperature shape memory alloys (HTSMA), ternary alloys, and solidification defects.

The alloy design procedure entails defining objectives, conducting a literature review, selecting alloy compositions, assessing process compatibility, performing small-scale testing, iterative optimization, and characterization/validation. The talk highlights the challenges that arise in alloy design for AM, particularly in SMA, ternary alloys. SMA alloys present challenges due to complex phase transformations and the need for precise control over transition temperatures and functional properties. Additionally, ternary alloys lack comprehensive data in existing software such as (Thermo-Cala), making their design and optimization more challenging. Furthermore, the solidification range plays a crucial role in AM, as it can lead to cracking during melt pool solidification, presenting a significant challenge in alloy design.

Rapid alloy and powder-making tools such as lab scale ultrasonic powder atomizers offer a solution by expediting small-scale testing. It enables rapid evaluation of phase transformation behavior of atomized powder and follow-up single track experiments helps in identification of solidification defects in AM of SMA alloys, facilitating the optimization of shape memory effect and superelasticity for a variety of applications. As such multiple NiTi-X alloys are evaluated based on their printability using computational tools. Printability is further investigated through single track experiments. Finally, each alloy is atomized to make enough of powder and further characterized. Therefore, this presentation showcases the role of rapid alloy-making instruments in addressing cracking challenges, and streamlining the metal alloy design process, specifically for NiTi-X as a desirable high-temperature shape memory alloy.

KEY WORDS: Rapid alloy design for additive manufacturing, phase transformations in AM-produced alloys, ternary alloy, high temperature shape memory alloy.

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The selective laser sintering: Modeling & optimization

The additive manufacturing technologies such as selective laser sintering technique, is very complex process and need a good interpretation of models which describe all the phenomena interact in the powder bed of polymers. In this study we present a different model of the selective laser sintering process of polymers for the optimization.

Do dislocations evolve during metal 3D printing? – an *in situ* synchrotron X-ray diffraction study

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ABSTRACT

Dislocation structures are ubiquitous in any 3D printed alloy and they play a primary role in determining the mechanical response of an alloy. While it is understood that these structures form due to rapid solidification during 3D printing, there is no consensus on whether they evolve due to the subsequent solid-state thermal cycling that occurs with further addition of layers. In order to design alloy microstructures with desired mechanical responses, it is crucial to first answer this outstanding question. To that end, a novel experiment has been conducted by employing high resolution reciprocal space mapping, a synchrotron-based X-ray diffraction technique, in situ during 3D printing of an austenitic stainless steel [1]. It reveals that dislocation structures formed during rapid solidification undergo significant evolution during subsequent solid-state thermal cycling, in particular during addition of the first few (up to 5) layers above the layer of interest.

KEY WORDS: Dislocations; Synchrotron diffraction; Solidification; Intrinsic heat treatment; Microstructure evolution; XRD

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Investigation of Laser Beam Attenuation and Energy Partitioning during Coaxial Laser Directed Energy Deposition Process

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ABSTRACT

A predictive multiphysics powder stream model has been developed to investigate the dynamics of laser beam interaction with the in-flight powder stream during the coaxial laser directed energy deposition process. The interaction of the laser beam with the powder stream results in significant laser beam attenuation which can result in melt pool oscillations and process instabilities. To understand this beam attenuation phenomenon, a one-way coupled Eulerian-Lagrangian (CFD-DEM) model has been implemented. Firstly, the gas dynamics (carrier, shaping, and optics) in the nozzle channels and the region from the nozzle outlet to the substrate have been predicted by solving continuity, momentum, and k-ε turbulence equations. Then using the gas flow field solution, powder-stream trajectory, in-flight temperature rise of the powder particles, Gaussian laser beam shadowing, beam attenuation, multiple reflections, and beam scattering by powder particles are predicted using the discrete element modeling (DEM). The novelty of this work is the numerical implementation of scattering and multiple reflection phenomena of the laser beam by discretizing into a Lagrangian photon stream. The model is utilized to predict the in-flight temperature rise of the powder particles for a set of processing conditions (varying gas flow rate). Thereafter, the influence of powder mass flow rate, stand-off distance, carrier gas, and shielding gas velocities on the beam attenuation and shadowing have been investigated and a beam attenuation process map has been generated for an enhanced fundamental understanding of laser directed energy deposition process. Finally, the numerically predicted powder stream characteristics (waist location, morphology, and velocity) are compared with the measurement results of in-house performed high-speed visible imaging.

KEY WORDS: Directed energy deposition, laser beam attenuation, turbulent gas dynamics, energy partition

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RECRYSTALLIZATION MECHANISMS IN AN ADDITIVELY MANUFACTURED OXIDE DISPERSION-STRENGTHENED SUPERALLOY

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ABSTRACT

Several recent studies have successfully demonstrated melt-based additive manufacturing of oxide dispersion strengthened (ODS) nickel-based superalloys [1][2]. However, modifying the grain structure of these ODS materials through post-processing heat treatments remains a challenge. This study investigates the recrystallization behavior of an additively manufactured ODS NiCoCr medium entropy alloy, focusing on the effects of a liquid phase and Al microalloying additions on recrystallization kinetics. Gas atomized NiCoCr powders were decorated with oxide dispersoids using resonant acoustic mixing then consolidated with laser powder bed fusion (LPBF). The as-printed ODS materials were fully dense with retained nano-dispersoids, but had high dislocation densities and a fine grain structure – features which degrade high-temperature creep resistance. Conventional wrought ODS alloys achieve coarse columnar grains through directional recrystallization heat treatments. A goal of this study was to assess whether directional recrystallization can also be used to effect a coarse columnar grain structure in additively manufactured ODS alloys. The as-printed materials were subjected to static annealing and zone annealing at soak temperatures between 800 and 1410 °C, the solidus temperature determined with differential scanning calorimetry. The material proved remarkably resistant to recrystallization during static annealing, only recrystallizing at temperature above the solidus temperature or when contaminated with Al, which accelerated the coarsening kinetics of the oxide dispersoids. These insights were then used to develop alloy chemistries and processing procedures that promoted directional recrystallization.

This study contributes to an improved understanding of the microstructural evolution and grain growth behaviors of additively manufactured ODS nickel-based superalloys. By highlighting the beneficial role of a liquid phase or Al microalloying in accelerating recrystallization, this research paves the way for optimized post-processing heat treatment strategies to optimize high-temperature mechanical properties.

KEY WORDS: Additive manufacturing, oxide dispersion-strengthened, nickel-based superalloys, directional recrystallization heat treatment, microstructural evolution

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Dynamic strain aging in additively manufactured Inconel 718 lattice structures

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Abstract:

Strut-based lattice structures are characterized by a specific spatial arrangement of beams, resembling to a cellular structural configuration [1]. Lattice structures are of great interest to industries such as aerospace, automotive and biomedical since they enable the replacement of solid parts, maintaining similar absolute strength but much higher specific strength [2].

This work focuses on the manifestation of the phenomenon of dynamic strain aging (DSA) in body centred cubic (BCC) and face centred cubic (FCC) lattice structures fabricated by laser powder bed fusion (LPBF) with Inconel 718. To investigate the occurence of serrations as a manifestation of DSA, the as-built lattice structures were subjected to uniaxial compression tests with varying strain rates ranging from $1x10^{-5}$ to $5x10^{-2}$ s^{-1} and at temperatures of 25, 300, 450 and 600 °C. The prevalence of serrated flow was related to the strain rate sensitivity and to the work hardening rate. It was observed that the manifestation of DSA is topology dependent, occurring at a wider range of testing temperatures in the FCC lattice, where the overall stress level is higher. The work effectively highlights the necessity of analyzing DSA in additively fabricated lattice structures aimed for structural utilization.

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