An investigation of Laser Metal Drop Deposition for Additive Manufacturing

Oral Presentation

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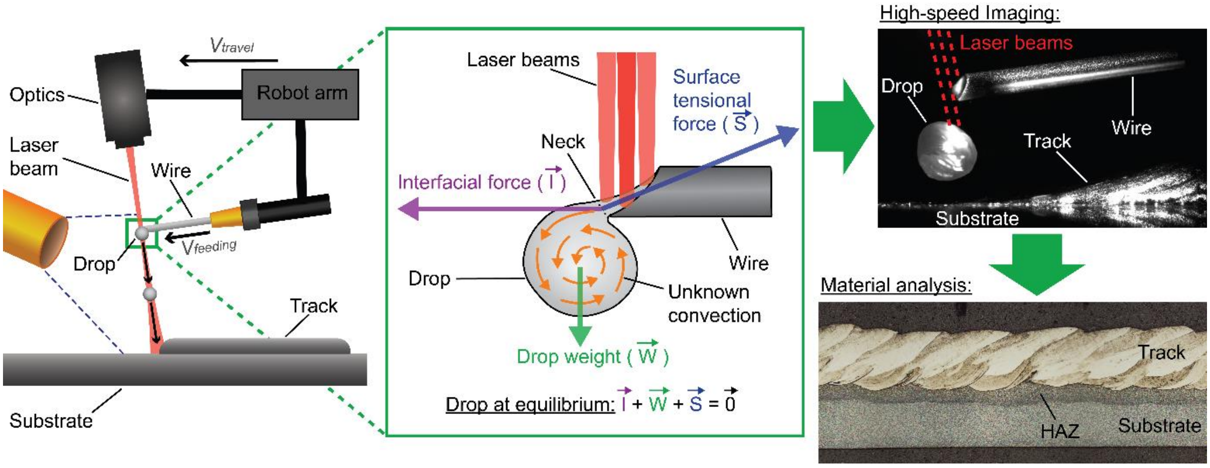

Additive Manufacturing includes numerous techniques, some of which have reached very high levels of development and are now used industrially. In this presentation, a novel technique is investigated: Laser Metal Drop Deposition. Arc processes (welding or WAAM) have seen a lot of development by evolving from continuous wire deposition to drop-by-drop deposition to increase their efficiency and reduce the heat input in the material. However, most of the equivalent laser processes still use continuous wire deposition. Thus, this laser-drop deposition technique is expected to be a more efficient and flexible alternative to Laser Metal Wire Deposition. Laser Droplet Generation experiments were carried out in an attempt to accurately detach metal drops towards a desired position. High-speed imaging was used to observe drop generation and to measure the direction of detachment and acceleration of the drops. Different drop detachment techniques were investigated and the physical phenomena leading to the drop detachment are explained, wherein the drop weight, the surface tension and the recoil pressure play a major role. During their fall, the drops are accelerated towards the substrate by the laser-induced recoil pressure. Optimized parameters for an accurate single drop detachment and attachment were identified and then used to build multi-drop tracks. Tracks were produced based on drops detached from 316L, Inconel 625 and AlSi5 wires, where the microstructure was influenced by the numerous drop depositions.

Alloy design and characterization of Ni-base superalloys for additive manufacturing

Oral Presentation

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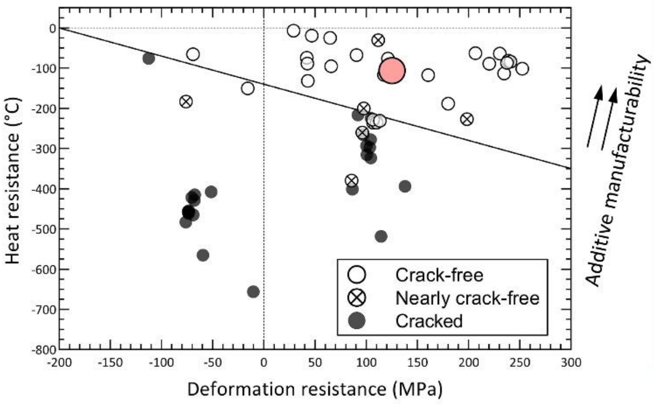

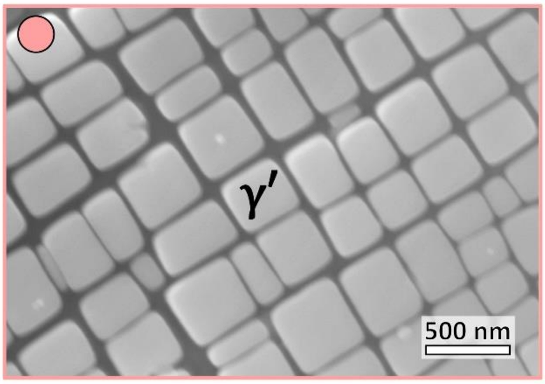

Nickel-based superalloys, an alloy system bases on nickel as the matrix element with the addition of up to 10 more alloying elements including chromium, aluminum, cobalt, tungsten, molybdenum, titanium, and so on. Through the development and improvement of nickel-based superalloys in the past century, they are well proven to show excellent performance at elevated service temperatures. The success of nickel-based superalloy systems is attributed to both the well-tailored microstructures with the assistance of carefully doped alloying elements and the intently developed manufacturing processes. The recently developed additive manufacturing (AM) techniques, acting as the disruptive manufacturing process, offers a new avenue for producing nickel-based superalloy components with complicated geometries. However, γ′ strengthened nickel-based superalloys always suffer from micro-cracking during the AM process, which is barely eliminated by the process optimization.

On this basis, the new grades of high-performance nickel-based superalloy adapted to the AM process are of great interest and significance. This study sought to design novel γ′ strengthened nickel-based superalloys readily for AM process with limited cracking susceptibility, based on the understanding of the cracking mechanisms. A two-parameter-based, heat resistance and deformation resistance (HR-DR) model, has been successfully proposed to predict the printability on accounting for the relation between chemical composition (both major and minor elements) and cracking susceptibility. By considering the combination of additive manufacturability, creep and oxidation resistance performance, a novel γ′ strengthened nickel-based superalloy, MAD542 has been developed based on the materials selection procedure from 921,600 candidate compositions.

The MAD542 superalloy shows the capacity of being fabricated in crack-free condition by laser powder bed fusion. This work also presents the post-processing treatments optimization for this superalloy. High-temperature mechanical behaviours, especially creep performance was investigated and discussed.

Precipitation kinetics and structure-property corelation in novel Al-Mn based aluminium alloys tailored for LB-PBF process

Oral Presentation

Bharat Mehta* [1] , Lars Nyborg [1], Karin Frisk [1,2]

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High strength aluminium alloys derive their strengths majorly from precipitation hardening with solid solution strengthening and grain refinement strengthening as secondary strengthening mechanisms. This study elucidates the outcome of ageing on novel Al-alloy design tailored for LB-PBF process, which led to an Al-alloy family which is hot cracking resistant and high dissolution of solutes. Upon heat treatments, it was observed that two families of precipitates namely Al(Mn,Cr) and AlZr precipitates were seen. Interestingly, Al(Mn,Cr) precipitates were seen to grow selectively at grain boundaries whereas AlZr precipitates were seen to grow on Al(Mn,Cr) precipitates. Upon adjusting the ageing temperature, it was seen that the growth of these two families of precipitates could be optimised to achieve high hardening response with a stable peak hardness over time. Thus, peak hardness of 143 HV0.3 was achieved, thus suggesting high strength abilities of these alloys along with possible high temperature properties.

Fracture charactarization of Chemically Post-Processed Electron Beam Melted Ti-6Al-4V

Oral Presentation

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The fatigue behavior of additively manufactured (AM) structural parts is sensitive to the surface and near-surface material conditions. Chemical post-processing surface treatments can be used to improve the surface condition of AM components, including geometries with surfaces difficult to access.

In this work, surfaces of electron beam melting (EBM) produced Ti-6Al-4V were subject to two different chemical post-processing surface treatments, Hirtisation and chemical milling. As-built and machined surfaces, as well as hot isostatic pressing (HIP), treated conditions were also investigated. Fatigue testing was carried out in four-point bending to ensure a surface adjacent stress gradient. The investigation focused on the relationship between fracture mechanisms and total life through fractographic documentation and analysis. It was found that a majority of fractures were initiated from surface-near internal defects or process-related surface defects. Chemical post-processing was found to smoothen the surface but to leave a surface waviness. It also opened up near-surface defects. In the HIP treated material, fractures initiated at defects open to the surface. Despite the improved material condition, only slight improvements in minimum life were observed for all conditions.

Laser powder bed fusion of arbitrarily shaped powders

Oral Presentation

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Laser powder bed fusion (LPBF) has become a widely recognized process for manufacturing components of complex geometry and light weight by minimizing material consumption and building parts in one step. However, to make the process more cost-efficient, agile and sustainable, it is important to expand a variety of powder materials currently available for use in LPBF.
Therefore, this study reports on the laser beam-material interaction phenomena, with a particular focus on the behaviour of dissimilarly-shaped gas and water atomized low alloy steel powders in laser powder bed fusion. The study contains research on the processability of near-spherical and non-spherical powders, their particle movement and denudation behaviours on a powder bed as well as their interaction with the laser beam. The impact of particle shape and bulk composition on the process behaviour was investigated, revealing significant changes in the melt pool stability when using water atomized powder. To establish a correlation between material packing characteristics and track formation, the powders' packing densities were measured. Differences in powder spattering and denudation phenomena when processing arbitrary-shaped powders were also discussed in detail. The influence of particle morphology on the dynamics of gas and water atomized powder particles was studied by measuring distances of particle entrainment towards the melt pool and by calculating the drag force, acting on powder particles of various shape. Throughout the study, high-speed imaging was used as the main tool to observe the process and analyse the results.

In-situ nitride formation in additive manufacturing with nitrogen as a reactive process gas

Oral Presentation

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An inert gas such as argon is commonly used to minimise impurity incorporation during metal additive manufacturing from residual reactive gases. However, if intentionally employed, reactive gases can enable compound formation and provide opportunities for tailoring the properties, for example local nitriding.

With this approach, local compound formation is investigated in metallic-glass ceramic composites formed in an 3D-printed Zr-based amorphous alloy ($Zr_{59.3}Cu_{28.8}Al_{10.4}Nb_{1.5}$, trade name AMLOY-ZR01, Heraeus Holding GmbH). Printing with AMLOY-ZR01 in nitrogen resulted in an overall decrease in glass forming ability, even if no ZrN was observed by X-ray diffraction. Another option for composites is therefore explored: The surface of X-ray amorphous samples printed in an EOS M100 (EOS GmbH) in argon is subsequently additionally laser melted in nitrogen (purity: $N_2 \geq 99.999$ %). Nitrogen incorporation and the formation of ZrN in the surface layer is observed. With adjustment of the process parameters, other crystalline phases can be minimised to form a ZrN - metallic glass composite layer on top of the amorphous bulk piece.

To study the laser nitriding process under additive manufacturing conditions in more detail, compound formation was triggered during writing a single laser track on bulk Ti in nitrogen. Multiple remelting events of this track resulted initially in an increased nitride fraction. Based on the process understanding obtained from these experiments, limitations and opportunities for in-situ nitriding, including the realisation of custom local nitride formation for more complex material systems and geometries can be enabled.

Microstructural characterization of interstitial solid solution strengthened CoCrNi medium entropy alloy

Oral Presentation

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The aim of this work is to study the stability of nitrogen as an interstitial alloying element in the CoCrNi medium entropy alloy produced through laser powder bed fusion. Equiatomic CoCrNi is one of the most widely researched medium entropy alloy due to its excellent strength, ductility, oxidation resistance and corrosion resistance, enhanced hydrogen embrittlement resistance, and excellent cryogenic mechanical properties. Addition of interstitial elements such as carbon and nitrogen are known to improve the mechanical properties the HEAs by provoking interstitial solid solution strengthening and lowering the stacking fault energy and hence bringing in the twinning induced plasticity effect. Though the interest in additive manufacturing of high/medium entropy alloys is rapidly increasing, there has been little focus on the development of interstitial high entropy alloys by additive manufacturing. The influence of nitrogen addition on the microstructure and room-temperature mechanical properties of CoCrNi was evaluated. Two different variants of CoCrNi, one without any nitrogen and the other pre-alloyed with 0.18 wt% nitrogen, were studied. It was seen from both thermodynamic calculations and experimental studies that nitrogen is stable as an interstitial addition in the as-printed state, devoid of any detrimental phase during the printing process. It was also found that the addition of nitrogen significantly improved the hardness and yield strength while maintaining the ductility of the nitrogen-free counterpart in the as-printed materials.

Challenges and possibilities of processing magnesium alloys by powder bed fusion - laser beam

Oral Presentation

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Powder bed fusion - laser beam (PBF-LB) of magnesium alloys is gaining increasing attention for the production of complex biodegradable orthopedic implants. However, for a successful implementation of magnesium-based implants produced by PBF-LB, some important challenges concerning the process need resolving. In particular, the degradation rate remains too high, thus an increased understanding of the influence of the process on corrosion properties is needed.

Herein these challenges will be discussed in relation to the process parameter development of a Mg-Y-Nd-Zr alloy on an EOS M100. Key features of the resulting microstructure will be presented, along with the sample's corrosion behavior.

A fundamental challenge is the high oxygen affinity of magnesium. This leads to formation of a stabilizing surface oxide. The oxides' high melting temperature, together with magnesium's low boiling temperature, makes it challenging to melt the powder without substantial evaporation of magnesium. Indeed, if oxygen content is too high while printing, the melted magnesium oxidizes instantly, and printing becomes impossible.

During process parameter development, magnesium evaporation was observed for all parameters, but was mainly removed by the gas flow. However, some condensates was deposited on the build plate. Nevertheless, three process parameters sets with varying hatch distances were established.

A typical microstructure of a PBF-LB Mg-Y-Nd-Zr alloy was observed, with Mg-Y-Nd precipitates and $Y2O3$ flakes, along with strongly textured larger grains, and smaller equiaxed grains with weaker texture. The tendency regarding the corrosion properties was that a higher energy input induces a higher corrosion susceptibility. A higher energy input increases magnesium evaporation, thus an increased alloying content and more precipitates. This enhances the micro-galvanic corrosion.

Finally, a trabecular bone replicate was successfully printed with said established parameters, highlighting future possibilities of the PBF-LB process. Future work should include studies of the influence of oxygen on microstructure and resulting material properties.

On the Residual Stress in Biodegradable Magnesium Alloys Produced by Powder Bed Fusion Laser Beam

Oral Presentation

Lisa Larsson* [1], Hanna Nilsson-Åhman [1,2], Tuerdi Maimaitiyili [2], Cecilia Persson [1]

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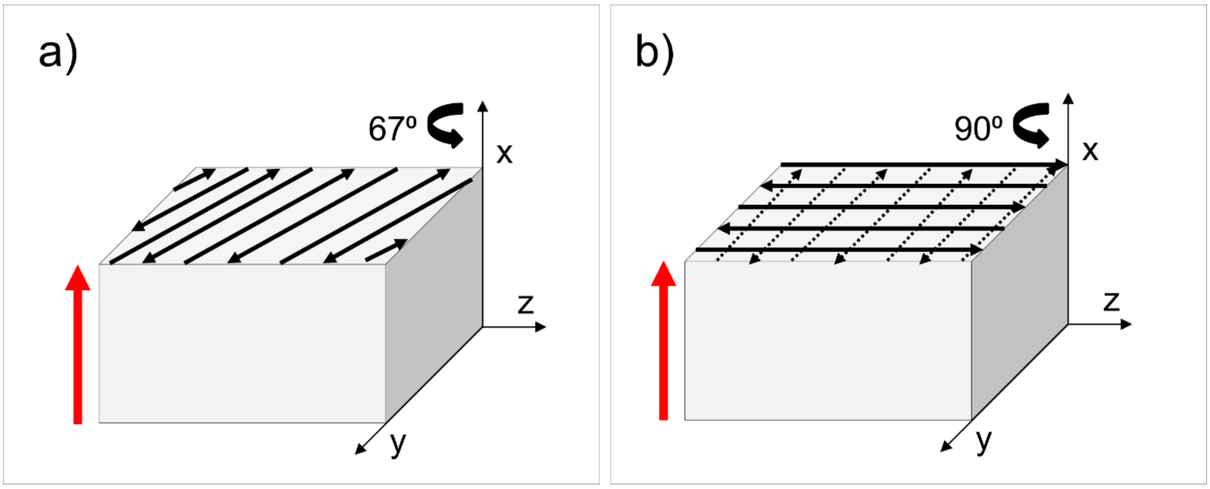

Additive manufacturing (AM) by powder bed fusion laser beam (PBF-LB) has opened up new possibilities in metal manufacturing. It is particularly interesting for the medical industry since it allows for the manufacturing of patient specific implants with complex geometries at a relatively low unit cost. However, the unique thermal history of PBF-LB materials, related to the high cooling rates as well as the cyclic melting and solidification, results in a microstructure that is widely different from that of the conventionally manufactured metals. The thermal cycles typically also result in large inhomogeneous residual stresses being built up in the material, which can negatively impact the corrosion properties of the finished parts.

Novel biodegradable magnesium (Mg) alloys destined for degradable implants generally has a higher corrosion rate than desired. Accurately characterizing the residual stress formation in Mg-alloys manufactured by PBF-LB is therefore crucial for understanding and controlling the dissolution behavior of degradable Mg-based implants. Recent studies on Mg-laser welded joints and hybrid AM suggest that residual stresses would also be significant in Mg alloys processed by PBF-LB.

The PBF-LB process is known to lead to a high degree of texture in as-built Mg-alloys. This, together with the hexagonal close packed crystal (HCP) structure of Mg, makes residual stress determination in these materials challenging with conventional stress-measurement techniques. Neutron and synchrotron diffraction techniques provides non-destructive residual stress determination in HCP alloys and offers a high spatial resolution and high penetration depth. In this study, the residual stress of samples printed in an EOS M100 machine with gas-atomized spherical powder of biodegradable rare-earth magnesium alloy WE43 (Mg-4wt%Y-3wt%Nd-0.5wt%Zr) was successfully measured by neutron and synchrotron diffraction. The influence of the hatch distance, build direction and scan strategy (fig. 1) during the PBF-LB process was evaluated.

Microstructure and Mechanical properties of additively manufactured samples using in-situ SEM micro testing

Oral Presentation

Kumar Babu Surreddi*
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Study of mechanical behaviour of additively manufactured (AM) samples by conventional methods, such as uniaxial tensile test require relatively large samples. Micro tensile testing is beneficial when the printed material is limited. The study of deformation behaviour of small sized AM samples is possible using in-situ micro tensile testing under scanning electron microscope (SEM). In this work, the mechanical properties of Inconel 718 alloy samples produced by electron beam melting (EBM) and Hastelloy X produced by selective laser melting (SLM) obtained from in-situ micro testing are presented. The microstructure evolution during the micro testing was studied using SEM and electron backscatter diffraction (EBSD). The results show that the in-situ micro testing can be used to understand the relationship between the microstructure and mechanical properties of AM samples. Various challenges and possibilities of testing small sized AM samples using micro mechanical testing under SEM will be discussed.

A sample environment for in-situ synchrotron X-ray studies on electron beam powder bed fusion (E-PBF) of metal

Oral Presentation

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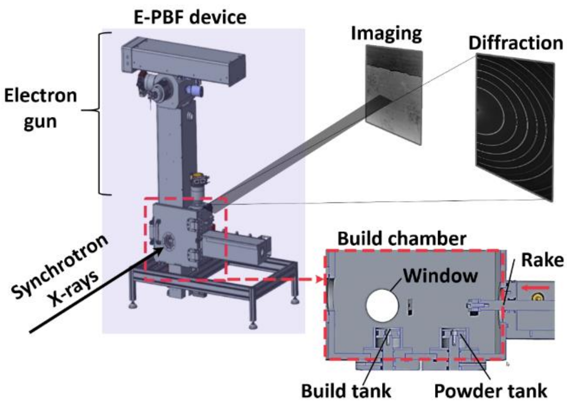

Powder bed fusion (PBF) technologies are successfully implemented processes in additive manufacturing (AM) of metal components. While Laser-PBF (L-PBF) has a larger share of production capacities, Electron beam-PBF (E-PBF) is particularly promising for manufacturing of high-performance alloys that need to be processed at high temperatures and under vacuum.
To foster the development of E-PBF essential understanding of the physics behind the complex and rapid phenomena occurring during the repeated heating, melting and solidification cycles of E-PBF is necessary.
Synchrotron X-ray characterization techniques (imaging, diffraction and small-angle X-ray scattering) offer real-time and in-situ observations with high spatial and temporal resolution, and have led to profound insights on solidification and microstructure evolution, as well as melt pool- and powder dynamics during the L-PBF process.
E-PBF has not yet been studied in such experiments, probably due to the high equipment demands compared to L-PBF. Although L-PBF and E-PBF are conceptually similar, there are significant differences between those, mainly related to the nature of the energy sources, the process steps and the different processing environment, thus, knowledge by synchrotron studies on L-PBF are not transferable to E-PBF.
In this work, we are developing of an environment that facilitates in-situ synchrotron X-ray measurements during E-PBF and thus enables studies of electron beam-matter interactions under realistic E-PBF processing conditions.
The design is based on an industrial E-PBF system, Freemelt ONE, but includes a custom-built process chamber optimized for synchrotron experiments. We present the design considerations, the setup details, its implementation at three beamlines at the synchrotron radiation source PETRA III, at DESY, and the measurement possibilities it provides.

High throughput printability screening of AlMgSi alloys for AM

Oral Presentation

Freddy Leijon*, Svein Skjervold
Hydro Extruded Solutions AB. Johan Moverare, Department of Management and Engineering (IEI), Linköping University

The AlMgSi (6xxx) alloys are the most extensively used aluminium grades, with the main advantage in their good balance of strength to corrosion resistance. Unfortunately, in powder bed fusion (PBF) additive manufacturing (AM) most 6xxx series compositions are not printable due to problem with hot cracking. Therefore, the composition space of know printable AlSiMg alloys is currently very limited. At the low alloyed end, with composition in the range of 6060, printing is possible and in the other end, at high Si levels and moderate Mg levels, AlSi10Mg is printable. In addition, adding grain refining elements like Ti, Zr and Sc can also extend the printable composition space.

From a recyclability point of view, a printable AlMgSi alloy is highly desired, as it would have a high compositional compatibility with today's already existing scrap loops. However, a need for high amounts of grain refining elements would lower the compositional compatibility, making the materials less valuable for recycling.

In this work hot cracking is mapped out over the composition space Mg 0-10, Si 0-4 wt%, with a high throughput method. The method is based on the creation of a two-dimensional compositional gradient using co-sputtering and laser re-melting to mimic the microstructure of laser PBF. The crack response over the compositional space could be divided into 3 distinct zones, where high and low alloy additions being absent of hot cracks and mid alloyed being non-printable due to hot cracks. The low alloyed printable zone could be described with Si+Mg<0.5wt% whereas the high printable zone was present for Si+2/3Mg>4wt%. The experimental result from this study agreed well with modeling work and the reported printability for the few individual compositions available in the literature.

Acoustic Data from Laser Powder Bed Fusion Processes

Oral Presentation

Ivan Zhirnov* [1], Dean-Paul Kouprianoff [2], Mikael Åsberg [1], Pavel Krakhmalev [1]

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Process monitoring in laser powder bed fusion is an essential step towards the quality and repeatability of the build parts. Hundreds of research show the efficiency of using different methods and sensors type. Due to the high complexity and duration of the process, an enormous amount of monitoring data (0.5 Tb data per build) is produced as an output of the system. Different machine learning techniques are widely developed and applied to manage the data, find correlations in multiply features from monitoring system signals, predict desirable properties of the final part, and aim to in-line control the build process. We believe that to make any machine learning algorithm in line with the LBPF process for decision-making, any data from the monitoring system should be in compact representation. In this research, we equipped a commercial LBPF machine with an acoustic monitoring system based on a microphone and accelerometer. Raw data from different melting processes were acquired, and only acoustic features were used for build quality prediction. Current research aims to create a diversified database that will be a key for LPBF digitalization and control, suitable for real-time control of the process, part quality optimization and, more importantly, for helping with decision-making algorithms.

Experimental design strategies for improving productivity of 316L stainless steel produced by laser-based powder bed fusion

Poster Presentation

Rasmus Gunnerek*, Dr. Zhuoer Chen, Prof. Eduard Hryha
Chalmers Unversity of Technology - Centre for Additive Manufacture Metal (CAM2)

One of the main drawbacks of the laser-based powder bed fusion (LB-PBF) process is the high production costs associated with the long production time. To speed up the process, one can increase the layer thickness, the laser scan speed and the hatch distance, so that number of layers to be processed or the time required for processing each layer is reduced. Meanwhile the higher production rate comes at the cost of part qualities, such as rougher surfaces and porous parts. This work aims to develop LB-PBF process recipes with higher productivities than the state of the art and predictable quality, namely relative density. A response surface design approach was used to correlate the relative density to the processing parameters using modern statistical tools. The work investigates the influence of 3 factor increase of hatch distance from 90 µm to 270 µm on pore characteristics of as-built 316L samples at 20, 40, 60 and 80 µm layer thicknesses. Metallographic characterizations of etched sample cross-sections reveal the importance of overlapping between neighboring scan tracks on the sizes, shapes, and distributions of the pores. Based on this, a parameter was introduced as the ratio of the melt pool width to hatch distance (W/h). At small W/h ratios lack of fusion defects were found to be interconnected across deposition layers and aligned with the build direction. Within the investigated window of process parameters, regression analysis shows that the hatch distance has the greatest effect on the porosity measured in the specimens. A larger laser power allows the use of large scan speeds and hatch distances while maintaining relatively high density.

Surface Roughness Considerations in Design for Additive Manufacturing

Poster Presentation

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[1] Luleå University of Technology, Sweden,
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The Additive Manufacturing (AM) process Laser Powder Bed Fusion (LPBF) has enabled the manufacture of intricate metallic component designs with reduced weight, reduced part numbers and quicker production times. This makes it attractive for manufacturing of complex metallic parts in the space industry. The inherent surface roughness of LPBF could impede part performance, especially from a structural perspective. Costly and or time-consuming post-processing rough surface or support structure removal is an option, but in cases such as enclosed consolidated parts it can be impossible. Engineers must therefore understand the influence of surface roughness on part performance and how to consider it during initial Design for AM (DfAM). Today there is an apparent lack of DfAM guidance available for engineers wanting to utilise AM without compromising on performance due to surface roughness.

A systematic literature review of research related to LPBF surface roughness and how research is trending over a one-year period is presented, identifying current and future research on how surface roughness should be considered during DfAM. Also, a proposed DfAM method using AM Design Artefacts is studied in practice to investigate the relationship between design, surface roughness and fatigue performance. The results highlight the importance of a systematic approach to resolving uncertainties during the design process.

Digitalization- a critical issue for enabling DfAM

Poster Presentation

Tina Hajali*
Chalmers University of Technology, Sweden

Additive Manufacturing (AM) is undergoing intense development, where advancements are made on materials, manufacturing processes, and how to design for additive manufacturing, and more. It is well known that AM relies on tight process control – that is enabled by sensors and control activities producing a huge amount of data in form of machine data, image and video data, test and measurements, and so forth, frequently tied to concepts such as “Digital Threads” and “Digital Twins”. A central question remains: How can engineers and designers make use of the vast amount of data becoming available, already in the design phase?
An initial combined use case and literature study in the DIDAM research project has been conducted that revealed although digital aspects are frequently mentioned, there are outstanding issues such as the format incompatibility that hinder the effective flow of information in industrial processes, and the difficulty of utilizing data from manufacturing for new designs. There is a large potential to make use of e.g., Machine learning to assist developers, yet few reports have been found that explains how this can be done. The poster presentation will raise critical questions that will be investigated further in the research project.

Industrialisation of AM - Identification of impacting factors

Poster Presentation

Adam Mallalieu*, Tina Hajali, Ola Isaksson, Massimo Panarotto, Lars Almefelt
Chalmers University of Technology, Sweden

Additive Manufacturing (AM) is a relatively new manufacturing approach that is expected to have a significant impact on manufacturing in industry. In the project DIDAM, we investigate how to industrialize AM – focusing on the digital aspects. Industrial partners have provided use cases, where different aspects of AM are being investigated. Several critical aspects have been identified where industrialization rely on an effective digital infrastructure comprising the value chain. This poster addresses the findings from a combined use case analysis and literature study, looking into identified industrialization issues for AM. More specifically, how digital aspects are treated in the methods and tools proposed in research literature are studied. One main issue identified was that most reports treat digital aspects to a low extent and that most tools were commonly evaluated in a research-based context only. This highlights the need to obtain a better understanding of the industrial context and how it affects the implementation of developed AM methods and tools. An observed example in industry is that that the current design practices are seemingly insufficient to design for AM. A list of observed problems from literature and use cases will be highlighted and presented for discussion, including how they can be addressed.

Influence of post-heat treatment and cell structures on the fatigue behaviour of LPBF stainless steel 316L

Poster Presentation

Luqing Cui, Ru Lin Peng, **Johan Moverare***

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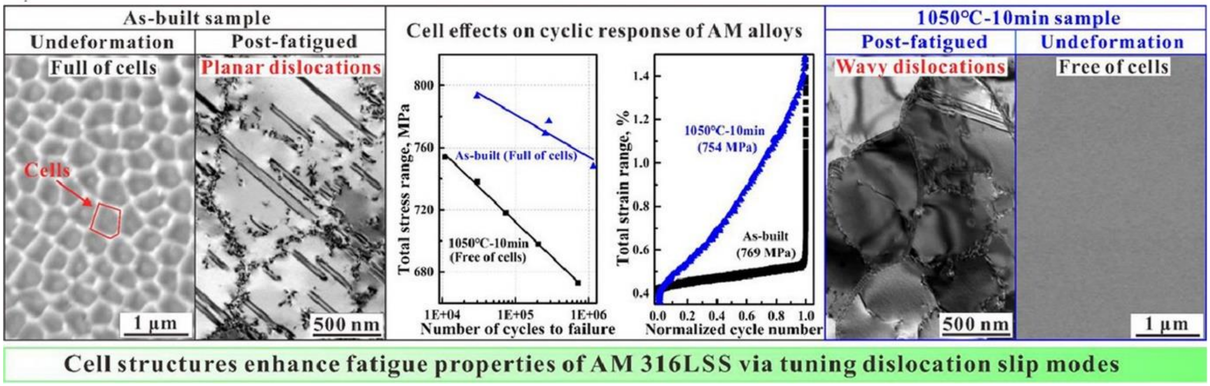
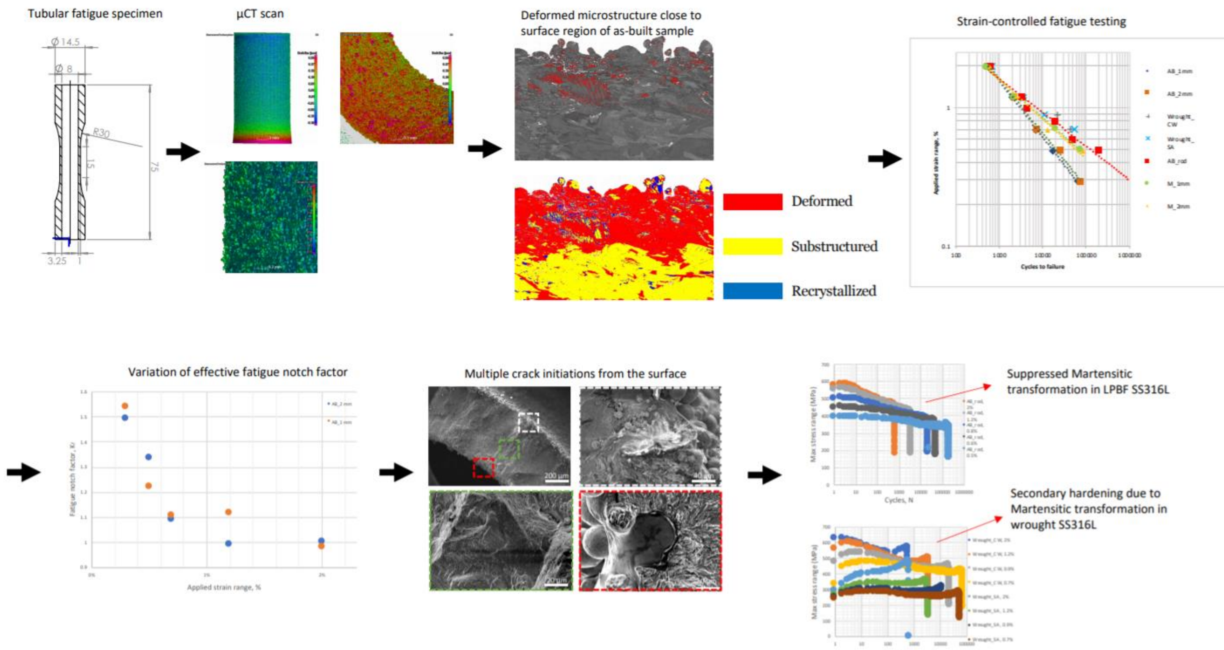


Due to the rapid cooling during laser powder bed fusion (LPBF), a unique cell structure is formed within the microstructure of the material. In this study, LPBF of the stainless steel 316L with different concentrations of cell structures are compared with respect to the fatigue response. In the first stage, different heat treatments were applied to reveal the thermal stability of the cell structure in LPBF 316L. In the second stage, the fatigue response is compared for samples with different heat treatments, where the heat treatments were carefully selected to produce samples with different degree of cell structure, while having all other microstructure characteristics roughly the same. Compared with the fully annealed samples, the fatigue process of the as-built samples only consists of the steady and overload stages, without an initial softening stage. Moreover, the as-built sample possesses higher cyclic strength, lower cyclic softening rate, and longer fatigue life. For all samples, microscopic analyses show no difference in grain orientation, dimension and shape. However, the distinct microstructure evolution investigated by TEM sheds light on understanding of the fatigue behaviors. In the deformed as-built samples, the dominate dislocation configurations are planar dislocation structures, stacking faults and deformation twins, promoted by the cell structure, leading to a uniform strain accumulation. On the contrary, in the deformed fully annealed sample (1050°C - 10 min), dislocations arrange themselves from a random distribution state into a well-defined wavy dislocation vein-like substructure, causing strain localisation. From this study it can be concluded that the fatigue performance of LPBF 316LSS was significantly enhanced by the cell structures via the change in dislocation slip modes.

Low cycle fatigue of LPBF thin-walled stainless steel 316L

Poster Presentation

Cheng-Han Yu, Ru Lin Peng, **Johan Moverare***
*Division of engineering materials, Linköping University



The process of laser powder bed fusion leads to characteristic microstructure of the as-built component, such as high surface roughness, cell structure and high surface residual stress. To examine the microstructural effects on the low cycle fatigue properties when the printed component is close to the dimensional limitation, tubular fatigue specimens with different wall thicknesses, 1mm and 2mm, were tested at room temperature. The advantage of using tubular specimens is to avoid possible buckling when the fully revered fatigue test is carried out. The comprehensive effects of surface roughness and heterogeneous microstructure at different applied strain range are quantified by estimating fatigue notch factor, Kf, which the influence becomes severe when approaching lower applied strain range. Furthermore, the same fatigue tests have also been applied to a reference group of wrought stainless steel 316L, and a suppressed martensitic phase transformation is observed in the additively manufactured specimens.

Process development for Electron Beam Melting of stainless steels

Poster Presentation

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Stainless steels are today the standard selection of material for many demanding applications in the engineering world. The introduction of Additive Manufacturing (AM) has opened up new possibilities of processing a powder feedstock into complex near net shape objects. The Powder bed fusion (PBF) method Electron Beam Melting (EBM) has the advantage of a highly adjustable process taking place in a vacuum environment, yielding material properties adaptable to the application at hand. EBM process parameters such as build temperature, beam current, beam deflection rate and beam focus are, among others, grouped into process parameter sets referred to as themes. The relationship between process parameters themselves and their influence on resulting material properties are complex. The development of a proper theme is therefore paramount to achieve the excellent material properties commonly seen in EBM-processed materials. By manufacturing large quantities of small samples, each assigned an individual theme, efficient evaluation of a wide array of themes is possible. Samples are thereafter investigated for undesired process-induced porosity so that a process window for obtaining solid, non-swelling, specimens is obtained. Mechanical properties for promising candidates are evaluated by tensile testing. Further investigation includes characterization of microstructural features and elemental composition utilizing an Electron dispersive X-ray spectroscopy equipped scanning electron microscope. In the scope of this work lies the development of EBM themes for the common austenitic 316LN stainless steel (EN 1.4429 / UNS S31653) and Super Duplex stainless steel 2507 (EN 1.4410 / UNS 32750). The results show that 316LN is a good candidate for further industrial EBM applications. Preliminary results indicate that the adaptability of the EBM process makes processing of 2507 powder possible with good as-built properties and phase distribution.

Effect of electron beam parameters on reaction synthesis of aluminum metal matrix composites and upcoming E-PBF work at KTH

Poster Presentation

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In this work, Al 6061 metal matrix composites (MMCs) were created in situ in electron-beam freeform fabrication (EBF3) via exothermic reaction synthesis wire feedstocks that produce ceramic and intermetallic inoculant particulates. Three sets of electron beam parameters were used to produced single-bead wall builds using a focus-and-rastered (FR) or defocused (D) beam with high or low heat input (HQ and LQ, respectively). These different parameters are expected to affect the temperature gradients present during solidification, the solidification rate, and the heat input into the melt pool, which should subsequently affect the degree of reaction synthesis achieved, which will dictate the number of heterogeneous nucleation sites available during solidification and the heat released as a result of the exothermic reactions. The EBF3 builds were sectioned and imaged with LOM and EBSD, which revealed varying degrees of refinement and columnar-to-equiaxed transition for the three different beam parameter sets. The FRHQ parameters were found to produce the most refined grains, presumably by increasing the extent of reaction synthesis combined with faster cooling rates.

Thermal profiles and grain growth were also modeled using closed-form equations to more closely analyze the effects of each electron beam parameter set. The results from these calculations indicated that FRHQ formed between 1 and 2 vol.% of Zener-pinning particles, FRLQ formed slightly less than 1 vol.%, and DLQ formed little to no Zener-pinning particles. In addition to grain growth restriction by Zener pinning, the calculations also indicated that solute drag and the relatively fast cooling rates limiting the time at high temperatures also have a large impact on determining the final grain diameter.

From expertise gained through this work, research is ongoing at KTH to explore the tailorability of steel microstructures using the open source Freemelt ONE electron beam-powder bed fusion AM platform.

ROBODAM - ROBust Optimisation in Design for Additive Manufacturing

Poster Presentation

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Networks or lattices possess an important possibility to solve several issues in additive manufacturing (AM). It can give the opportunity to design light weight structures and can be integrated in optimized solutions to increase robustness to handle e.g. loads in directions that was not anticipated during the design stage. Lattices can also be integrated into components to additionally serve as a support structure during build so that there is no need for removal after the manufacturing stage. This may significantly reduce the cost for AM processing. An additional possibility is to use lattices is to integrate these structures in heat exchange solutions for increased heat transfer through increased surface areas. Knowledge on lattice structures, their properties function and how to use them in design optimization is however not fully present.

The ROBODAM project is focusing on the further development and validation of a fully integrated design optimization process where both the product performance and the producibility of the product is taken into account in the design stage. The project also will build knowledge on internal properties, primarily material properties, is affected by component geometry and build direction (given the materials and process parameters) in order to build a foundation for how to use this knowledge in the design optimization process for optimal product properties and producibility. This will be done with a focus on periodic surface lattices rather than strut based lattices.

Combinatorial sputtering for high throughput mapping of compostions suitable for AM of soft magnetic metallic glasses

Poster Presentation

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Metallic glasses have been shown to have high hardness and stability against corrosion, but also interesting magnetic properties. The lack of long-range atomic order result in low magnetic coercivity and high electrical resistivity. For soft magnetic materials, used in AC applications, this result in very low energy losses.

The Additive Manufacturing (AM) method Selective Laser Melting (SLM) has shown great promise as a way to synthesize metallic glasses. The materials are built layer-by-layer and applying and removing the heat supply with a laser is almost instant. Thus, compared to e.g. casting, a very small volume is heated at a time. This improves the quenching rate, which opens up new opportunities for the size of parts as well as possible compositions. To optimize the composition before developing a powder, needed for SLM, can save time and reduce the cost. In this study, an initial mapping is done using the high throughput method Combinatorial Sputtering of thin films, before scaling up to bulk. This creates thin films with constituent gradients, which gives a continuous series of compositions to evaluate. FeCoNbB-thin films were synthesized using the aforementioned method and their structures were analyzed using Grazing Incidence X-Ray Diffraction (GI-XRD) and X-Ray Reflectivity (XRR). Their magnetic properties were evaluated using a Magneto Optic Kerr Effect (MOKE) system and a Vibrating Sample Magnetometer (VSM). All measured compositions were x-ray amorphous with low coercivities of around 160 A/m. The next step is to make samples using the rapid cooling method Splat Quenching for the most promising compositions, which would be more similar to the ones made with SLM. Then the powder development for SLM will be well informed before the search for the right printing parameters begins.

The influence of graphene on the microstructure and mechanical properties of 3D printed 316L stainless steel

Poster Presentation

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Graphene-metal composites are of high interest in additive manufacturing due to the possibility of both enhancing the processability of the powders and the properties of the printed parts. Initial studies of mechanical properties in 316L stainless steel printed with different graphene-like additives have been promising, but further understanding is needed regarding the distribution, effect on microstructure and reactions of the graphene-derivatives during processing in laser powder bed fusion. In our study, we have shown that coating 316L stainless steel powder with functionalized graphene improved densification (>99.9%) compared to reference when processed with laser powder bed fusion, using a laser power of 95W and scanning speeds of 475-575 mm/s. The yield strength and ultimate tensile strength could be increased by up to 11.8% and 9.8% respectively compared to reference. Larger increase was seen for tensile samples built horizontally compared to vertically and for higher functionalized graphene content. A stronger <011> crystallographic texture along the build direction could also be observed for the functionalized graphene containing samples. SEM and EDS analysis of the fracture surfaces indicates the survival of the functionalized graphene after the printing process. Future work will, among other things, include investigating if texture or preferential orientation of the functionalized graphene could be the cause for the varying strengthening effect seen for differently oriented tensile samples during manufacturing.

Local microstructural tailoring of the Z-direction in Electron Beam Melting

Poster Presentation

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Electron beam melting (EBM) is one of the leading Powder Bed Fusion (PBF) methods for the additive manufacturing (AM) of metals. In the process, the EBM system uses a set of parameters grouped in so-called themes. Although EBM offers great control over the manufacturing process, the potential of the beam parameters is not fully exploited in the available themes. Parameters such as beam intensity and speed will greatly influence melt pool size, grain growth, solidification rates or even allow for selective evaporation of some alloying elements. By manipulating the build files and melting themes, it is possible to locally steer the solidification process, and consequently tailor the microstructure, which has been referred to in the literature as 4D printing or microstructural engineering. This approach enables not only to combine the complex geometries possible with AM, but also to control the material properties in specific regions of the build. EBM has previously been explored to allow microstructural changes in the XY-directions. One challenge with the application of this practice in the Z-direction is that every layer will be re-melted and affected by any heat from the layers around it. The aim with this work is to gain a better understanding of how independent changes of parameters can influence the microstructure and layer surface. This is evaluated by analyzing melted tracks on solid metal plates. The work is complemented by microstructural characterization in Scanning Electron Microscopy as well as Energy Dispersive X-ray.

In-situ detection of redeposited spatter and its influence on the formation of internal flaws in laser powder bed fusion

Poster Presentation

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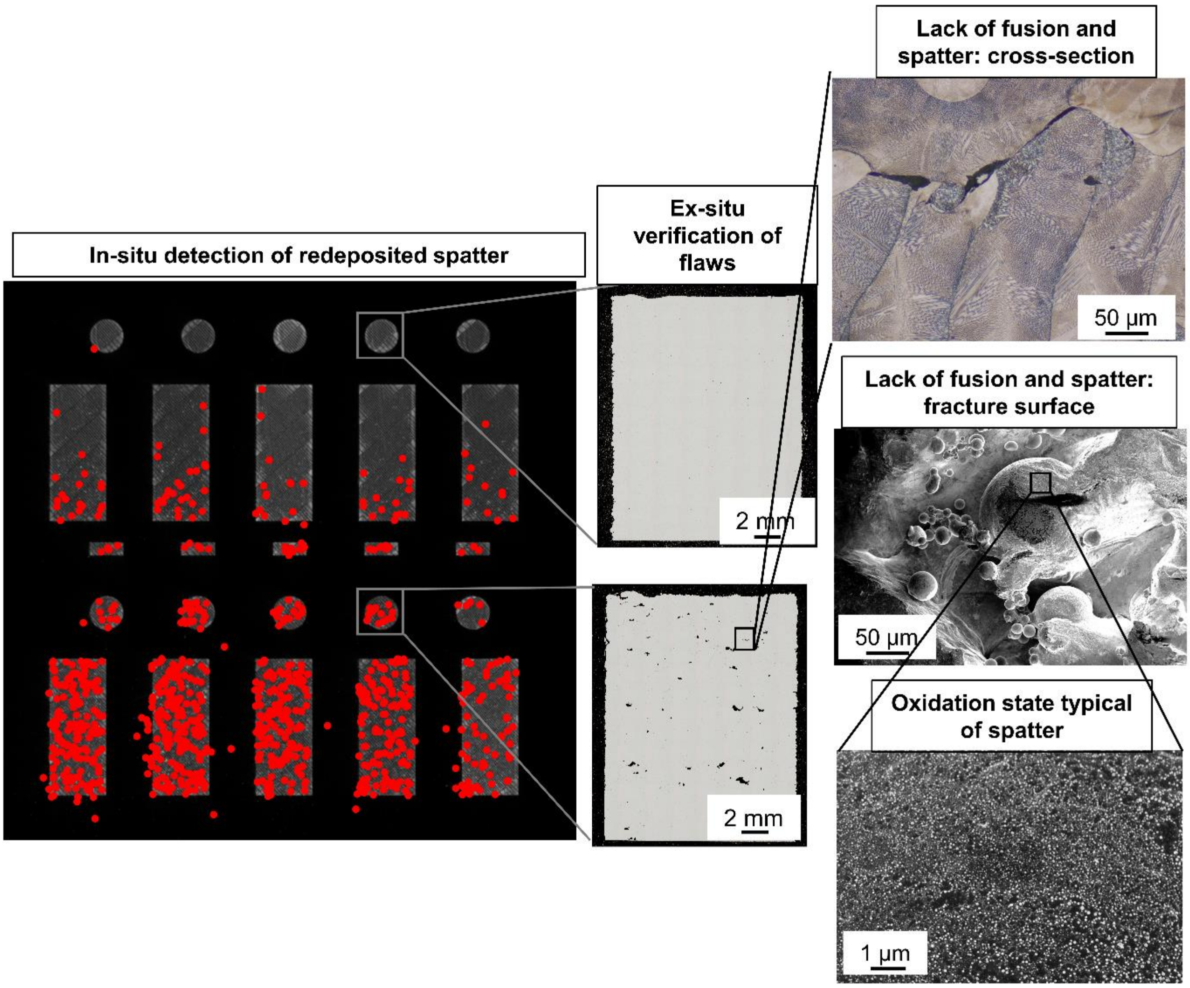

The pervasive adoption of laser powder bed fusion (LPBF) as an industrial manufacturing technique relies on the improvement of its repeatability, currently limited by the stochastic formation of flaws. Considering that large flaws can form randomly and despite the optimization of process parameters, an in-situ monitoring technique suitable for detecting deviations that originate these critical flaws is paramount. The redeposition of spatters on the build area has previously been identified as one of the factors responsible for the rise of internal flaws, but so far limited are the efforts towards their detection. This study aims to detect spatter redeposits via in-situ monitoring and to couple the detections to lack of fusion. For that, long-exposure near-infrared in-situ monitoring associated with image analysis is employed to determine the exact locations and quantify the incidence of spatter redeposits across three full builds performed at varying layer thicknesses. The existence and distribution of internal flaws is verified ex-situ by means of ultrasonic inspection and metallography. The formation of internal flaws is attributed to spatter redeposits after detailed characterization of size, particle and surface morphology of spatter and identification of particles with identical characteristics on the fracture surface in the adjacencies of lack of fusion. It is found that spatters preferentially redeposit on the adjacencies of the gas outlet, but that the affected portion of the build area and the prevalence of detections is heavily dependent on the powder layer thickness employed in the manufacturing process. The monitoring system setup preferentially acquires signal from spatters redeposited on print regions, making it particularly suitable for flaw detection.