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APPLICATIONS / 0

On the additive processing of a premium tool steel using high temperature systems: An holistic discussion on challenges and potentials

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The process-inherent advantages of Laser Powder Bed Fusion (L-PBF) have been exploited for many different applications nowadays, including the production of highly stressed inserts for the Al die-casting industry. However, similar to conventional production routes, performance and lifetime of AM-produced tools are still significantly determined by the specific material properties. Here, high-performance tool steels as the BÖHLER W360 AMPO places highest demands with tight specifications on the L-PBF process in order to exploit its full potential. Against this background, extensive developments have been carried out in order to fully understand the specific process and material interactions for the BÖHLER W360 AMPO, processed on advanced L-PBF Systems. Therefore, this study provides an overview about extensive characterizations of the microstructure, process-induced defects and the obtained mechanical properties. Furthermore, it is demonstrated why this challenging production route is still worthwhile from a holistic point of view and which possible advantages can be derived for further applications.

ADDITIVE DESIGN / 1

On Fatigue Analyses of Additive Manufacturing Parts: Review of Hybrid Techniques

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Different aspects of quality assessments for Additive Manufacturing (AM) parts are founded on complicated phenomena governed by intrinsic multi-physical and multi-phase interactions. To investigate the dynamic and fatigue performances of AM parts, variety of techniques including new hybrid physical-data driven scheme have been investigated. Hybrid modelling is one of the new trends in analyses and design optimization of AM parts where data modelling techniques have increasingly been combined with physical and analytical modelling for dynamic and fatigue assessments. An effective use of appropriate modelling schemes for fatigue analyses of AM parts and their agility of dealing with sophisticated effects of the manufacturing processes (e.g., defects, pores…) on service-life of products would briefly be reviewed herein. With the introduction of hybrid physical-data driven modelling techniques for the new AM process technologies and digitization drive, the need for integration of smart data-driven and physical-based models has willingly raised in the current research work. Different hybrid and data-driven schemes which include data mining, data handling, data processing and data modelling have rigorously been employed by researchers and engineers for dynamic and fatigue life simulation of AM parts at industrial scale. Furthermore, attempts have been made to setup full integrated data-bases where the available measured\mined\simulated data which are based on material characteristics and process conditions can semantically be gathered within single data depository. In the research work herein, some aspects of hybrid fatigue life assessment scheme for AM parts have been reviewed and analytical and computational benefits are scrutinized. Additionally, the employment of an efficient artificial Intelligent (AI) and Machine Learning (ML) schemes for industrial AM parts are tersely presented.

AM PROCESS and QUALITY CONTROL / 2

Exploring the Detection Limits of Powder Bed Defects Using a Structured Light Monitoring System For Powder Bed Fusion Additive Manufacturing

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abstract in summary section

AM PROCESS and QUALITY CONTROL / 3

Development of a novel in- situ alloying 3D printing procedure exemplified on the permanent magnetic Fe-Cr-Co alloy system

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In recent years, the method of additive manufacturing has become more and more important in the production of magnetic materials due to higher demands for miniaturization and complex- shaped magnet parts. With the method of Laser beam- powder bed fusion (LB-PBF), an in- situ alloying process for the additive manufacturing of the Fe-Cr-Co system has been developed. With this novel method that has been extensively studied in this work, the production of complex alloys with a composition accustomed to each specific case of application can be achieved directly in the printing chamber by the use of elemental powders or simpler commercial alloy powders as base materials.
First, the influence of different printing parameter on the homogeneity of the element distribution in the as- printed samples has been examined by EBSD measurements coupled with EDS. The homogeneity of element distribution in in- situ alloyed samples is not only of crucial importance for the magnetic properties in this material, but also for materials properties of in- situ alloyed materials in general. Obtaining a homogeneous distribution of elements during the in- situ alloying process without the need for a subsequent heat treatment for homogenization can be of economic benefit for the producer. Therefore, the effectiveness of different methods to increase the homogeneity from parameter variation and variation of particle size distribution has been examined.
With this information in mind, the influence of printing conditions and the elemental homogeneity on the microstructure and magnetic properties of the alloy system has been studied by different methods like SEM/ EBSD, TEM, magnetic characterization and dilatometry.

POWDER FOR MAM / 4

Intelligent powder production: Data-driven optimization of productivity

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A powder atomization plant for the production of high-quality metal powder for Additive Manufacturing (AM) was developed at SMS group. Low cost and simultaneously highest quality powders are key enablers for AM on its way to the next revolution in manufacturing. SMS strives for highest availability, productivity and yield of the powder atomization process through implementation of data-driven analysis of the process.
Due to the activities in the Additive Manufacturing Competence Center at SMS in Mönchengladbach, the powder production process become constantly optimized economically and technically by the aggregated knowledge and data at the pilot plant.
The powder production plant is highly digitalized and generates massive cloud-based production data. Countless sensors in the plant ensure the automated data collection during production. Material flows, pressures, temperatures and positions are recorded in the database. Massive initial data has been collected here over the last two years. SMS is working on the data evaluation and the implementation of Artificial Intelligence. Goals like a self-optimizing process, predictive manufacturing and even predictive maintenance can be realized and guarantees the costumer to be successful.

AM PROCESS and QUALITY CONTROL / 5

Correlative microstructure investigations of additive manufactured parts

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Complex metallic structures additively manufactured via laser powder bed fusion (L-PBF) is an already established technique in this rapidly growing industry branch. However, the development of alloys for field-specific applications and the quality and functionality of the final parts strongly depends on the micro- and nanostructure morphology, crystallography and chemical composition.

Within this paper correlative microscopy studies performed on 3D-printed parts of Fe- and Ti- alloys are presented [1-4]. Scanning and transmission electron microscopy (SEM and S/TEM) coupled with analytical characterization methods were used for advanced microstructural analysis of the as-built and heat-treated parts. Evolution of the microstructure during the ex-situ heat-treatment was first studied in detail in order to better comprehend the mechanical properties of the printed parts.

Furthermore, in-situ heating measurements at high spatial resolution provided information regarding the evolution of nanometric amorphous/crystalline phases and coarsening/shrinking of grains,

diffusion of alloying elements and nucleation and evolution of secondary phases at different temperatures [5].

This work received financial support by the Austrian Science Fund (FFG): SP2018-003-006 (Microstructure of 3D printed metallic parts) and from the European Union's Horizon 2020 research and innovation program under grant agreement No 823717 – ESTEEM3.

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AM PROCESS and QUALITY CONTROL / 6

Multiscale Microstructural Investigation of 17-4 PH Stainless Steel Produced by Laser Powder Bed Fusion

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Additive manufacturing (AM) generates complex multi-scale microstructures in metallic components, differing from conventional microstructures in terms of grain structure, cell substructure, elemental distribution, and residual stress. It is therefore important to analyse AM microstructures across multiple length scales using correlative microscopy techniques to establish comprehensive understanding of the microstructural evolution. This will unlock a greater level of microstructure and property control for future applications of AM.

We investigate 17-4 precipitate hardening stainless steel, a high-strength multi-purpose alloy with applications in the aerospace and petrochemical industries. Samples were fabricated by laser powder bed fusion using a variety of scanning patterns and differing laser powers. We utilise scanning electron microscopy, electron backscattered diffraction, neutron scattering analysis, electron probe microanalysis, and atom probe tomography to characterize the microstructure across different length scales. Results show clear variation in sample texture, residual stress, phase fraction and distribution, and compositional variation as a function of the processing parameters. The main phase of the as-printed microstructure is δ-ferrite with a low volume fraction of austenite, which is mainly observed at melt pool boundaries. The total fraction of austenite increases as the time between adjacent passes of the laser decreases. In the as-printed state, samples are shown to be highly stressed, suggesting

heat treatments must be applied before any practical implementation in engineering applications. Higher laser power leads to an increase in ferrite grain size and intensity of <100> texture along the build direction due to the enhanced effect of epitaxial growth.

AM PROCESS and QUALITY CONTROL / 7

Residual stress quantification for additively manufactured aluminium samples via laser-powder bed fusion

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Metal additive manufacturing is gradually being integrated into industrial production lines due to its unique advantages such as design freedom, low raw material wastage and short design-to-market lead time. Despite the many benefits, one huge problem is the property inconsistency among the manufactured products. This could happen between products from different fabrication batches, and sometimes even different parts within the same build. Currently, there is still no clear understanding on the effect of fabrication conditions towards residual stress accumulation and consequently the mechanical performance. To a large extent, the difficulty lies in the accurate quantification of residual stress content with respect to the matching microstructural features. Conventional residual-stress measurement techniques such as hole-drilling and x-ray diffraction could only provide a volume-based stress determination without microstructural information. In the current study, we employed cross-correlation electron backscatter diffraction (CC-EBSD) and FIB-DIC ring-core milling to unambiguously quantify the residual stress content at individual grain boundaries. Through this, the relationships among the fabrication conditions, the residual stress content and the mechanical properties could then be established. It will guide future AM users for fabrication condition selection and the explanation for certain mechanical behavior of AM-built components.

ADDITIVE DESIGN / 8

Topology optimized unit cells for laser powder bed fusion

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The rise of additive manufacturing has enabled new degrees of freedom in terms of design and functionality. In this context, this contribution addresses the design and characterization of structural unit cells that are intended as building blocks of highly porous lattice structures with tailored properties. While typical lattice structures are often composed of gyroid or diamond lattices, this study presents stackable unit cells of different sizes created by a generative design approach to meet boundary conditions such as printability and homogeneous stress distributions under a given mechanical load.

Suitable laser powder bed fusion (LPBF) parameters were determined for AlSi10Mg to ensure high resolution and process reproducibility for all considered unit cells. Stacks of unit cells were integrated into tensile and pressure test specimens for which the mechanical performance of the cells was evaluated. Experimentally measured material properties, applied process parameters, and mechanical test results were employed for calibration and validation of finite element (FE) simulations of both the LPBF process as well as the subsequent mechanical characterization.

The obtained data therefore provides the basis to combine the different unit cells into tailored lattice structures and to numerically investigate the local variation of properties in the resulting structures.

APPLICATIONS / 9

Hochfest und korrosionsbeständig mittels AM – Neue Aluminiumwerkstoffe für den industriellen 3D-Druck, ein Beitrag zur ressourceneffizienten Fertigung

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Im Rahmen des Vortrages werden neu entwickelte Hochleistungswerkstoffe der AM Metals GmbH und Ihre Anwendungsfelder im Automobil vorgestellt. Dabei werden die spezifischen Beanspruchungen und Anforderungen anhand beispielhafter 3D Druck Applikationen veranschaulicht. Durch gezielte Legierungs- und Prozessentwicklung wurden Aluminiumwerkstoffe entwickelt, die sowohl das Festigkeitsniveau konventioneller Knetlegierungen (EN AW 7075) als auch vergleichbar gute Korrosionseigenschaften von Schmiedewerkstoffen (EN AW 6082), erreichen. Anhand von Mikrostrukturanalysen werden die Eigenschaften und Herausforderungen der Prozessentwicklung veranschaulicht. Fatigue und Kriecheigenmschaften werden im Vergleich zum Stand der Technik diskutiert.
Die fertiglegierten Pulver sind frei von keramischen Bestandteilen und können deshalb einfach im Umlauf wieder genutzt werden. In Verbindung mit der einfachen Rezyklierbarkeit leisten die neuen Werkstoffe einen Beitrag für ein positives LCA des Gesamtsystems.
Die AM-Metals GmbH ist ein Entwicklungspartner zur Applikations- und Prozessentwicklung im metallischen 3D Druck. Ausgehend von der konstruktiven Bauteiloptimierung, über die fertigungstechnische Realisierung auf Systemen des Anlagenherstellers EOS (Serie M), bis hin zur Qualitätssicherung, Wärmebehandlung, Oberflächenfinish und CNC Bearbeitung, können alle für den additiven Prozess notwendigen Fertigungsschritte hausintern abgedeckt werden.
Die AM Metals GmbH gehört zur Dr. H.J. Langer Gruppe.

POWDER FOR MAM / 10

Crack Mechanism Analysis of a Laser Powder Bed Fused Carbon-Free FeCoMo Alloy

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Laser powder bed fusion (LPBF) facilitates near-net-shape fabrication of geometrically complex tools. This leads to significantly reduced post-processing effort compared to conventional manufacturing, for example in the case of hobbing cutters. However, due to the high carbon equivalent of high-speed steels, cracking of the brittle carbon martensite is very likely during LPBF. In contrast, carbon-free maraging steels promise enhanced processability due to the formation of a soft martensite. Hardening of the latter is guaranteed by the precipitation of intermetallic phases. A novel maraging steel for cutting applications (Fe25Co15Mo (weight%)) has been developed in recent years. This alloy might therefore be a candidate for LPBF.

In the present work, the LPBF processability of this novel cutting alloy was investigated. Despite its low carbon content, severe cracking has been observed. The crack surface analysis revealed transcrystalline cleavage fracture. It is assumed, that silicon oxide inclusions on the crack surface are responsible for this brittle failure. Additionally, epitaxially elongated coarse grains were found, which may also contribute to cracking. An influence of brittle ordered FeCo domains, that are potentially formed during cooling in the LPBF process, could not be confirmed. Based on the obtained findings, solution approaches for the fabrication of crack-free parts are presented.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 11

Maximum overhang on WAAM parts without part manipulation and the effect on path planning

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A popular technique for creating medium to large scale metallic components is Wire Arc Additive Manufacturing (WAAM). This technique melts a metal wire by creating a short-circuit arc between the wire and a workpiece, this short-circuit arc pinches of drop by drop the melted material and is often manipulated by a 5-axis positioner or a robot, to allow non-planar material deposition. Compared to many other metal AM techniques, WAAM allows manufacturing of parts with large overhangs (up to 45 degrees). Without having to change parameter settings or taking into account gravitational forces.

This is especially useful in case the workpiece cannot be rotated and tilted to keep the deposition perpendicular to water level. Within this research walls are created with a thickness of 4 mm, starting at 90 degrees perpendicular to water level up to 45 degrees and different path programming strategies are investigated in order to stably deposit overhanging walls. Finally a case study with different overhangs is presented, here an adapted slicing strategy based on first results had to be adopted for creating a 90° bend. The bend has a cylindrical base which evolves to an ellipse.

For creating such overhang structures it is important to slice the part in segments. This allows to program overhang structures without losing layers on the outer radius of the curve. Another important parameter is the steepness of the surface wall. This is normally not implemented in CAM software for creating toolpaths.

Images of the results after using adapted slicing strategies

APPLICATIONS / 12

Microstructure and mechanical performance of Sandvik Osprey Inconel 625 produced via laser powder bed fusion

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Inconel 625 is a solid-solution strengthened alloy of great interest for the aerospace and oil and gas industries, due to its good mechanical and corrosion properties, besides microstructure stability up to 540 ℃, providing a great potential for the additive manufacturing segment. In this study, Sandvik Osprey Inconel 625 powder, atomized via vacuum induction melting inert gas atomization (VIGA), was printed via laser powder bed fusion process (L-PBF) and specimens were evaluated in terms of microstructure and mechanical performances. The VIGA process allows the production of powders with high circularity and limited satelliting, which positively contributed to achieve highly dense printed specimens. Solution annealing was done at different conditions in order to evaluate the best performances: 1048 ℃ followed by air cooling or water quenching, and a lower annealing temperature, 1000 ℃ followed by air cooling aimed to minimize grain growth. Microstructural analysis was carried out for all variants, including as-built condition in order to observe potential cellular structure, segregations and the microstructure evolution for the different annealing routes. Mechanical testing, including tensile, impact and hardness measurements were performed at room temperature for all the considered variants. High temperature tensile testing at 540 ℃ was done after annealing at 1048 ℃ and air cooling to evaluate the potential for the Sandvik Osprey VIGA Inconel 625 powder to be used at these temperatures.

POWDER FOR MAM / 13

Solvent on Granules 3D-Printing of WC-12Co Cemented Carbide Parts

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Solvent on Granules 3D Printing (SG-3DP) is a sinter-based additive manufacturing technique allowing the net-shape processing of metal, ceramic and metal-ceramic parts. It consists of growing a green part layer-by-layer by selective solvent jetting on powder-polymer granule beds, which is followed by debinding and sintering. In this work, 3D printed WC-12Co green parts have been processed from granules based on presintered cemented carbide powder. Part consolidation has been performed by liquid phase sintering at different temperatures, followed by hot isostatic pressing. The influence of the processing variables on the microstructure and final properties is discussed. The highest hardness is obtained with the finer final microstructure of 1.16 µm WC grain size, after thermal debinding, sintering at 1420℃ and HIP at 1360℃ under 100 MPa Ar pressure. The parts are fully dense and exhibit microstructure, hardness and toughness comparable to the properties of commercial fine-grained WC-12Co.

POWDER FOR MAM / 14

Development of Al-Ni based alloys for Laser Powder Bed Fusion

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While Laser Powder Bed Fusion (L-PBF) has gained significant traction as the most widely used metal additive manufacturing technique both in industrial and scientific applications, the number of well-processable, high-strength aluminium alloys is still limited. This is mainly due to the high solidification cracking tendency of many commercial high-strength aluminium alloys.
Alloys based on the Al/Si eutectic such as AlSi10Mg or AlSi12 offer great resistance to hot cracking. However, due to their moderate mechanical properties, these alloys are not expected to meet the needs of demanding structural applications. In contrast, Al-Ni alloys based on the Al/Al3Ni eutectic exhibit a similarly low hot cracking susceptibility, but are characterized by higher temperature stability 1 and represent a promising starting point for alloy design.
In the present work, the feasibility of employing Ni as eutectic-forming element in aluminium alloys developed specifically for L-PBF is investigated. Al-Ni alloys are synthesized in situ from elemental powder mixtures using an optimised remelting scanning strategy which ensures high chemical homogeneity. In this way, a range of different compositions can be produced efficiently, eliminating the need for expensive pre-alloyed powders which is a major challenge in alloy development. In addition to binary Al-Ni alloys, ternary and quaternary alloys with additions of Zr and Cr are fabricated. The microstructure of as-built and heat-treated samples is characterised by a combination of experimental techniques including SEM, EBSD, and APT. Furthermore, the ageing response of the different alloys as monitored by the Vickers hardness is compared and rationalised on the basis of thermodynamics and precipitation kinetics.
1 C. Suwanpreecha et al., New generation of eutectic Al-Ni casting alloys for elevated temperature services, Mater. Sci. Eng. A. 709 2 (2018) 46-54.

POST-PROCESSING / 15

Evolution of microstructure and properties after heat treatment and HIP of E-PBF cold work tool steel

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Additive manufacturing (AM) of cold work tool steel is challenging due to the material's proneness to thermal cracks and defects. These issues can be reduced by the use of electron powder bed fusion (E-PBF) manufacturing which provides higher build chamber temperature, pre-heating of the build and slower cooling of the builds compared to laser powder bed fusion (L-PBF). Still, microstructure and properties of the as-build parts significantly differ from the conventional manucaftured material, so post treatment is required to achieve high levels of required characteristics. This research reveals the influence of heat treatment and heat treatment + HIP on defects, microstructure and properties of E-PBF high-alloy (Cr-Mo-V) tool steel. Focus is paid on changes in carbide type and morphology, analysis of prior austenite grain size, elimination of defects and morphology of martensite. A correlation between changes in microstructure and mechanical properties of heat-treated and HIPed E-PBF high-alloy (Cr-Mo-V) tool steel is discussed in a comparison to microstructure and properties of conventionally manufactured materials.

AM PROCESS and QUALITY CONTROL / 16

Cracking behavior of a Zr-blended aluminum 7075 alloy processed by laser-based powder bed fusion under argon and nitrogen and various argon-nitrogen mixtures

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This study aims to investigate the influence of different process gases on the processing of a Zr-blended aluminum 7075 alloy by laser-based powder bed fusion. Two common gases for this process, argon and nitrogen, are compared. The objective is to study the effect of the gases on crack formation in the bulk material with respect to the possible formation of nitrides. In order to assess this phenomenon, bars at different heights will be printed with an in-situ change of the process gas in steps from pure argon to pure nitrogen. During the post-process analyses, special focus will be placed on investigating the crack formation. The preliminary results on specimens from initial build jobs showed differences in the cracking behavior with a varying amount of nitrogen in the process gas. A higher amount of cracking was found in the specimens produced with pure nitrogen compared to the specimens fabricated under argon atmosphere. This may be due to less Zr dissolved into the aluminum matrix under nitrogen processing conditions. The higher amount of cracks might therefore be attributed to the creation of fewer Al3Zr-precipitates that are needed for grain refinement and crack mitigation in this aluminum 7075 alloy.

AM PROCESS and QUALITY CONTROL / 17

Investigation of microstructure and cracking prevention of M4 HSS processed by selective laser melting

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The processing of tool steels by selective laser melting (SLM) is an important additive manufacturing technology that faces a challenge when it comes to the production of high-speed steels. In this work, the successful production of the high-wear resistant M4 high-speed steel (HSS) with a Carbon content above 1.30 m% processed by selective laser melting is demonstrated. By systematic variation of the process parameters, crack-free and high-density M4 samples (>99.5% relative density) have been produced. The influence of SLM process parameters on the microstructure and defect appearance of the material is examined, although preheating temperatures of 500℃ have the strongest influence to prevent the HSS steel from cracking during the process. Besides the thorough microstructure characterization of martensite, austenite, and carbides, this work gives an outline of how the process parameters affect both microstructure and cracking behaviour of this SLM-produced material.

POWDER FOR MAM / 18

Further development and deployment of powder spreadability testing

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It is now widely accepted that there is an urgent need for a test to determine if a powder can be spread in to thin layers, as it must be for powder bed additive manufacturing. There is not yet any accepted or standardised test for this behaviour. Several techniques have been proposed in the last few years, most based on automated film applicators. A layer can be formed using similar settings to those in a 3D printer and then analysed using optical analysis or by measuring the mass of powder in the layer. The current work outlines recent progress in automated optical analysis of defects in the layer using directional lighting and the effects of dispensing strategy and roughness of the surface on which the powder is spread. A discrete element model has also been made and compared to experimental findings to benchmark the capability of the technique to replicate reality.

POST-PROCESSING / 19

Effect of post-processing thermal treatments on fatigue resistance of additively manufactured 18Ni300 maraging steel

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The microstructure of laser powder bed fusion (L-PBF) processed 18Ni300 differs from that of manufactured using conventional processing routes. The L-PBF steel, due to the non-equilibrium solidification, comprises a cellular/dendritic solidification structure with the presence of intercellular austenite as a result of heavy micro-segregation of alloying elements. On the other hand, the conventionally manufactured counterpart shows a fully martensitic microstructure in solution annealed condition. This difference appears to be insignificant in view of the static mechanical properties (e.g., tensile properties) after ageing heat treatment. Therefore, it is suggested that the L-PBF 18Ni300 can be directly aged from the as-built condition without a need for prior microstructural homogenization. However, the influence of the initial microstructure on the dynamic mechanical properties of the age hardened parts such as impact toughness, and fatigue resistance has not been systematically studied. In this work, the effect of homogenization and solution annealing treatment prior to ageing on mechanical properties and fatigue resistance of an 18Ni300 maraging steel is investigated. The results show an improvement of fatigue resistance by application of proper homogenization heat treatments.

POWDER FOR MAM / 20

Influence of powder recycling on the feedstock attributes and the final properties of SS316L components processed by L-PBF

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In Laser Powder Bed Fusion (LPBF), a significant amount of metallic powder is not melted by the laser beam. Costs and material yield strongly depend on the ability to reuse metal powder efficiently. However, some of the unfused powder is exposed to high temperatures during the manufacturing process in an imperfectly controlled atmosphere. Therefore, there is a need to study and understand powder degradation during the process and its direct effects on the printed parts. One batch of gas-atomized 316L stainless steel powder was used, recovered, sieved and reused to produce 12 successive LPBF prints without adding any virgin powder. Both recycled powders and elaborated parts were characterized throughout each iteration. Particles analysis was carried out using laser granulometry, scanning electron microscopy, flowmeter funnels, inert gas fusion, and X-ray diffraction. Solidified specimens features were investigated by means of optical microscopy, scanning electron microscopy, electron backscattered diffraction, microhardness and uniaxial tensile testing. Powders morphology, rheology, microstructure and oxygen content display slight changes with recycling, along with parts density and mechanical properties. The effects of processing conditions, especially the chamber oxygen content were also studied, and strongly influence the kinetics of degradation.

MODELLING & SIMULATION / 21

Simulation of microstructural evolution during additive manufacturing of Haynes 282

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Haynes 282 is a creep resistant nickel based superalloy with good weldability. Recently, additive manufacturing of nickel based superalloys are extensively researched for their potential applications in aerospace and power generation sectors. Additive manufacturing (AM) of Haynes 282 is relevant because of its excellent creep resistance and weldability. AM potentially allows us to optimize the local properties via controlled microstructure by adjusting the process parameters. The modelling and simulation tools can help in tuning the process parameters to obtain desired microstructure. The laser-powder interaction was modelled using finite volume method (FVM) implemented in OpenFOAM® software. The obtained temperature data served as input for further microstructural simulations. The dendritic growth during solidification was simulated using phase-field model implemented in Micress® software. The grain structure evolution during AM was simulated using kinetic Monte Carlo implemented in SPPARKS software. Langer-Schwartz theory implemented in TC-Prisma® software was used to predict the microstructural evolution during post-processing steps. The above mentioned tools along with experiments are integrated to predict the microstructure evolution during AM.

MODELLING & SIMULATION / 22

Computational design of high γ′ nickel-based superalloys for laser powder bed fusion

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Additive manufacturing makes it possible to produce highly complex components such as turbine blades with integrated cooling channels directly from a digital 3D CAD model. However, the material selection of nickel-base superalloys for the laser powder bed fusion (LPBF) process is limited to a few alloys that reveal a high printability, such as IN625 or IN718. These alloys, however, exhibit only moderate high-temperature and creep properties compared to nickel-base superalloys with higher γ′-content, such as CM247LC, that currently cannot be produced crack-free via LPBF.

Based on an industrially widely used but not yet printable reference alloy CM247LC, adjustments to the chemical composition (e.g., C, Hf, Ti, Al content) are made to improve processability with LPBF. High-throughput CALPHAD-based screening is applied to pre-select promising chemical compositions from a multidimensional alloy space with respect to specific target properties to accelerate alloy development significantly. In the following, the melt pool geometries, 3D temperature distributions, cooling rates, and thermal gradients during the LPBF process of selected alloy compositions are simulated with CFD-melt pool simulations. The melt pool simulation results are essential to simulate the solidification behavior and microstructure development of adapted AM nickel-base superalloys with high γ′-content by a phase-field approach in the following. Based on the computational alloy design approach, strategies for improving the processability of high γ′ nickel-base superalloys are discussed.

RECENT RESEARCH TOPICS / 23

Integration of optical fibers in parts resulting from additive metal fabrication processes

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During the last ten years, additive manufacturing by using power bed fusion technology has become a very reliable technology to produce complex metallic parts. Layer by layer manufacturing allows the integration of a fiber bragg grating inside the parts during the fabrication. The latter opens a lot of possibilities for structural health monitoring. It has a critical impact for the monitoring of the nuclear structure and nuclear waste management, and allows to assess the usability of the parts without taking any risk of outside aggression on the sensor such as corrosion or break during the transport. The methods used during our analysis were the following: i) a parametric study of the laser powder bed fusion processing conditions for 316L stainless steel parts; ii) a study for the adaption of the optical fiber (thermal resistance, impact of the laser, diameter); iii) the optimisation of the bonding between the optical fiber and the metallic component. Fibers have been successfully embedded without coating inside the parts, which demonstrates the feasibility to insert components into the additive manufacturing process. The structural and the mechanical behaviours of the parts remain

the same after the insertion of the fiber.. As a conclusion our results show the possibility to embedded a fiber without coating and it could become a game changer in structural health monitoring.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 24

Study on the selective laser melting of aluminum matrix composites reinforced with AlN particles

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Particle reinforced aluminum matrix composites (PRAMCs) have a great application potential among the aerospace and automotive industries due to their high strength-to-weight ratio. Ceramic particles such as Al2O3, SiC, TiC, etc. are mostly considered as reinforcement for PRAMCs. In comparison with the above-mentioned additives, AlN particles have superior thermal properties, high hardness, thermal expansion coefficient close to aluminum, and chemical stability in the interface. The purpose of the present study is to develop and optimize the selective laser melting (SLM) process of AlN/AlSi10Mg PRAMCs. The relevance of the study is explained by the increasing demand for the manufacturing of complex geometrical shapes objects due to the improvement of computer-aided engineering (CAE).
AlSi10Mg powder with 10-63 um fraction was used as a base material because of reliable printing parameters and a relatively broad technological window. Various compositions of AlN/AlSi10Mg were prepared and cubic samples were printed out. The porosity and mechanical properties of 3D printed objects are highly dependent on the distribution of AlN particles in the melt pool. Suitable combinations of main parameters involving laser power, scanning speed, layer thickness, and hatch spacing were found. Mechanical tests of printed PRAMCs were carried out and compared with PRAMCs manufactured by other technologies and 3D printed AlSi10Mg without additives.

AM PROCESS and QUALITY CONTROL / 25

The influence of laser scanning strategies on the crystallographic texture evolution and mechanical properties of LB-PBF 316L

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Additively manufactured (AM) samples exhibit a pronounced texture formation along the build direction (i.e. along z-axis) that predefines an anisotropic mechanical behavior of the final bulk materials. Consequently, different mechanical properties can be measured in tensile tests along and perpendicular to the build direction, depending on the initial orientation of the sample in the powder bed. In this study, we investigated the influence of three different hatching strategies on the texture formation of stainless steel 316L. Therefore, six rod-like samples (Ø 5mm, 40 mm height) were synthesized on an EOS M290 machine using two different parameter sets. The samples were scanned in transmission geometry at the high-energy material science (HEMS) beamline P07B at the storage ring PETRAIII at DESY in Hamburg using an energy of 87.1 keV. The three applied scanning strategies led to the formation of (i) a <001> fiber texture, (ii) a biaxial texture and (iii) a mixture of <100> and <110> fiber textures. Moreover, micro-tensile samples (with a diameter of ˜500 µm) were fabricated and tested to assess the mechanical properties. Observed differences could be correlated with the different textures. The results indicate that the mechanical properties of AM bulk metals that can be effectively tailored by adjusting the crystallographic texture within the AM components.

AM PROCESS and QUALITY CONTROL / 26

ICME-based approach to correlate residual stress generation with micro-structural evolution and solidification cracking during laser powder bed fusion process

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Abstract:

Integrated computational materials engineering (ICME) approach has been pursued since about a decade to reduce the cycle time for the development of new engineered materials and products. During laser powder bed fusion (L-PBF) based additive manufacturing techniques residual stresses augmented by phase transformations and cracking during solidification or subsequent heat treatment process are seen as current challenges. A physically based approach taking the material properties and its phase evolution during the additive manufacturing process can offer insights to address these challenges. Due to rapid solidification and repeated heating and cooling cycle, selective laser melting (SLM) of IN-718 alloy presents challenges during powder layer deposition concerning the buildup of residual stress, micro-segregation of Nb, and undesired Laves phase formation in the as build state. Build up of residual stress during solidification when combining with undesired brittle phase may lead to hot cracking. In this work, Simufact Additive® software equipped with a thermo-mechanical model was used to predict residual stress generation during the laser powder bed fusion process. The Thermal cycle obtained from macro-scale simulations was used to simulate microstructure evolution using a multi phase-field model coupled with the CALPHAD database. The simulated microstructure was used to calculate the effective macro-scale material properties using the asymptotic homogenization technique implemented in Homat®. A simplified empirical cracking criterion that considers the strength of the material, solid fraction, residual stress, and temperature distribution in the melt pool is adapted here. An ICME based workflow is presented with suggestions for granular validation.

Keywords: Laser Powder Bed Fusion Process, Residual Stress, Solidification Cracking

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 27

Thermomechanical and thermochemical endurance of hot work tool steels and PVD-coatings for high pressure die casting

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- Strategies for the improvement of the overall service lifespan for high pressure die casting dies and the common failure mechanisms that lower this lifespan, like soldering and thermal fatigue behaviour with the correct combination of conventional and additive manufactured materials
- A comparison of conventional hot work tool steels, maraging steels and nickel-based alloys with their additive manufactured counterparts
- The benefit of additive manufactured steels for the overall service life span
- Their behaviour under heavy thermochemical and thermomechanical stress loads
- Effects of additional surface treatments, like nitriding and PVD-coatings, on the overall service lifetime of these steels

POST-PROCESSING / 28

Optimized HIP and Heat Treatment for Fatigue Strength of Additively Manufactured Ti6Al4V

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Critical components made of high-performance materials subjected to fatigue loads have extreme demands on qualification and production control. Additive Manufacturing is now an increasingly important technology for implementation of bionic lightweight designs.
Over recent years, a great deal of research work has been carried out on additively manufactured grade 5/23 titanium (Ti6Al4V) in safety-critical applications such as aerospace, medical or car racing. Lightweight designs bring about lower safety margins, which in turn create a need for high fatigue strength together with a robust production process resulting in a very low standard deviation of mechanical material properties.
Post-processing, mainly consisting of hot-isostatic pressing (HIP), heat treatment (HT) and surface finishing, is an integral part of a robust production process and should be ideally tailored to a particular alloy. This is especially interesting and rewarding in the case of such a widely-used and well-researched alloy as Ti6Al4V, taking the best out of both the novel microstructure of the AM process as well as of more established heat treatment methods known from forgings or castings.
High-pressure Heat Treatment (HPHT), developed by Quintus Technologies for combining traditional
HIP cycles with an integrated, subsequent inert gas quenching cycle is used with great advantage on
additively manufactured Ti6Al4V for maximizing the fatigue strength in a lean, fast and robust process.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 29

Process gas and its influence on additive manufactured AlSi10Mg

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EOS and Linde combined their respective expertise to jointly undertake research in the field of additive manufacturing and material-gas interaction. The aim of this study was to improve AISi10Mg properties according to customer needs. The influence caused by different impurities of the process gas on the generated material quality as well as the influence on the process itself were analyzed.
In this study the influence of residual oxygen and a special shielding gas mixture during the DMLS® process in relation to the material properties of AlSi10Mg were investigated. With higher oxygen levels the variance of the material properties can increase, as can powder quality and life-cycle due to oxidation.
Nevertheless, in terms of porosity only a minor change in the maximum defect size can be observed when the oxygen level is decreased. Results confirm a quite stable process behavior of AlSi10Mg when using EOS AlSi10Mg powder material, optimized process parameters and the EOS M290.
First analyses of the recorded OT-Monitoring data show a visible influence when using the argon/helium mixture. Special gases like these have a slightly higher price, but if the scrap rate can be reduced, a business case for this gas mixture could be possible.

In addition to the material and process results, there were interesting learnings in terms of the hardware used. To avoid a variation in the oxygen level during the DMLS® process, it is necessary to have a closed loop control to maintain the residual oxygen content within the process gas. The positioning of the oxygen sensors is important and thanks to this study, the optimal location close to the platform was ascertained.
EOS and Linde will continue to work closely together to develop a controllable shielding gas atmosphere for both existing and upcoming DMLS® systems like the EOS M290.

POST-PROCESSING / 30

Effect of cold rolling on the microstructure and the mechanical properties of 316L stainless steel parts produced by Laser Powder Bed Fusion

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Additive Manufacturing (AM) technologies provide new opportunities to enhance some piece-producing processes in the industry: AM offers the possibility to produce complex-shaped parts that could require multiple manufacturing stages. Moreover, microstructures from Laser Powder Bed Fusion (LPBF) can heavily differ from microstructures usually obtained through traditional processes, showing extremely fine cells caused by the rapid cooling.
In this work, several LPBF preforms were constructed along different directions in order to study the anisotropic properties inherited by the LPBF technology. Then, the as-built samples were cold rolled at different deformation rates. Two 316L powders that produce two different microstructures were used: one exhibiting columnar grains and the other quasi-equiaxed ones. Optical microscopy

(OM) and scanning electron microscopy along with electron backscatter analyses (SEM-EBSD) were used to determine the microstructural evolutions. Tensile testing was carried out to determine the mechanical properties.
The first results show that the LPBF 316L is ductile while being more resistant than the traditional wrought 316L. In addition, the orientation of the building direction (BD) compared to the rolling direction (RD) seems to have an influence on the material properties during cold rolling. Indeed, mechanical twins were observed when the BD is collinear to the RD while slip bands are present when the BD is orthogonal to the RD, even if one of the studied microstructure is almost isotropic with quasi-equiaxed grains and almost no texture.
The final goal of this study is to analyse the potentialities of integrating the LPBF technology in the conventional manufacturing processes. This integration would then simplify and enhance key parts production, especially in the nuclear industry.

POWDER FOR MAM / 31

A Novel Vacuum Inert Gas Atomization System enters the Market – Design, Experience and Outlook

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A continuous growth for high quality metal powders in Additive Manufacturing applications forced INTECO to develop a novel vacuum inert gas atomization system, as standard atomization equipment has not seen major developments or improvements to fulfill the demanding tasks from the industry. The new system is characterized by special features which are supposed to overcome disadvantages of common atomization systems, like low yield or limited reproducibility. A peculiar focus was put on the automation of all process steps, including the casting and atomization procedure. This is essential to eliminate undesired influences from operators which would end in a significant volatility of the powder´s properties. Additionally the plant is designed to achieve a quick and precise cleaning of all parts when changing the produced grades. The high pressure gas nozzle was developed to not only grant a high efficiency but also to manufacture powder particles with low amounts of satellites. Low tap-to-tap times are achieved by optimized and synchronized process steps like evacuation, melting, atomization, and powder handling. Latter is supported by a unique powder cooling for a quick availability of the produced powder for subsequent operations. With the help of an integrated production management tool called IMAS the complete production is logged and documented.
Results of the commissioning of two plants including production experience is presented. The practical knowledge lead to further aspects of possible improvements. An outlook is given towards ongoing and further developments.

RECENT RESEARCH TOPICS / 32

Metal Additive Manufacturing via Powder Layer Fusion Technology

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We present new insights into our patented powder layer fusion technology for the additive manufacturing of metal components. Conventional additive manufacturing (AM) systems based on the dominating powder bed fusion technology have made good progress in terms of productivity and build quality, however, the fundamental limitations of this technology such as high powder consumption, non-accessibility of the component during printing and the resulting process limitations cannot be overcome. Our new powder layer fusion technology enables additive manufacturing of metal components with minimal powder consumption, part accessibility during printing and the use of different energy sources to facilitate melting of the metal powder feedstock.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 33

Investigation of Cooling Rate and Microstructure with the Aim of Alloy Development using Extreme High Speed Laser Material Deposition (EHLA) exemplified by 316L

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As Additive Manufacturing (AM) technologies mature, the lack of tailored alloys becomes more and more of an obstacle for a widespread application for AM. Alloy development has historically been a costly process taking decades or centuries. In the case of AM, however, new improved alloys have to be developed much faster, calling for time- and resource-efficient alloy development methods. These methods have to fulfill two essential criteria: firstly, in situ alloy mixing must take place locally. Secondly, the cooling rates must be controllable in a wide range in order to match different AM processes ensuring matching microstructures and mechanical properties.

The newly developed Extreme High Speed Laser Material Deposition (EHLA) process meets these two criteria. However, the correlations between its numerous process parameters, resulting cooling rate and microstructure are not yet understood. In this paper, the influence of parameters such as laser power, process speed and powder mass flow on resulting cooling rate and microstructure of 316L is studied using metallographic methods and Scanning Electron Microscopy (SEM). Process parameters with a significant influence on cooling rate and microstructure will be determined, taking one of the first steps for alloy development guidelines for AM.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 34

Influence of Laser Metal Deposition Process Parameters on Geometric Accuracy and Residual Stresses of IN718 Thin-Walled Structures

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Laser Metal Deposition (LMD) is an established repair process for components such as thin-walled turbine blades. Repair of thin-walled structures encounters several challenges due to the limited heat transfer. If the narrow process window is not met, mechanical properties and geometric accuracy deteriorate. Because of the rising temperature during the LMD process, its parameters usually need to be adjusted with increasing build height. Currently, the development of repair processes for thin-walled structures is usually based on iteratively adjusting the process parameters. For a predictive process development, the fundamental influence of LMD process parameters on part deviation and the resulting mechanical properties must be understood. In this paper, the influence of build strategy and process parameters such as laser power and feed rate on geometric accuracy and resulting residual stresses is investigated. To approximate the heat transfer within thin-walled structures, material is deposited onto the edges of IN718 sheets. In situ thermography is used to study the temperature curve. Furthermore, geometric accuracy and residual stresses are measured post mortem.

POWDER FOR MAM / 35

Energy efficient production of spherical powders for DMLS Applications

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The provision of the metal raw material (due to a low product yield) and inert gas consumption are the main energy consumers in powder production for additive processes. In standard gas atomization processes, any effort to produce finer powder (to increase product yield) is achieved by increasing inert gas consumption.

In order to decrease the carbon footprint of additively manufactured parts, a new powder production process was established at Metalpine GmbH. With the inhouse developed combination of melting system, gas atomization nozzle and closed gas circuit, high product yields are achieved at a strong decrease of gas consumption. The resulting powders are spherical, satellite-free and pore-free.

First evaluations of the printed parts show that the mechanical properties of the printed parts are compareable to the ones printed with powders from long-time established powder production processes.

POWDER FOR MAM / 36

Zinc-Magnesium Alloys for Bioresorbable Medical Implants manufactured by Laser Powder Bed Fusion

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Bioresorbable materials for use in medical implants are attracting interest in current research projects. Recent studies show promising results for Zinc-Magnesium (ZnMgx) alloys as biodegradable materials due to the combination of degradation rate and high strength resulting from grain refinement due to magnesium addition. By using Additive Manufacturing (AM), complex scaffold-like structures and patient-specific implants can be realized. This work aims to clarify the effect of AM process parameters and magnesium content of binary ZnMgx alloys on the relative density and resulting mechanical properties. Furthermore, process monitoring and non-destructive testing will be explored for quality assurance.

For the experiments atomized pure Zn and pre-alloyed ZnMgx powder is used. The test specimens are manufactured on a modified Laser Powder Bed Fusion (LPBF) laboratory system with tailored shielding gas circulation. For each alloy, cuboid test specimens with different energy inputs are manufactured and evaluated regarding relative density. Next, one set of parameters is chosen to manufacture cylinders and lattice-structures from those alloys in order to determine the mechanical properties. In addition, Optical Tomography will be used to detect irregularities and µCT data will be matched to ensure a reproducible manufacturing of samples. This gathered information will be used to manufacture a bioresorbable implant as a medical demonstrator using LPBF.

ADDITIVE DESIGN / 37

Integration of cooling channels in additive manufactured parts using PMD® (Plasma Metal Deposition)

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Plasma Metal Deposition (PMD) is a Direct Energy Deposition (DED) method which allows to fabricate large and heavy parts by using wire or powder as feedstock which are fed into a plasma arc. PMD® allows the building of structures using deposition rates in the kilogram range. Besides the manufacturing of structural parts, the PMD process can be used for the fabrication of integrated cooling structures. Additionally, the combination of wire and powder feedstock allows to integrate hard facing surface directly on the 3D fabricated part. Tools or moulds used for carbon fiber composite manufacturing with integrated cooling channels allow to increase the processing speed in the manufacturing due to reduced cycle times.

ADDITIVE DESIGN / 38

Integration of electrical conductors into metallic structures by DED technologies

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In the Horizon 2020 project MULTI-FUN, the manufacturing of fully integrated multi-functionalities of metal parts is in the main focus. These functionalities include enhanced active/passive heat management embedded fibre-optical sensing as well as integrated electrical conductivity.
Several additive layer manufacturing technologies are under development to generate both the internal functional layers (lines/layers/volumes) as well as the final outer geometry of structural parts or manufacturing tools.
In this paper, the sequential application of several direct energy deposition technologies and different material, respectively, is presented, aiming at a multi-material setup offering electrical conductivity. Aluminium is used as a substrate as well as for the filler wires used for the last step of covering the multi-material design by wire+arc AM.
Between substrate and WAAM layer, a stack of layers providing isolation (by aluminium oxide) and electrical conductivity (by copper) is deposited.
The investigations contain variations in layer design, the presented results include electrical and mechanical properties in as-built as well as mechanically loaded conditions as well as microstructures of materials and their interfaces.
The industrial application of embedded electrical conductors in several demonstrators developed in project MULTI-FUN will be addressed.

RECENT RESEARCH TOPICS / 39

Lithography-based additive manufacturing of functional metal components

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Lithographic additive manufacturing (AM) technologies are based on the concept of photopolymerization and are known for their process inherent high precision and good surface quality compared to other AM techniques. In this work, metallic suspensions comprising a photoreactive binder and 316L powder (50vol%) were used as starting material. After printing, the obtained green parts undergo a subsequent thermal treatment similar to what is done in metal injection molding (MIM). After this debinding stage, the structure can be sintered to a relative density of 98.5%. By this approach highly complex parts made of 316L could be manufactured showing a good geometrical accuracy and very low surface roughness; the mechanical properties of the AM structure are comparable to conventionally manufactured 316L (tensile strength > 500MPa). Since the final part is developed by a classical sintering process, the same basic microstructure as in MIM is realized.

Plenary Talk / 40

Past and future challenges for Additive Manufacturing in Space Industry

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During the last 20 years, the terms referring to "Additive Manufacturing" (AM) have evolved significantly. In the early days, reference was made to a process called "rapid prototyping" and "rapid manufacturing" was the consecrated term. This terminology remained even beyond the time in which the community started realising that, in fact, it is not necessarily a rapid process. While fashionable names such as FFF, standing for Free Form Fabrication, or Direct Manufacturing came and disappeared, today mainly two terms are employed: "3D printing" when speaking to a public

audience and "Additive Manufacturing" when addressing a technical one. AM technologies represent a world of opportunities for innovation and change the way we think about manufacturing, in particular for highly demanding applications like those encountered in Space Industry. However, understanding what is required to use AM for critical space applications remains challenging.
ESA, the European Space Agency, took a leading role in the development of AM for space starting from the early 2010s. The developments funded by ESA began with mildly loaded brackets and now cover an always-expanding panel of space applications. It quickly became apparent that alongside every successful development new challenges arise that need to be resolved. This presentation will bring insight into some of the completed developments of the past 10+ years which shaped current and future development paths of AM for Space. The focus is ensuring the availability of technologies that will allow designing, manufacturing and testing the next generations of European spacecraft. The presentation will also address the different markets and their associated challenges.

APPLICATIONS / 41

3D printed tools to reduce residual stresses, thinning and martensite content during deep drawing of metastable austenitic steels

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In contrast to the single-stage process, high deformation degrees can be achieved using multi-stage deep drawing strategies. However, the first forming step already leads to significant changes in the overall sheet metal forming behavior. Temperature changes are caused by friction and plastic deformation in an inhomogeneous manner, which in turn affect the whole subsequent drawing steps and the final part itself.
As worst case, deep drawing components in question may already fail during the first drawing step due to excessive formation of deformation-induced martensite or delayed cracking, which might happen to the final part even hours or days after production.
In this study the influence of the tool temperatures are investigated to reduce the residual stresses and the martensite content. As a result, the forming forces and sheet metal thinning can significantly reduced.
For this purpose, a special 3D printed tool is tested, which is manufactured by selective laser melting (SLM) and offers the possibility to temper the blank holder, the die and the punch.
The results show that an optimized tool temperature strategy reduces the forming forces, residual stresses, martensite content and sheet metal thinning for the metastable austenitic steel used.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 42

Improvement of part accuracy by combination of pulsed wave (pw) and continuous wave (cw) Laser Powder Bed Fusion

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Geometric accuracy of parts manufactured by Laser Powder Bed Fusion (LPBF) is deteriorated by powder particles sintered to the part surface as well as excessive melting due to overheating by limited heat flow at sharp contour corners. While the sintered powder particles increase the surface roughness, overheating leads to deviations of the as-built part geometry from the CAD geometry. Use of pulsed wave Laser Powder Bed Fusion (pw-LPBF) has shown an increase in detail resolution as well as an improvement of the part accuracy in the field of micro Powder Bed Fusion (µ-PBF) due to improved melt pool controlling by discrete solidification of adjacent melt pools generated by the laser pulses. However, process efficiency (e.g. build up rate) of pw-LPBF is in general lower compared to continuous wave LPBF (cw-LPBF). Hence, to transfer the results to large-scale parts, an adaptive processing strategy is developed for alloy Inconel 718. Pw and cw laser emission are combined, while pw irradiation is used for contour exposure and cw irradiation for volume exposure, respectively. In this study, process parameters are developed for different part geometries (e.g. sharp contours). Geometric deviations and surface quality of the parts are evaluated using light optical microscopy, Scanning Electron Microscopy and optical surface measurement, respectively. It can be shown that both geometric accuracy and surface roughness is improved by pw contour exposure compared to state of the art cw exposure while sufficient process efficiency is ensured by cw volume exposure.

Speaker Country:

MODELLING & SIMULATION / 43

Prediction of residual stress development and subsequent spring back deformation, using multiple simulation methods and a comprehensive experimental verification- and validation method.

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To accurately describe the Selective Laser Melting with the goal to study residual stress development and deformations induced by the manufacturing process is very challenging due to the complex physics of the process. A concentrated, fast moving heat source on a very small scale in intricate patterns, multiphysics and metallurgy combined creates quite a challenge. In this work, methods from the field of Verification and Validation are applied to quantify the predictive capacity of the employed simulation tools.

In the project, a Design of Experiments approach was utilized whereby several input variables (specimen geometry and manufacturing process parameters) were varied. For each of the DoE points a physical specimen was manufactured which was then subjected to a cutting operation resulting in a geometrical distortion due to the residual stress state. The change in geometry was measured both using Digital Image Correlation (DIC) and laser scanning. The obtained data was then used to evaluate the predictive capacity of the employed simulation tools.

Macroscopic input variables like cantilever thickness and preheater temperature are evaluated with macroscopic simulation methods (low-resolution simulation) while microscopic input variables like scan geometry are evaluated with microscopic (high resolution) methods. The low-resolution simulation methods are Simufact mechanical (inherent strain) and thermomechanical solvers on a component scale. The high resolution simulations are FCC:s in-house LastFEM on up to 10 power layer scale. The high-resolution simulation has also been evaluated to provide inherent strain distribution input to low resolution mechanical simulation. Extensive material characteristics for maraging tool steel grade has been provided from Uddeholm.

The project illustrates how validation approaches can be used to support the process of developing and evaluating simulation tools and their ability to predict the characteristics of a component manufactured through additive manufacturing.

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 44

LB-PBF processing limits for Cr-Mn-Mo low alloy structural steels

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Additive manufacturing of heat treatable low alloy steels by Laser beam powder bed fusion (LB-PBF) offers a number of difficulties, which is the reason why their use in commercial AM is rather limited today. In the present study, processing of several AISI 4xxx type steels (Cr-Mn-Mo alloyed) has been studied, and the processing windows have been defined for 2 different machines, with particular focus on the laser power. Furthermore, typical defects occurring when processing is done outside the optimal windows were investigated by metallographic studies.

Speaker Country:

POWDER FOR MAM / 45

Investigation of the Impact of Powder Shape on Spreading Dense Layers Using the Spreading Tester

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In laser powder bed fusion processes, spreading as dense and fully covered powder layers as possible is of crucial importance for good processability of powders. Poorly covered layers or layers with unappropriated features in it such as for instance elongated, powderless craters in the direction of spreading might result in insufficient quality of the printed parts. The reason for this could be either poor powder quality or a poorly adjusted build job. To investigate the surface coverage of a single spread layer, a new method was developed using the Spreading Tester. With this, two powder grades differing mostly in their shape were used to investigate the impact of powder shape on the surface coverage.

MODELLING & SIMULATION / 46

Creating Competitive Metal AM Production with High Volume and Flexibility Based on Digital Twins

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The Danish industry has been reluctant to adopt Metal AM, despite the enormous potential for tailored and flexible manufacturing. A national granted project called: "AM-LINE 4.0" (2018 – 2021) has paved the way for the Danish manufacturing industry by removing barriers preventing implementation. The project has a total budget of 12M EUR and is a partnership with the leading industrial partners: Grundfos, Danfoss, SLM Solution, and TWI; together with The Danish Technical University.

The Danish Technological Institute is project manager, and this oral presentation will summarize the main results of the project from a combined industrial and academic point of view. The following topics will be discussed during the presentation:

• Identification of business cases in large organizations and redesign for Metal AM. Examples for Grundfos and Danfoss will be shown together with State-of-the-Art optimization methods as: Distortion compensation with thermomechanical simulations, lattice structures, and thermal topology optimization.

• Quality Assurance procedures for Metal AM by utilizing IoT. An effective cloud-based storing of all production data, that can be used to make cost-effective Quality Control - combined with the main results from the article: "Towards a digital twin of laser powder bed fusion with focus on gas flow variables" [Klingaa, et al] will be submitted later in February 2021 to Elsevier Journal of Manufacturing Process.

• Various micro- and macro-based modelling approaches on laser powder bed will be discussed. These models cover different topics as for instance: Micromechanics and fatigue life estimation, tailored heat treatments of additively manufactured materials, porosity estimation, and geometrical distortion. Several publications have been made by the Danish Technical University and this presentation will cover an overview of the main results.

POWDER FOR MAM / 47

Mechanical properties of Additively manufactured builds from maraging steel

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In the present study, AM (additively-manufactured) specimens from 1.2709 maraging steel were investigated. AM is an increasingly widespread technology in the world. The AM method used was DED (Directed Energy Deposition), where the powder is fed continuously to a melt pool and is completely melted by a high power energy source – fiber laser. This method generates a minimal amount of pores. Maraging steel 1.2709 offers many advantages as high strength at temperatures of up to 500 °C, high resistance to cracking high toughness making it suitable for tooling applications, aircraft industry (landing gear, helicopter undercarriages). The advantage of this method is the ability to print directly on damaged parts, which can lead to an increase in part lifetime. The

present study focused on mechanical properties, pin on disc testing, and comparing of the results with conventionally produced maraging steel.

POWDER FOR MAM / 48

Characterization of local fracture properties of DED deposited multiple material components

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Additive manufacturing (AM) processes are being widely investigated and being gradually applied for engineering applications. Presently, there is main focus on single material systems deposition, where there are still many issues with process stability and repeatability. However, further huge leap in the field of AM processes development will be design of multiple material – heterogenous components. The current study is presenting investigation of local fracture behavior of experimental builds consisting of multiple layers of the stainless steel and Inconel 718 that was created by Powder Blow Direct Energy Deposition system allowing multiple materials deposition. The investigations are focused on properties assessment in relation to the original build orientation of interface layers being oriented horizontally (X-Y) and vertically (Z-X). Investigated are properties of the single layers as well as the properties of interfaces between single layers for both considered deposition orientations. Quasi-static properties under room temperature conditions are investigated in terms of tensile tests, fracture toughness tests and fatigue crack growth rate tests using miniaturized test specimens. The investigations of mechanical properties are supported by metallographic and proctographic analyses of the materials investigated.

RECENT RESEARCH TOPICS / 49

Serial production of additive manufacturing orthopedic implants using SLM and EBM.

Author: Jelle ten Kate[1]

Co-author: Henk Jansen

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Additive manufacturing (AM) has gained traction in orthopedics, so why isn't it a plug-and-play technology yet? While AM has existed for years, mass implementation takes longer than most expect because AM requires a different approach to design and comprehensive knowledge of the entire process. This presentation will review ways that AM can add value and save when design and process are properly planned and executed.

AM requires important design rules. The technology adds or melts layers. Therefore, there is a limit on the angle for overhanging surfaces. Engineers must think about the build orientation. In the event that large overhanging surfaces can't be prevented, support material (SM) is needed. This material will support the layers on top of this SM and also function as a heat sink. Residual stresses occur due to rapid heating and cooling. SM can transfer this heat to the build platform and make sure that the part doesn't deform or crack. These design rules can differ between the SLM and EBM process. Furthermore, the full AM process must be taken into account. Parts made by AM undergo

more process steps than those that are traditionally manufactured. SM has to be removed, parts have to be clamped for milling and if required, marking is needed. Designing for the right AM process and the whole process chain has a high-added value.

Consistent part quality needs to be confirmed through validation of the whole AM process. Speeding up the implementation of AM requires more than just attention to manufacturing. The whole process chain has to be taken into account. While this way of thinking takes more time up front in the commercialization process, it allows for proper AM execution and will save time and money in the end.

Speaker Country:

POWDER FOR MAM / 50

Processing elemental powder blends with miniaturized process chamber designed for material development with laser powder bed fusion

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Most alloys used in laser powder bed fusion (LPBF) are conventional materials, which were designed for specific conventional processes and their constraints. These alloys are not capable to adapt to the special conditions in LPBF process e.g. the rapid solidification and cyclic heat treatments. Therefore, thermodynamic simulations are used to design new alloys for additive manufacturing (AM).
However, testing digitally developed alloys under real LPBF conditions generates great effort in powder manufacturing. To minimize these costs and reduce time for material development, Fraunhofer ILT has developed the miniaturized and modular process chamber "Petit", which can be integrated into existing LPBF-systems. While the module uses the optical- and laser system of the existing LPBF machine, it allows the utilization of significantly reduced amounts of powder material (approx. 300 ml) to manufacture material samples from elemental powder blends. Furthermore, the transferability of the results to large processes is given.

Speaker Country:

Deutschland

POST-PROCESSING / 51

Microstructure and heat treatment of a ultrahigh strength Maraging steel fabricated by Direct laser metal deposition

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Maraging steels are a class of ultra-high-strength martensitic steels, strengthened by precipitation of intermetallic particles in the Fe-Ni martensite upon aging. Due to their low carbon content, these

steels demonstrate excellent weldability and negligible dimensional changes after heat treatment, and hence several types of maraging steels have been developed for laser-based additive manufacturing (AM) during the past decade. AM-MAR60HRC is a recently developed powder for AM to satisfy the requirements in some demanding applications, reaching strength levels up to 2600 MPa (~60HRC). This steel can be hardened in several minutes in the temperature ranges of 450-600°C, making it a proper candidate for Direct Laser Metal Deposition (DLMD), specifically for tooling applications, as it is suitable for very localized heat treatments on the deposited surface without affecting the core material hardness and strength. This work aims to investigate the processing parameters, and to study the microstructure and aging behavior of DLMD-MAR60HRC.

Speaker Country:

Italy

MODELLING & SIMULATION / 52

Process modelling and realization for laser-metal powder additive manufacturing

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Metal Additive manufacturing (AM), opposite to traditional material removal processes but fabricating components by adding melted metal powders or wire feedstock layer by layer, offers maximum product design freedom and is a feasible means to manufacture complex structural components for hard materials. Based on the idea of directed energy deposition (DED), laser metal deposition (LMD) process is one of the popular AM technologies for producing complex structural component or remanufacturing high-value components. It makes use of laser as the intensive thermal source to melt the substrate/powders, form a melt pool and finally solidify fully-densed component directly from CAD files without using dies, tooling or machining, which greatly reduce the lead-time and production cost. However, the LMD process varies with many factors; the consistence and reliability of the deposited components' quality during the practical production is also not always well maintained. Trails and errors method is an expensive and time-consuming way to find the suitable processing parameters for quality components. Although there is also challenge due to the involvement of multiple physical processes as well as accompanied mass and heat flows, accurate simulation of the laser-metal powder deposition process and investigation of its parameter's effect seem to be a feasible and cost-effective means to reduce the trials.

In this paper, the LMD process simulation based on the specific AM machine at NMIS is proposed and realized by CFD modelling. Temperature field distributions caused by moving laser beam and the resultant molten pool on substrate are analysed. The liquid/solid interfacial behaviours during the deposition and subsequent solidification process of the molten pool are simulated. The predicted bead geometry (e.g. bead width and height) from the CFD simulation are compared with those from LMD trials. With the proposed process model and corresponding trial validation, we can insightfully investigate the relevant physics in the LMD process and facilitate the realization of high quality deposited components with consistency by using optimized processing parameters. The process simulation results will facilitate the practical production or remanufacturing the geometrically-complex, high-value components used in the industry of aerospace, automotive and medical devices, etc.

Speaker Country:

Scotland

AM PROCESS and QUALITY CONTROL / 53

Residual stress heterogeneity induced by SLM of carburizing steel 20MnCr5 and its influence on contact fatigue

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Due to the raster heat inputs, steep temperature gradients and rapid cooling, the selective laser melting (SLM) process generally induces high residual stresses heterogeneity across the fabricated parts. In the case of gears, such variations on the teeth flank may have a negative effect on the fatigue behavior. This study analyzes the influence of residual stresses heterogeneity induced by SLM on the contact fatigue behavior of carburizing steel 20MnCr5 samples reproducing gear applications. Residual stress maps and depth profiles obtained by X-ray diffraction along the dimensions of rod-shaped samples are correlated to ball-rod contact fatigue results. The fatigue scatter is then discussed in view of the residual stress heterogeneity.

Speaker Country:

Brazil

POWDER FOR MAM / 54

New high strength and corrosion resistant stainless steels by AM via modification of feedstock powders

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Stainless steel (SS) of type 316L is one of the go-to materials for metal additive manufacturing (AM), due to its good weldability. As-printed 316L SS made by AM has unconventionally good mechanical properties exhibiting both high strength and high ductility. However, the corrosion resistance is inadequate, and not on par with conventional 316L. Our research team has demonstrated proof of concept for the lab-scale manufacturing of modified 316L with excellent corrosion resistance combined with superior mechanical properties as compared to "conventional" AM. The method entails modification of the feedstock powder, while the MAM method remains unchanged. The microstructure of the modified 316L is comparable to that of 316L manufactured by L-PBF. Elongated austenite grains with the mechanically beneficial internal cellular substructure were obtained. The powder modification resulted in a Vickers hardness increase of about 40 HV0.1 in the as-built condition. The modification also improved the corrosion resistance, as measured by weight loss after immersion in 5.6% FeCl3 solution for 10 days.
The method has also proven useful for strengthening of duplex stainless steels, and is also expected to be applicable for achieving strength and corrosion resistance in ferritic stainless steels, and for enhancing the AM processability of martensitic stainless steels. The present contribution will also showcase different aspects and applications of the technology.

Speaker Country:

Denmark

LASER MELTING, ELECTRON BEAM MELTING & DIRECT ENERGY DEPOSITION PROCESSES / 55

Laser Powder Bed Fusion of Carbon-Containing Ferrous Alloys: Martensite Formation and its Properties

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Carbon-containing ferrous alloys with >0.2 wt.% carbon are considered difficult to weld materials and are thus expected to have poor processability when using Laser Powder Bed Fusion (L-PBF). This is connected to the high cooling rates of L-PBF that result in the formation of martensite and internal residual stresses that create a significant risk of cold cracking within the material. However, the characteristics of martensite formation, its substructure and its properties in L-PBF produced ferrous alloys is a subject that remains poorly understood. Presented work summarizes the effect of carbon on the formation and properties of martensite over a range of model Fe-C alloys as well as low-alloy steels, with a specific focus on martensite properties and its effect on L-PBF processability. This was done using a combination of hardness measurements, optical and scanning electron microscopy, transmission electron microscopy and atom probe tomography, that helped analyze the substructure, carbon distribution and precipitation within L-PBF produced martensite. Results indicate that ferrous alloys with up to 0.75 wt.% carbon can be produced defect-free by tailoring the laser scan strategy and build plate preheating to enhance the intrinsic heat treatment that takes place during processing.

Speaker Country:

Sweden