4th Symposium on Materials and Additive Manufacturing

Additive 2024

12 - 14 June 2024
Bremen, Berlin & Online

Book of Abstracts

A symposium organized by the
DGM | The network for **materials science** and **engineering**

Chairpersons

Prof. Dr. Vasily Ploshikhin
University of Bremen

Program Committee

Prof. Dr. Giovanni Bruno
Bundesanstalt für Materialforschung und -prüfung (BAM)

Dr.-Ing. Kai Hilgenberg
Bundesanstalt für Materialforschung und -prüfung (BAM)

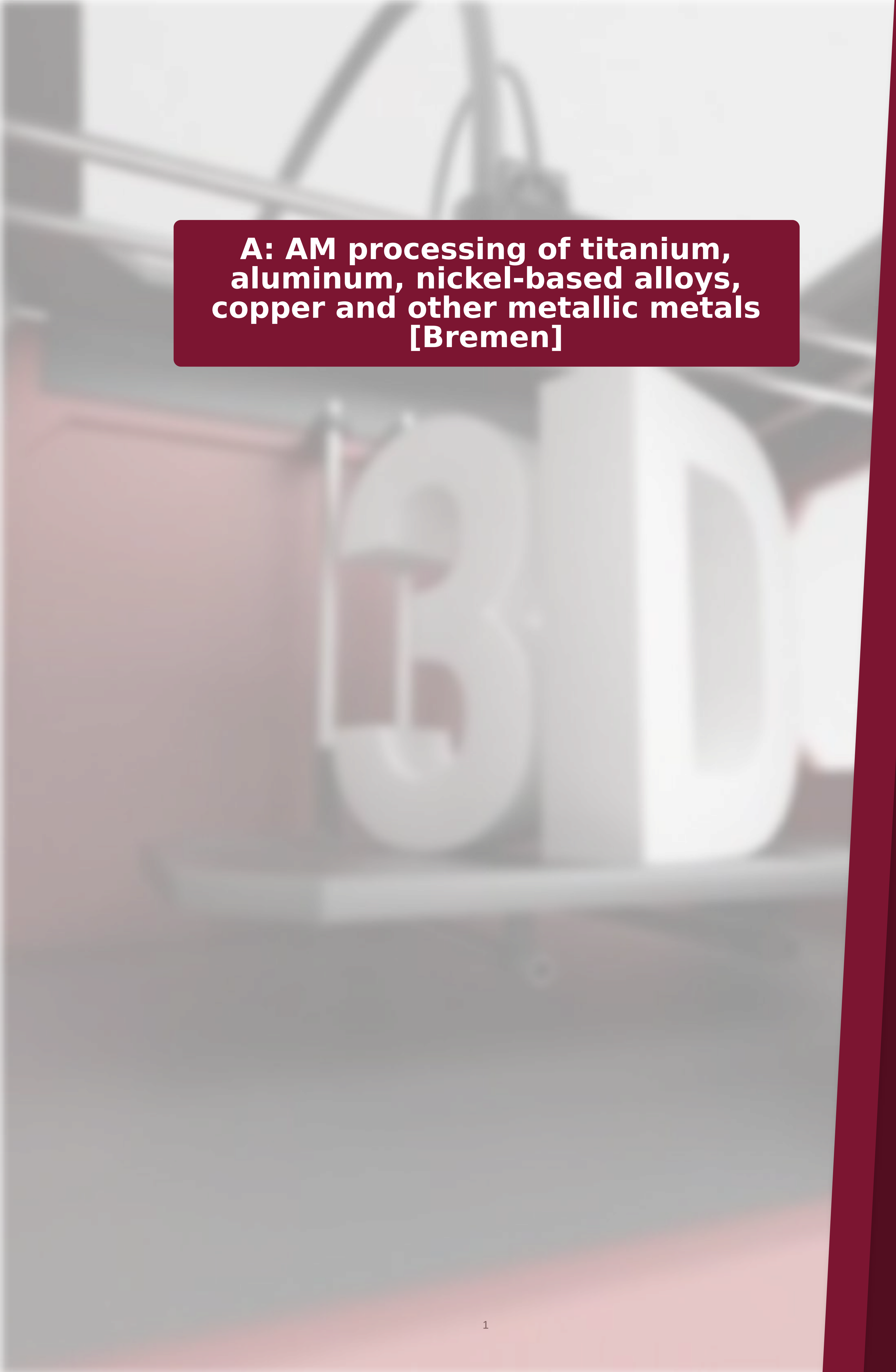
Prof. Dr.-Ing. Carolin Körner
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

Prof. Dr.-Ing. Christoph Leyens
Fraunhofer Institute for Material and Beam Technology IWS Dresden

Prof. Dr.-Ing. Thomas Niendorf
University of Kassel

Prof. Dr. Gerd Witt
University of Duisburg-Essen

Table of contents



A: AM processing of titanium, aluminum, nickel-based alloys, copper and other metallic metals [Bremen]

A novel STA heat treatment for Powder Bed Fusion – Laser Beam Ti-6Al-2Sn-4Zr-6Mo alloy

G. Pirro[1], A. Martucci[2], A. Morri[1], M. Lombardi[2], L. Ceschini[1]

[1] Department of Industrial Engineering (DIN), Alma Mater Studiorum – University of Bologna, Viale del Risorgimento 4, Bologna, 40136, Italy
[2]Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24,10129, Italy

Ti-6Al-4Zr-2Sn-6Mo is one of the most recent Powder Bed Fusion – Laser Beam (PBF-LB) processed titanium alloys. It could replace the Ti-6Al-4V in automotive and aerospace applications thanks to the higher mechanical properties (about 10% on UTS and YS). In the as-built (AB) condition, the material is characterized by the presence of the soft orthorhombic α'' martensite. A post-process heat treatment for its decomposition is therefore needed to increase the mechanical properties of the AB alloy. Usually, PBF-LB Ti6246 components undergo an annealing process that transforms the α'' martensite into an α−β lamellar microstructure [1].

The main goal of the present research was to obtain an ultra-fine bi-lamellar microstructure reinforced by precipitation hardening, developing a Solution Treating and Aging heat treatment (STA) tailored to the peculiar microstructure induced by the additive process. The effect of solution temperature in the α+β field (between 800-900 °C), cooling media (air and water), and aging temperatures were investigated to identify the heat treatment parameters to obtain a suitable bilamellar microstructure. The microstructural characterization was done through optical (OM) and electron microscopy (SEM) analyses, as well as by XRD analyses to evaluate and identify the crystalline phase transformations. Preliminary microhardness tests were performed to assess the effect of different heat treatment parameters on mechanical performance. Tensile tests were performed on samples heat-treated according to the most promising parameters. The comparison of the results of mechanical characterization and literature data highlighted that the optimized STA heat treatment increased the hardness and strength of 35% and 23%, respectively, compared to the annealed alloy, with a reduction of the elongation to failure of 53%. Fracture surface analyses of tensile tests were carried out to study the fracture mechanisms. In Figure 1 is possible to notice the bilamellar microstructure obtained after the STA heat treatment and the effect of solution temperature on α lamellae width and tensile properties.

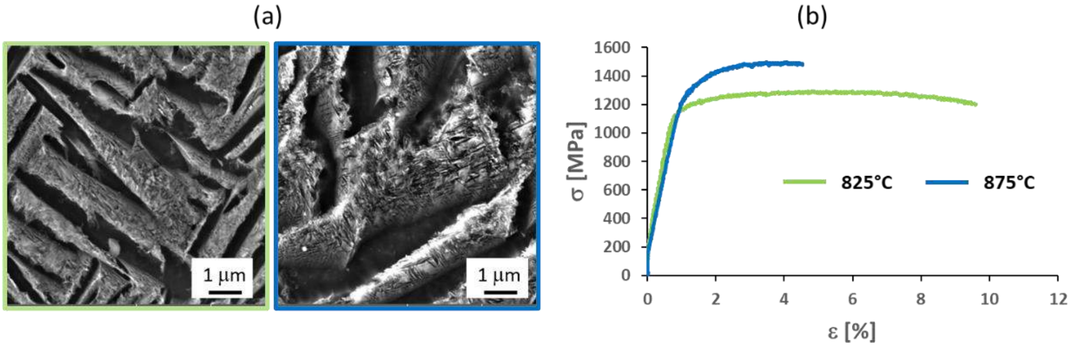


Figure 1. Effect of solution temperature (825°C in green and 875°C in blue) of an STA heat treatment on microstructure (a) and tensile properties (b)

References

[1] A. Carrozza, A. Aversa, P. Fino, and M. Lombardi, "Towards customized heat treatments and mechanical properties in the LPBF-processed Ti-6Al-2Sn-4Zr-6Mo alloy," *Mater Des*, vol. 215, Mar. 2022, doi: 10.1016/j.matdes.2022.110512.

Advancements in PBF-EB Spot Melting: Exploiting 3D Lattice Stacking

Y. Westrich[1,*], B. Wahlmann[1], C. Körner[1]

[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, Materials Science and Engineering for Metals, Erlangen, Germany
*Yannic.westrich@fau.de

Spot melting is quickly gaining ground with line-based scanning strategies (hatching) typically used in electron beam powder bed fusion (PBF-EB), offering a greater degree of freedom, suitability for complex geometries and the ability to control the local microstructure [1]. By capitalizing on the fast deflection capabilities of the electron beam (km/s), spot melting strategies have introduced a broad and complex parameter space which must be considered from two separate perspectives: the underlying geometric information, namely the lattice structure, and the spot sequence that governs the order in which locations are visited by the electron beam. This contribution explains why hexagonal lattices are preferable to commonly used square lattices [2, 3] and showcases the effects of different lattice stackings to produce unique, crystallographic, cell-like structures (hexagonal primitive, hexagonal close-packed, and cubic close-packed) on grain morphology and defect formation. A numerical study of the thermal effects induced by the applied strategies, complemented by experiments on the novel freely programmable 150 kV PBF-EB system AMELI (PB-EBM 30S) by pro-beam, dispels the common misconception regarding the high energy input required for spot melting compared to conventional hatching of the Ni-base superalloy IN718. Furthermore, an investigation using conventional metallography, SEM and high-resolution electron optical (ELO) imaging [4] reveals the typical defect structure present in spot melting and consequently advocates the use of CCP stacking to reduce the required energy input and eliminate the aforementioned defects.

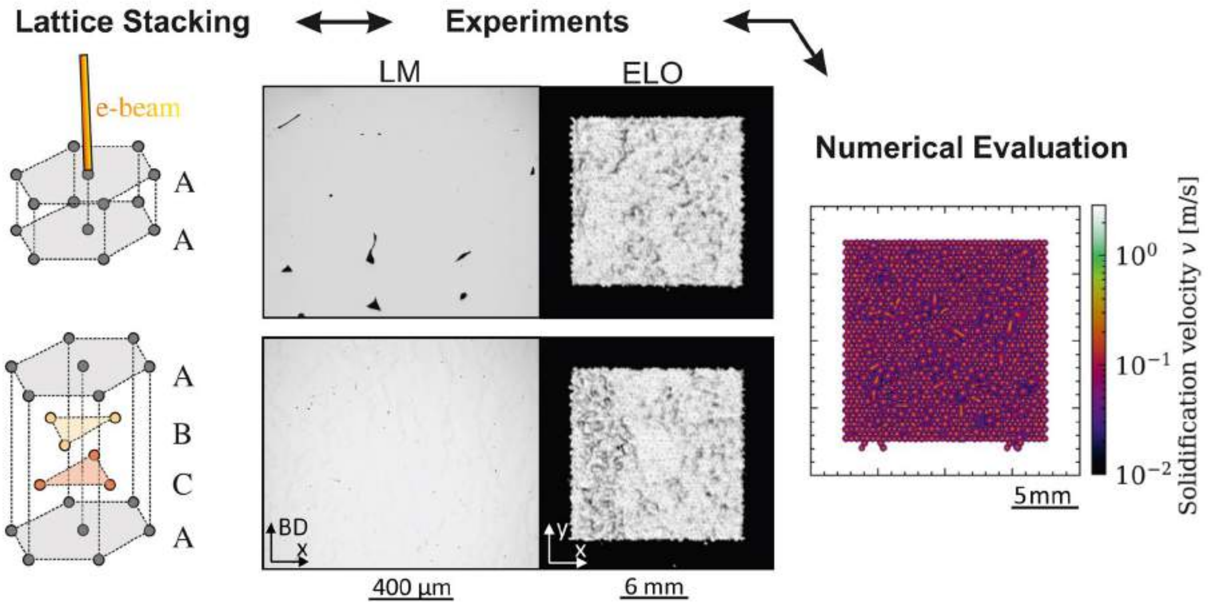


Figure 1. Visualization of 3D hexagonal point lattice stackings and associated methodology for analyzing the effects of the stacking on the microstructure and solidification characteristics of spot-melted IN718.

References

[1] A. Plotkowski, *Additive Manufacturing*, **2021**, 46, 102092
[2] P.L. Stephenson, *Additive Manufacturing*, **2020,** 36, 101581
[3] S.K. Rittinghaus, *Additive Manufacturing Letters*, **2023**, 7, 100159
[4] M. Franke*, Progress in Additive Manufacturing,* **2023**, 8, 55 – 60

Development and optimization of post-processing technologies for Cold Metal Fusion to enable cost-efficient series production of additively manufactured metal parts

C. Weigl[1*], N. Geis[2], H. Ruckdäschel[1]

[1] Neue Materialien Bayreuth GmbH, [2] University of Bayreuth, Polymer Engineering
*Christopher.Weigl@nmbgmbh.de

Cold Metal Fusion (CMF), developed by the start-up company Headmade Materials, is an innovative technology that enables the additive manufacturing (AM) of metal parts with high precision and significantly reduced manufacturing costs. The key component in the CMF chain is the material feedstock, which consists of a highly metal-filled polymer matrix supplied as a powder. The feedstock can hereby be processed into green parts using standard machines for the selective laser sintering (SLS) of polymer materials. This leads to a significant reduction in investment and overall production costs compared to metal powder production, without compromising on geometric accuracy or design freedom. Figure 1 shows the schematics of the cold metal fusion process. [1]

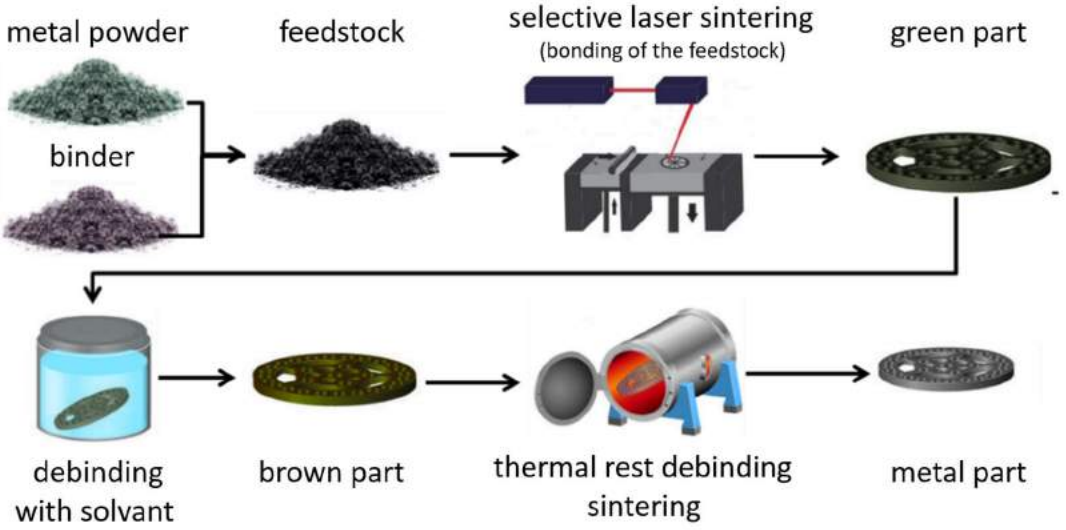


Figure 1. Schematic overview over the workflow of the Autosmooth Project

After printing in the SLS process, the green parts must be removed from the powder cake. In addition, thorough cleaning of all powder residues is required. The possibility of subjecting "green parts" to a surface treatment leads, among other things, to a reduction in costs, as the need for expensive and time-consuming surface treatment of metal parts no longer exists. Additionally, compared with metal powder based AM, no direct support structures on the parts are required which need to be removed. The post processed green parts are debinded with a solvant to produce brown parts with minimal left binder residue. The brown parts are sintered under high temperature to produce a metal part.

While the automation of depowdering processes and the surface treatment of metal parts has been the focus of interest for many companies and researchers in recent years, an automated process for CMF is currently lacking. The green parts have limited mechanical stability, which is an advantage for surface treatment, but at the same time represents a major hurdle for depowdering and automated handling processes. AM Solutions, a Brand of the Rösler Group, and the research institute Neue Materialien Bayreuth GmbH have teamed up with Headmade Materials as part of the publicly funded “Autosmooth” project to overcome this challenge. The aim of the project is therefore to develop an automated prototype for the depowdering, cleaning and surface finishing of CMF parts with maximum feedstock recovery. Automation paves the way for series production of CMF due to improved reproducibility and the avoidance of labor costs. The “Autosmooth” project and its initial results are presented in this presentation.

References

[1] Skz-Kfe Ggmbh,2020. Method for additively manufacturing a component, and an additively manufactured component. Christian Fischer, Christian Staudigel.25.06.2020. Filed: 02.03.2018. US20200198006A1

Development of an environmentally friendly production route for carbide milling tools printed using Fused Filament Fabrication

Y. Zheng[1*], N. Agarkov[1], U. Glatzel[1,2], W. Hofmann[3], K. Trott[4], R. Simon[4], H. Daoud[1]

[1] Neue Materialien Bayreuth, [2] University Bayreuth, [3]Peter Würtele, [4]Klaus Trott
* ying.zheng@nmbgmbh.de

Tungsten carbide is the most used carbide for milling tools due to its high fracture toughness and flexural strength [1,2]. However, conventional carbide tools are expensive to manufacture due to the lengthy grinding processes and long retooling times. Recently, additive printed tools have attracted a lot of attention. Microcracks, high residual stresses and brittle phases are still major obstacles [3,4]. In this study, the FFF (Fused Filament Fabrication) process is developed to print crack-free and low-stress milling tools made of hard metal (Tungsten carbide).

Figure 1. Development of a production route for carbide milling tools by FFF process.

The production of highly filled filaments with 94 wt% tungsten carbide is described. The effects of the process parameters, debinding and sintering on the porosity at the surface of the cutting edges will be discussed. The microstructure of the sintered samples was examined by electron microscopy. The hardness and residual stresses will be illustrated.

References

[1] R. Kieffer, F. Benesovsky, Springer-Verlag Vienna, **1965**, 1, 18.
[2] Y. Yang et al., International Journal of Advanced Manufacturing Technology, **2020**, 108, 1653-1673.
[3] W. Lenguar et al., International Journal of Refractory Metals and Hard Materials, **2020**, 82, 141-149.
[4] Y. Thompson, J. Gonzalez- Gutierrez, C. Kukla, P. Felfer, Additive Manufacturing, **2019**.

Grain refinement of EN AW-7075 through the addition of TiC nanoparticles in the LMD process

F. Bendixen[1*], T. Seefeld[1]

[1] BIAS – Bremer Institut für angewandte Strahltechnik GmbH
* bendixen@bias.de

EN AW-7075 (AlZn5,5MgCu) is an aluminium alloy with a high strength. However, very poor weldability due to hot cracking susceptibility makes additive manufacturing of EN AW-7075 not feasible without additional measures.

In this study laser metal deposition (LMD) of EN AW-7075 is enhanced by addition of TiC-nanoparticles (35-55 nm) up to a content of 1 %vol.

It was found that without TiC addition the most significant problems are hot cracking and growth of coarse strongly oriented grains. These issues can be overcome by feeding TiC nanoparticles into the process. In particular, the grain size could be reduced by almost two orders of magnitude by adding 1% vol. of TiC-nanoparticles. This documents that TiC-nanoparticles that are simply stirred into the powder feedstock can be transferred into the melt pool and serve as grain refiners. The grain size decreases with increasing content of nanoparticles.

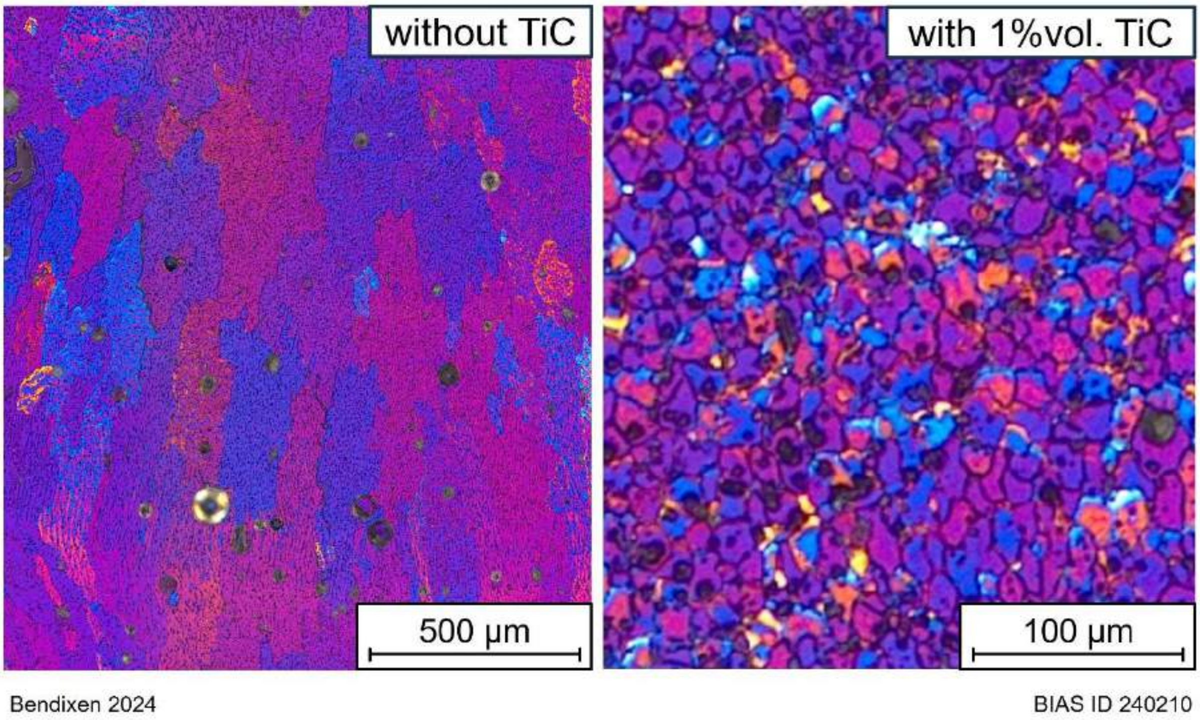


Figure 1. On the left a sample without the addition of TiC is shown. On the right a sample with the addition of 1 % vol. TiC nanoparticles is shown (different scale).

Also with increasing content of nanoparticles, the fraction of globular grains increases. A homogeneous microstructure was reached at 1% vol. of TiC. Furthermore, with this proportion the number of hot cracks can be minimized, and hot cracks are reduced in length when the microstructure shows small globular grains. Moreover, even at low concentration of nanoparticles, the surface quality of the produced samples increases.

High temperature properties of Nickel based alloys made by Plasma Metal Deposition (PMD®)

E.Neubauer[1*], E.Ariza-Galván[1], P.P. Curti[1], M.Scheerer[2], N.Stelzer[2]

[1] RHP-Technology GmbH, Seibersdorf, Austria, [2] Advanced Aerospace and Composites, Wiener Neustadt, Austria
*e.ne@rhp.at

Nickel based superalloys are widely used due to their excellent mechanical properties and corrosion resistance. Therefore they are especially of interest for high performance and demanding applications. Examples are here components used in industries such as space, aviation, energy generation or petro-chemistry.

The processing of this material class is costly due to the involvement of expensive raw materials and typically a high "build to use" or "buy to fly" ratio is typically required. Traditional processing techniques are casting in combination with forging operations followed by milling processes. Depending on the complexity of the geometry of a component this is directly related to a high raw material consumption.

Within this study the goal is to reduce the raw material consumption by using the Plasma Metal Deposition (PMD®) in order to fabricate near net shape components which only require minor milling operations and thereby help to save raw materials. In this case powders are injected into a melt pool, which is created by a plasma arc process followed by a layer by layer growth of a 3D structure.

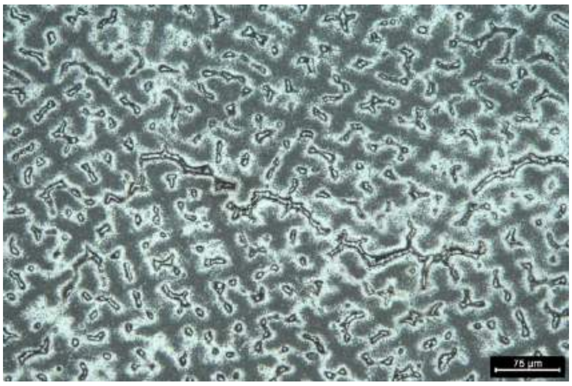


Figure 1. Microstructure of INCONEL with Al2O3 reinforcement fabricated by PMD process.

Especially of interest are the high temperature performance of Nickel based alloys such as INCONEL 718. Here the PMD process was used and materials have been tested at temperature of up to 1.000°C. In addition to that the commercial alloys fabricated from powder based feedstocks different modified alloys were investigated as well as a study of the introduction of ceramic reinforcements was assessed. It could be shown that the high temperature properties at 800°C and 1.000°C are linked to the raw materials used, the deposition parameters and the applied heat treatments. Improvement compared to commercial reference materials could be demonstrated.

Impact of thermoplastic polyurethane as a single backbone binder on material extrusion additive manufacturing of Mg Alloy

H. Kim[1*], T. McKenna[1], A. Azadi[1], E. O'Cearbhail[1], and M. Celikin[1]

[1] University College Dublin,
*Hyeonseok.kim@ucdconnect.ie

Material Extrusion Additive Manufacturing (MEAM) of magnesium (Mg) alloy implants is emerging as a promising technique for biomedical applications, attributed to its inherent biocompatibility and capability for patient-specific design [1]. A critical aspect in producing these Mg alloy parts is selecting an appropriate binder for the Mg powder feedstock. Conventional binder systems, such as paraffin wax and polyolefins, are limited by a restricted volume fraction of Mg alloy powder in the feedstock [2]. Additionally, oxidation of Mg parts and the lengthy duration of the debinding process are significant challenges [3, 4]. This study investigated the effects of thermoplastic polyurethane (TPU) as a single backbone binder throughout the additive manufacturing process, including debinding and sintering, and compares its effectiveness with conventional binders.

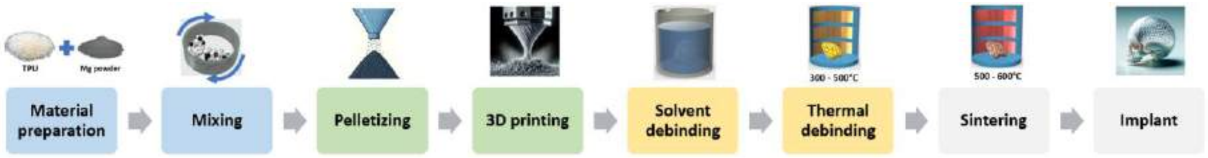


Figure 1. Schematic diagram of material extrusion additive manufacturing of metallic components.

A mixture of TPU and Mg alloy was employed as feedstock to produce a 3D printed part, termed the green part. This green part then underwent a debinding process, resulting in a brown part, which was subsequently sintered to create the final sintered part as shown Fig. 1. The dimensional and geometric accuracy of the green part was assessed using image analysis techniques. Furthermore, the impact on mechanical properties and oxidation levels of the brown and sintered parts was evaluated through energy-dispersive X-ray spectroscopy and electrochemical impedance spectroscopy. These outcomes were compared to the results from the parts produced using conventional binders.

The findings revealed that the high interaction between TPU and Mg alloy powder resulted in enhanced layer adhesion and increased Mg alloy powder loading in the feedstock. This improvement was crucial for maintaining shape retention during the debinding and sintering processes. Moreover, the use of TPU as a single backbone binder significantly improved the time and energy efficiency of the debinding process, while maintaining low oxidation levels in brown and sintered parts. In conclusion, the study highlights the potential of TPU as a single binder in material extrusion additive manufacturing of Mg alloy.

References

[1] V. Kaushik *Additive Manufacturing*, **2022**, *55*, 102802.
[2] M. Wolff *Journal of Magnesium and Alloys*, **2023**, *11*, 2750-2762.
[3] M. Wolff *Powder Metallurgy*, **2014**, *57*, 331-340.
[4] C. Suwanpreecha, *metals*, **2022**, *12*, 429.

Investigation of Titanium Alloy Behavior in 3D Extreme High-Speed Laser Metal Deposition (3D-EHLA) Process Using Specialized Nozzles

Simone Maffia[1*] (S. Maffia), Tobias Stittgen[1] (T. Stittgen)

[1] Ponticon GmbH
*simone.maffia@ponticon.de

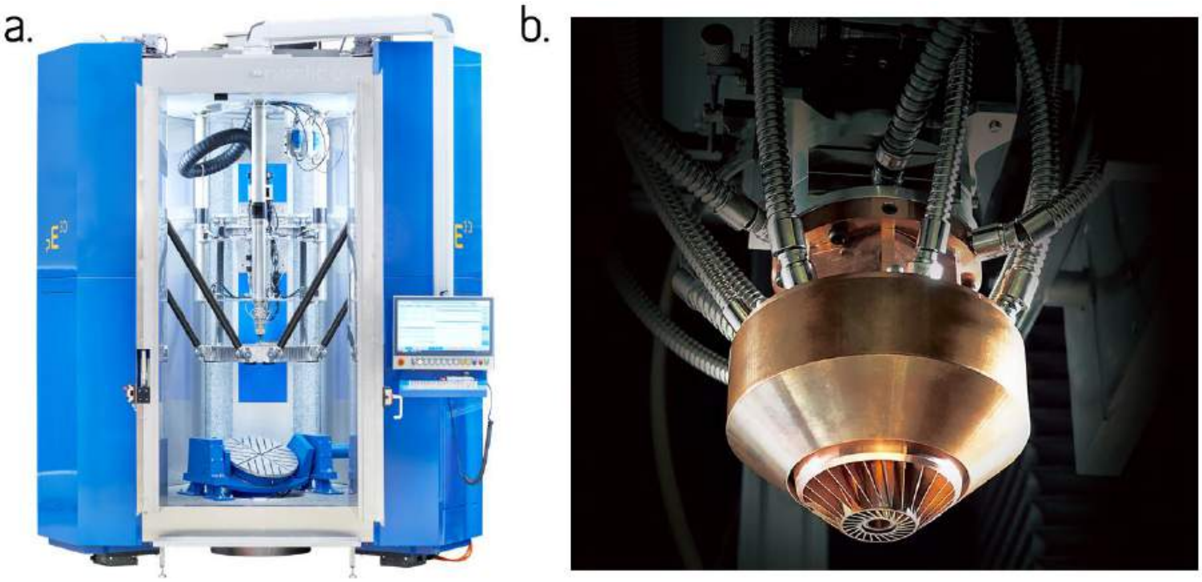


Figure 1. a. Ponticon pE3D system; **b.** Nidec special nozzle (courtesy: Nidec).

Additive Manufacturing (AM) has revolutionized production processes, offering unparalleled flexibility and efficiency. Titanium alloys, renowned for their high strength-to-weight ratio and corrosion resistance, are particularly significant in Aerospace and Oil & Gas applications. However, their high reactivity with oxygen and nitrogen at elevated temperatures poses challenges in processing, including the risk of contamination and the formation of undesirable phases. While Titanium alloys have been extensively applied in AM processes like Laser Metal Deposition (LMD), the emergence of 3D Extreme High-Speed Laser Metal Deposition (3D-EHLA) presents a new frontier. [1]

This study, conducted using the Ponticon's pE3D system (Figure 1.a), delves into the behavior of Titanium alloys within the 3D-EHLA process, aiming to investigate the tailored microstructure of components. The application of specialized nozzles from Nidec (Figure 1.b), designed to deliver exceptionally high shielding gas flow rates of up to 100 L/min, addresses the challenge of minimizing contamination during deposition of Titanium alloys. Despite the proven effectiveness of such nozzles in standard LMD processes, where they have proved to be a viable alternative to working in inert chamber environments, their performance in the extreme high-speed requirements of 3D-EHLA remains unexplored territory. [2,3]

Through comparative analyses between specialized Nidec nozzles and standard nozzles in the 3D-EHLA process, microstructural features including grain size, phase distribution, and the presence of contaminants and defects will be addressed.

In conclusion, this study contributes to advancing the understanding of Titanium alloys behavior in the 3D-EHLA process and provides insights into optimizing microstructural control and minimizing contamination. By addressing these challenges, the quality and reliability of additively manufactured components, particularly in critical industries like Aerospace and Oil & Gas, can be significantly enhanced.

References

[1] J. Schaible, *Journal of Laser Applications*, **2021**, *33*, 012021.
[2] M. Müller, *Journal of Laser Applications*, **2022**, *35*, 012006.
[3] J. Kaspar, *High Entropy Alloys & Materials*, **2023**, *1*, 361-378.

Laser Powder Bed Fusion of Copper-Tungsten Powders

S. Rauh[1,2*], S. D. Prabhu[1], G. Wolf[1], L. Fischer[1,3], P. Mayr[2]

[1] Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT), Germany
[2] Technical University of Munich (TUM) - Chair of Materials Engineering of Additive Manufacturing, Germany
[3] University of Applied Sciences Ingolstadt - Faculty of Mechanical Engineering; Germany
*simon.rauh@umsicht.fraunhofer.de

Abstract

The processing of pure copper (Cu) in the powder bed fusion laser beam (PBF-LB) process has been a focus of research in recent years in the field of laser based additive manufacturing. Cu reflects 97% of the radiation at a commonly used redlight laser wavelength of 1064 nm [1]. There are various solutions such as reducing the wavelength, increasing the energy density and increasing the absorption by alloying and coating the powders. In this study, the Cu powder surface was covered with sub-micrometer tungsten (W) particles to increase the absorptivity of the powder. The advantage of W is its insolubility in Cu [2]. Alloying Cu with additives decrease its thermal and electrical properties enormously. Two routes were developed to manufacture the powders. The first route of manufacturing Cu/W-powder was by means of a milling process using mechanical connection. The second manufacturing method was a co-injection atomization where a separate W particle jet is sprayed into the primary liquid Cu particle jet. This allows the Cu/W-composite to be manufactured in a single production step. The powders were produced and sieved in an inert atmosphere of nitrogen and analyzed with a combination of laser diffraction and scanning electron microscopy.

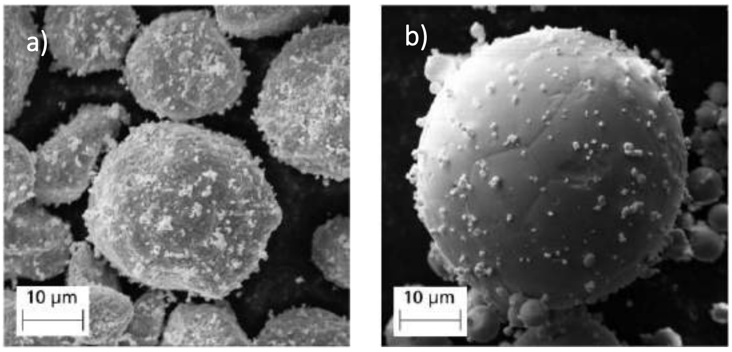


Figure 1. Scanning electron microscope images of a) Cu/W-powder made by the milling process b) Cu/W-powder made by co-injection atomization.

Test specimens were manufactured by a PBF-LB machine with a volume energy density of 171 J/mm^3. The relative density was measured both optically and using the Archimedes principle. The optical method yielding values in the range of 95% to 99%. The thermal diffusivity was analyzed by laser flash analysis and thermal-optical measurement. By eddy current measurement, the electrical conductivities of the specimens were determined. Also, the Vickers hardness was measured. It could be shown that 87% of thermal conductivity and 86% of electrical conductivity could be achieved compared to the pure copper.

References

[1] D., Becker; Dissertation, Apprimus Verlag, Aachen, **2014**, p. 42.
[2] P. R., Subramanian; D. E., Laughlin; Phase Diagrams of Binary Tungsten Alloys; Indian Institute of Metals, Calcutta, **1991**, p. 76.

Leveraging Sensor Data and Process Simulation for 3DPMD with Recycled Aluminium Powder

Y. Tong[1*], D. Vieweger[1], D. Herrmann[1], C. Canaz[1], P. Mayr[1]

[1] Technical University Munich
*yiyun.tong@tum.de

3D Plasma Metal Deposition (3DPMD), a specialized DED technique, represents a significant leap forward in additive manufacturing, allows for less stringent powder requirements and higher deposition rates. Yet, achieving accurate process simulations, a critical component for developing digital twins, due to the small process window of Aluminium. Aluminium's unique properties and the complex thermal dynamics in plasma-based MAM complicate both the manufacturing process and the acquisition of accurate data in research. In addition, plasma-based MAM itself presents challenges in modeling the thermal behavior due to the inherent different gas elements when compared to laser-based processes. [1–3]

Addressing this gap, our research plans to integrate diverse sensors to enrich the dataset available for process simulation as well as presenting a pathway forward for production quality monitoring (as seen in Figure 1). Quotient pyrometers are used for continuous temperature measurement of the melt pool, heat elements are mounted on the built plate as well as IR camera for reference of the cooling behavior. In addition, a spectroscopy sensor tracks emitted wavelengths which is used for the monitoring of material impurities as well as for continuous calibration of the quotient pyrometers. The integration of these data sources into process simulations enables more accurate modeling that accounts for the nuanced behaviors of aluminium under varying manufacturing conditions including the use of recycled aluminium. [4, 5]

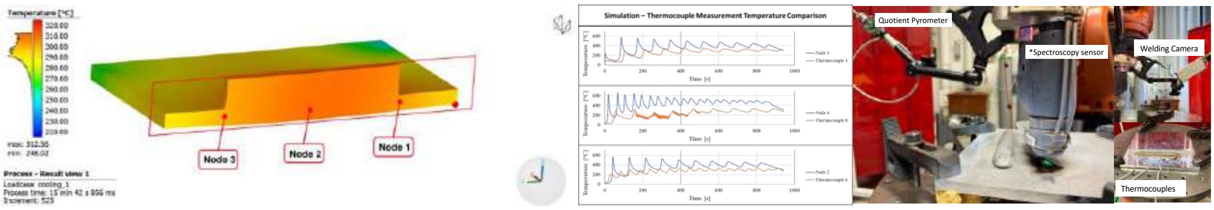


Figure 1. Model of the simulation on the left, comparison of process simulation with thermal simulation with preliminary sensor data in the middle, and a multilayer build-up with Al6061 powder with sensor setup

To test our developed simulation approach, empirical tests on two geometries of 20 layers would be performed, comparing the simulation's predictions with experimental results. This approach aims to verify the simulations' enhanced reliability with multi-source sensor data and highlight its potential to boost predictive modelling for digital twins. Our research emphasizes the need for diverse, high-quality data in process simulations, especially for aluminium additive manufacturing. These insights pave the way for advancements in digital twin technology for 3DPMD, promising greater efficiency, material use, and product quality, and encouraging wider use and optimization of 3DPMD for different aluminium alloys in both virgin and recycled state.

References

[1] N, Lammens; F, Gallego-Bordallo; J, Ni; et al. *Procedia Structural Integrity*, **2021**, *34*, 247-252.
[2] K, Hoefer; A, Nitsche; A, Haelsig; P, Mayr *Metals*, **2019**, *9*, 562.
[3] S, Hartmann; O, Murua; J.I., Arrizubieta; et al. *Simulation Modelling Practice and Theory*, **2024**, 132, 102881.
[4] S, Van den Eynde; D.J., Diaz-Romero; B, Engelen et al. *Procedia CIRP*, **2022**, *105*, 278-283.
[5] D.S., Ertay; M.A., Naiel; M, Vlasea; et al. *CIRP Journal of Manufacturing Science and Technology*, **2021**, 35, 298-314.

Locally adapted microstructures by temporal modulation of the energy input in LPBF

T. Laag[1*], N. Pirch[1], W. Meiners[1]

[1] Fraunhofer Institute for Laser Technology ILT
*Thomas.laag@ilt.fraunhofer.de

Laser Powder Bed Fusion (LPBF) enables the production of complex component geometries with increased functionality, such as components with integrated cooling channels or topology-optimised lightweight structures. In addition to the realisation of the geometry, the material structure is also created during the build-up process. This results in a further degree of freedom for component design, namely the local, application-oriented adjustment of the material structure and thus the mechanical properties within a component, which further expands the potential for function-optimised component design. The microstructure of an LPBF component is formed by melting a powder material track by track using a focused laser beam, which is guided continuously (continuous wave - cw) over the powder layer to be exposed. This generally results in directional, epitaxial grain growth, as the heat dissipation is mainly directed against the build-up direction into the underlying component volume. Studies at Fraunhofer ILT have shown that processing using a pulsed-modulated laser beam (pulsed wave - pw) can produce a fine-grained, isotropic microstructure and significantly suppress epitaxy in the material structure. Complementary use of cw and pw exposure allows the integration of complex spatial microstructures distributions with locally different properties within additively manufactured components. The implemented microstructure distribution is not affected by phase transformations during post-process heat treatments such as Hot Isostatic Pressing. Hence, the approach demonstrated allows tailoring of local mechanical properties, e.g., according to locally inhomogeneous load cases within additively manufactured components as well as the integration of microstructural watermarks for forgery-proof components

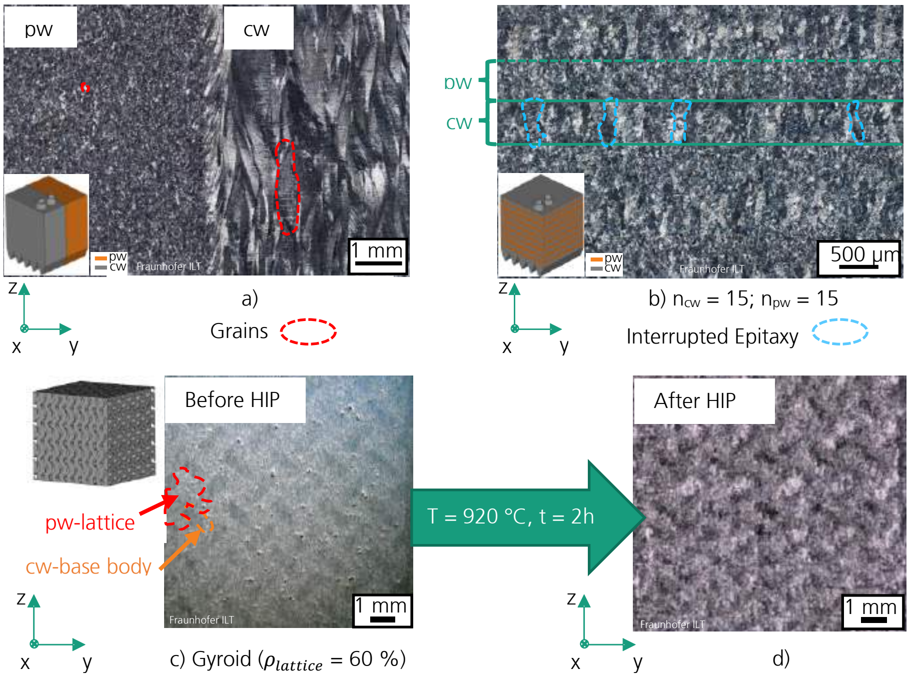


Figure 1. a) pw- vs cw-microstructure (as built) along build direction z, b) Interruption of epitaxial grain growth within cw-layers by following pw-layers along build direction, c) Volume integration of gyroid lattice structure (pw) into base body (cw), d) Microstructure distribution after Standard-HIP-treatment. Material: TiAl6V4

MoldJet and 3D Gel Casting: Material properties of IN713C and Ti Grade 5

T. Studnitzky[1]*, S. Riecker[1], R. Teuber[1], C. Zhong[1], T. Weißgärber[1,2]

[1] Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, [2] TUD Dresden University of Technology, Faculty Mechanical Engineering, Institute of Materials Science, Chair Powder Metallurgy
*Thomas.studnitzky@ifam-dd.fraunhofer.de

Laser powder bed fusion (LPBF) is dominating Additive Manufacturing of metals in equipment manufacturing, research, and applications. Since LPBF has still limitations in terms of geometries and materials as well as in terms of productivity, such sinter-based additive manufacturing (SBAM) processes are becoming increasingly important [1].

In addition to the established technologies Metal Binder Jetting or Fused Filament Fabrication, there are several new emerging technologies with good property profiles. From these technologies, this paper will focus on MoldJet and 3D Gel Casting. These processes address different application profiles. While 3D Gel Casting is currently limited to small quantities, MoldJet is targeting medium and large series production. In a technology comparison, the properties of the materials IN713C and Ti Grade 5 in regard to the powders used, microstructure, surface qualities, mechanical properties and surface qualities are determined also in comparison to established processes like LPBF and Metal Injection Moulding (MIM). In this work samples for material characterization as well as demonstrator geometries were printed and sintered.

It is shown that the typical values for MIM can be reached and exceeded with 3D Gel Casting and MoldJet using MIM powder. The values achieved for 713C are 1166 MPa for tensile strength with a fracture strain of 12.5 %, while the values for Ti grade 5 were 867 MPa (tensile strength) and 10 % (fracture strain). The residual porosity was < 3 % for both technologies and the surface values (Ra) without mechanical post-processing were below 3.5 µm. The sintering shrinkage was essentially identical in all three dimensions, the microstructure was also homogeneous, and the printed layer structure was no longer recognisable in the sintered specimen. Furthermore, initial conclusions are drawn regarding the economic advantages of these processes. MoldJet especially can reach high productivity at low costs while 3D Gel Casting shows superior surface qualities without postprocessing.

Figure 1. Printed injection nozzle made of 713c using MoldJet (left), excellent surface quality without post processing using 3D Gel Casting (right)

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

References

[1] T. Studnitzky, *Proceedings EuroPM*, 2023
[2] R. Teuber, *Proceedings WorldPM,* 2023
[3] S. Riecker, *Proceedings EuroPM*, 2021

Non-weldable Ni-based alloy MAR-m247 by fused filament fabrication: Microstructure and mechanical properties

E. Mese[1], W. Hofmann[2], P. Würtele[2], U. Glatzel[1,3], H. Daoud[1*]

[1] Neue Materialien Bayreuth GmbH, [2] Peter Würtele, [3] University of Bayreuth - Metals and Alloys
* haneen.daoud@nmbgmbh.de

Non-weldable materials such as various Ni-based superalloys have high thermomechanical properties and good corrosion resistance at high temperatures [1]. However, standard additive manufacturing processes, such as PBF, are not yet suitable for difficult and non-weldable alloys due to their poor weldability [2-4]. Therefore, fused filament fabrication (FFF) is used in this article to produce complex components from a non-weldable Ni-based superalloy. For this purpose, the alloy MAR-m247 is investigated. The elimination of the high cracking susceptibility of MAR-m247 during filament fabrication and the sinter-based FFF process is emphasised.

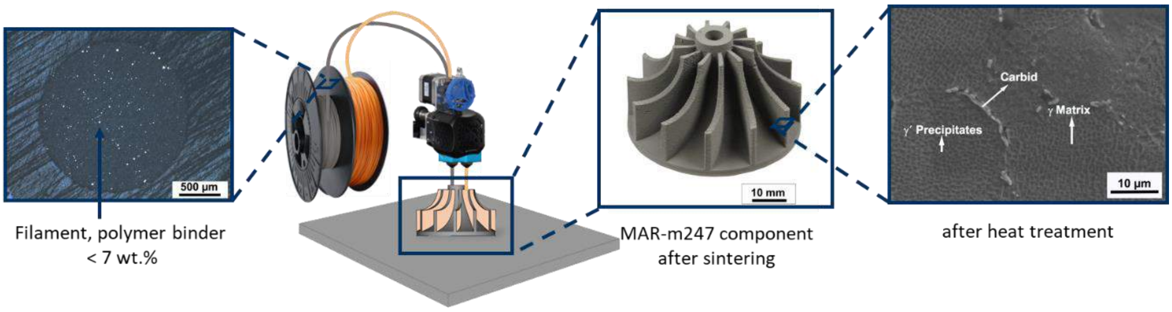


Figure 1. Additive manufacturing of non-weldable Ni-based alloy MAR-m247 by fused filament fabrication

The fabrication of highly filled filaments with 94 wt.% of metal is described. The effects of process parameters, debinding and sintering on the tensile strength and fatigue behavior at room and high temperatures are discussed. The microstructure of the sintered specimens after post-heat treatment was investigated by electron microscopy. The porosity in the sintered specimens is less than 2%, while the total shrinkage is about 14 %.

References

[1] B. Albert, R. Voelkl, U. Glatzel, *Metall Mater Trans A*, **2014**, *45*, 4561–4571.
[2] E. Chauvet, P. Kontis, E. Jägle, B. Gault, D. Raabe, et al. *Acta Materialia*, **2018**, *142*, 82-94.
[3] J. Xu, H. Brodin, R-L. Peng, V. Luzin, J. Moverare *Materials Characterization*, **2022**, *185*, 111742.
[4] D. Grangea, J-D. Bartouta, B. Macquaireb, C. Colin *Materialia*, **2021**, *15*, 101008.

On the Microstructure and Crystallography of Inconel X-750 manufactured by Powder Bed Fusion by Laser Beam

A. S. P. Pereira [1*], G. M. Volpato [1], G. J. Schlick [2], U. Tetzlaff [1**]

[1] Technische Hochschule Ingolstadt
[2] Fraunhofer-Institut für Gießerei- Composite- und Verarbeitungstechnik
* adriano.desouzapintopereira@thi.de
** ulrich.tetzlaff@thi.de

While extensive attention has been given to evaluating the additive manufacturing (AM) of Inconel alloys 718 and 625 [1], the energy and transport segments' interest in AM-superalloys restricts itself not only to these materials, since e.g. more than one polycrystalline alloy composes a turbine engine. There is also scientific value in researching the behaviour of alloys with different reinforcement phases, thus, with the intention of expanding our understanding of additively manufacturing superalloys, the influence of laser-AM in the processing of a polycrystalline γ'-reinforced nickel superalloy, Inconel X-750, is described. We report the effect of laser power and scan speed in the crystallography and microstructure of samples produced by Powder Bed Fusion of Metals using a Laser Beam (PBF-LB/M). A description of this material parameterization is novel.

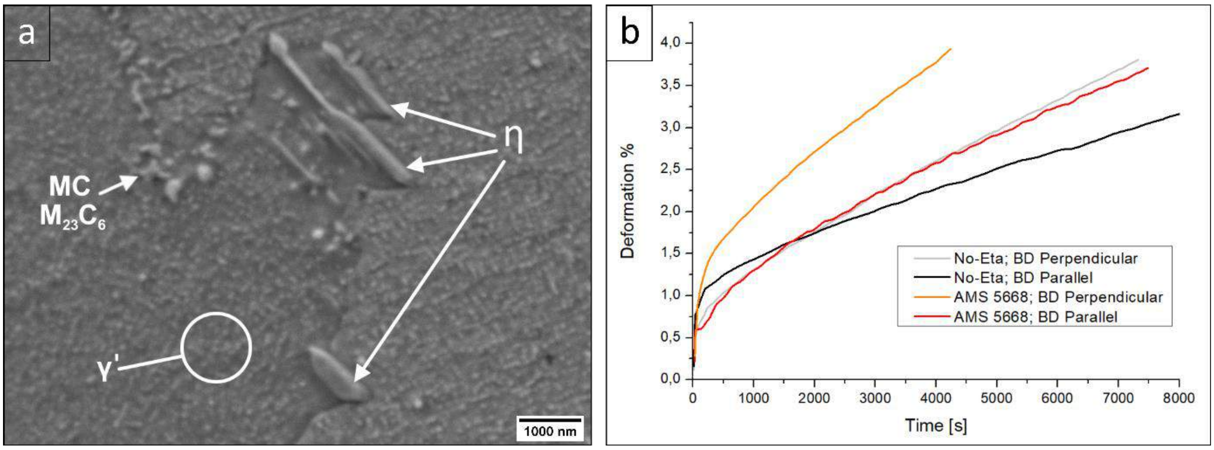


Figure 1. a) Microstructure overview of Inconel X-750 b) Effect of build direction and heat treatment in compressive creep behaviour (800°C, 280 MPa).

Findings were made regarding the phases precipitated during heat treatment, while the relation of the process parameters to the amount of geometric necessary dislocations, grain size, and crystal anisotropy is also described. Extensive electron backscatter diffraction (EBSD) and X-ray diffractometry analysis were performed for such. Information about the heat-treated material's texture is also provided by Synchrotron crystallography. As the presence of an unexpected intermetallic phase, the η-Phase, was detected after standard AMS 5668 heat treatment, in a likely manner to a previous publication [2], a new heat treatment which hinders this phase's precipitation was devised. Lastly, initial compressive creep results will be presented by comparing the effects of samples in two build orientations and under two heat treatment conditions.

With this, the project currently being performed around this alloy will be presented, hopefully granting insight into γ'-reinforced polycrystalline AM-alloys and resulting in fruitful exchange among the Symposium's attendees.

References

[1] G. M. Volpato, U. Tetzlaff, M. C. Fredel; *Additive Manufacturing*, **2022**, volume *55*.
[2] G.M. Volpato, A.S.P. Pereira, G. Lemos, M. Schmitt, U. Glatzel, F. Pyczak, U. Tetzlaff, and M.C. Fredel; *Metallurgical and Materials Transactions A*, **2023**, volume *54*, pages 1924 - 1936.

PBF-EB of hard phase containing steel in highly wear resistant applications

M. Franke-Jurisch[1*], A. Kirchner[2], C. Zhong[1], T. Weißgärber[1,2]

[1] Fraunhofer Institute for Manufacturing Technology and Advanced Materials, [2] TUD Dresden University of Technology
*marie.franke-jurisch@ifam-dd.fraunhofer.de

In times of fluctuating supply security and climate protection, materials are increasingly gaining a second life. This requires energy and wear-intensive recycling processes. Resource-efficient and high-quality processing of waste demands materials that are durable despite extreme conditions. In most cases, this is accompanied by more challenging machinability, hence the more wear-intensive variant is commonly chosen. In addition to the high material waste, this also leads to increased labor costs for the replacement of wear parts and thus to system downtimes.

Additive manufacturing makes it possible to design such components close to their final contour and adapted to their function. Powder Bed Fusion by Electron Beam (PBF-EB) also allows materials to be used that were previously difficult to process. These include steels containing hard particles. As such powders can only be atomized to a limited or even no extent, this makes it difficult to establish a suitable process window.

The study was conducted to produce powder mixtures of the material FeCr10V and the hard material TiC and to investigate the effects on processability in the PBF-EB process in more detail. For this purpose, parameters such as the power, the beam speed, the line spacing or the scanning strategy were varied and evaluated on metallographic sections. In addition to the investigation of porosity, microstructure and composition using light and scanning electron microscopy, final measurements of hardness and wear resistance were carried out.

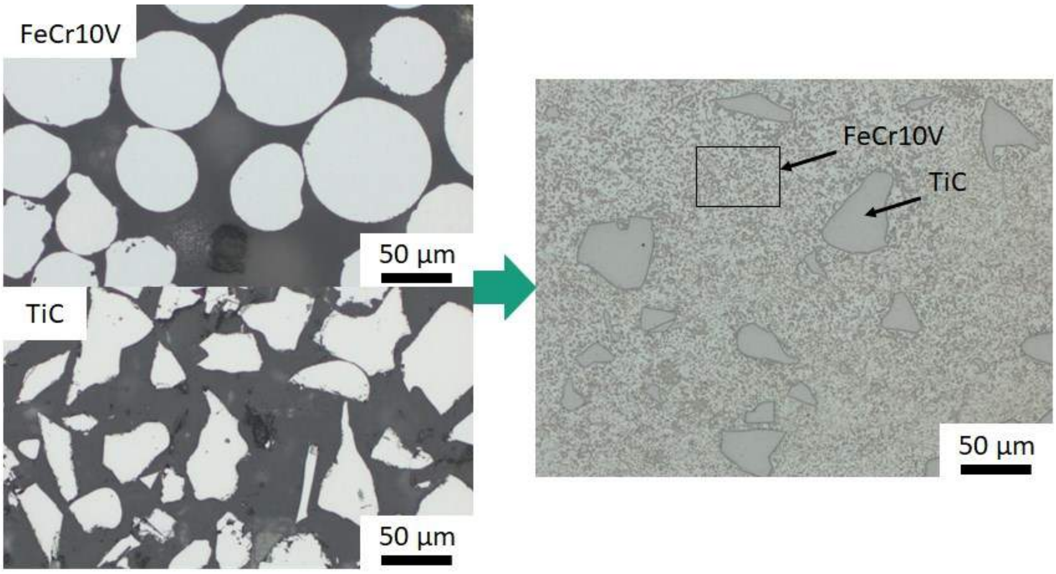


Figure 1. PBF-EB of powder mixtures of prealloyed FeCr10V and TiC powders (left) leading to a homogeneously distributed hard phase strengthened composite (right)

Selective Laser Melting of Pure Copper (Cu-ETP)

K. U. M. Miah[1*], A. Kloshek[1], R. Ossenbrink[1], H. Seidlitz[2,3]

[1]Brandenburg University of Technology Cottbus-Senftenberg
Department of Joining and Welding Technology
* Kamal.Miah@b-tu.de

[2]Brandenburg University of Technology Cottbus-Senftenberg
Department of Polymer-based Lightweight Design

[3]Fraunhofer Institute for Applied Polymer Research - IAP

Modern additive manufacturing (AM) processes, in particular selective laser melting (SLM), are used to manufacture 3-dimensional, lightweight metallic components. The ability of SLM has been successfully exhibited in the manufacturing of topology optimized complex components made from various materials, utilizing an infrared laser with a wavelength of approximately 1070 nm. Nevertheless, the manufacturing of components using highly reflective materials, such as pure copper and copper alloys, presents challenges due to their significant reflectivity at this wavelength [1][2].

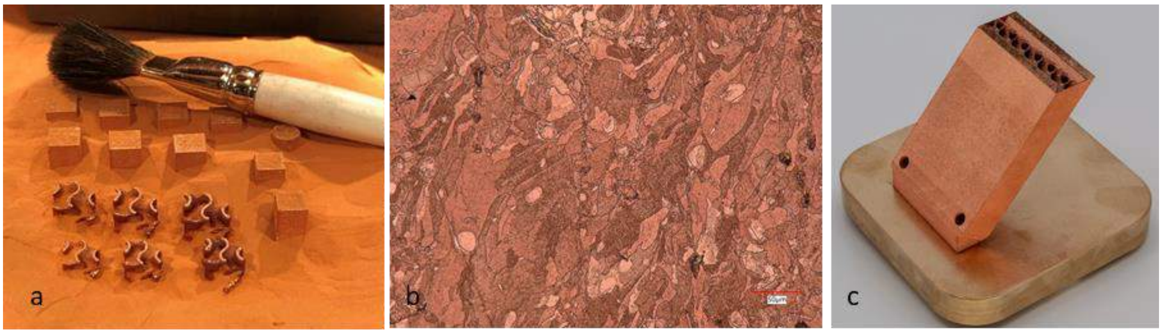


Figure 1. (a) Solid cubes and gyroid structures of Cu-ETP in SLM process chamber (b) Microscopic image from the cross section (c) Heat exchanger for high-performance electronics, designed with a gyroid structure, made of Cu-ETP and built on substrate of copper alloy

The main objective of this study is to address the difficulties related to the production of highly dense parts utilizing pure Cu-ETP powder. In order to achieve this goal, the SLM machine was modified by replacing the regular infrared laser with a laser operating in the range of 530 to 534 nm. Following this modification, a detailed experiment was conducted to determine the most effective procedural parameters for producing solid components and gyroid structures of Cu-ETP. The study determined that in order to produce a part density of 99.6 ± 0.2%, the following parameters are required: a laser power of 130 ± 10 W, a scanning speed of 350 mm/s, and a layer thickness of 25 µm. The microscopic anlaysis on the SLM-manufactured components showed a consistent grain structure across the build parts. Furthermore, it was discovered that exceeding the predetermined laser power and scanning speed parameters led to lower density of the parts. Conversely, decreasing the laser power and scanning speed below these thresholds was determined to be economically disadvantageous.

References

[1] A. Gebhardt, *Understanding Additive Manufacturing*. 2011. doi: doi.org/10.3139/9783446431621.

[2] P. A. Sugioka K, Meunier M, “Laser Precision Microfabrication - Springer- verlag,” vol. 135, pp. 1–8, 2010, doi: doi.org/10.1007/978-3-642-10523-4.

Study on processing of large-scale magnesium alloy AZ91 component manufactured by Plasma Metal Deposition (PMD®) for space applications

E. Ariza-Galván* [1], Ľ. Bača [2], M. Schnall[3], N. Stelzer [2], Z. Igniatov [4], S. Uscnick [3], E. Neubauer [1], M. Meisnar [5], L. Pambaguain [5].

[1] RHP-Technology GmbH, Seibersdorf, Austria, [2] Aerospace & Advanced Composites GmbH, Wiener Neustadt, Austria, [3] LKR Leichtmetallkompetenzzentrum, Ranshofen, Austria, [4] Beyond Gravity, Vienna, Austria, [5] ESTEC-ESA, Noordwijk, Netherlands.
*e.ar@rhp.at

In space applications, low density materials and high stiffness are required to reduce the vehicle weight and therefore increase the payload. For this reason, magnesium alloys are of interest, their low density would be beneficial to substitute aluminium in many aerospace structure applications, depending on the exact stiffness and load-bearing requirements. However, only few magnesium alloys are certified, hardly available as wrought alloys, and they are more challenging in processing than aluminium alloys.

Plasma Metal Deposition (PMD) is an advanced emerging additive manufacturing technique that belongs to the Direct Energy Deposition manufacturing group, using a plasma arc as energy source for melting powder or wire feedstock materials with high deposition rates [1,2]. The application of PMD manufactured Mg-alloys components in space hardware is beneficial as it allows implementing integral, complex and large designed structures.

In this study, the manufacturing and processing of AZ91 wires into a near net shape component using PMD is presented with the aim of producing a large scale, complex technological demonstrator.

Thin-wall structures were fabricated with small-batch wire feedstock AZ91, tensile test samples and test coupons were extracted to evaluate mechanical properties and microstructure of the as deposited and heat-treated material. Furthermore, to be qualified for space applications, stress corrosion cracking experiments are done on test coupons and thermal cycling behaviour of the AZ91 manufactured component is studied.

Figure 1. Magnesium alloy AZ91 demonstrator deposited via Plasma Metal Deposition (PMD).

References

[1] E. Ariza-Galván, I. Montealegre-Meléndez, C. Arévalo-Mora, E. Pérez-Soriano, E. Neubauer, M. Kitzmantel. Plasma Metal Deposition for Metallic Materials. *Advanced Additive Manufacturing. IntechOpen*; 2022.
[2] E.Ariza-Galván; I. Montealegre-Meléndez; E. Pérez-Soriano; E. Neubauer; M. Kitzmantel; C. Arévalo. Influence of Processing Conditions on the Mechanical Properties of 17-4PH Specimens Produced by Additive Manufacturing, *Machines,* 2022, 10, 976 .

Analysis of the topographical, microstructural and mechanical surface properties of AlSi10Mg for a broad range of additive-manufacturing process parameters

U. Klanjšček[1*], M. Kalin[2]

[1] Laboratory for Tribology and Interface Nanotechnology, Faculty of Mechanical Engineering, University of Ljubljana, Bogišićeva 8, 1000 Ljubljana, Slovenia
*urban.klanjscek@fs.uni-lj.si

With the need to save energy and minimize carbon emissions, additive manufacturing (AM) [1], especially selective laser melting (SLM) [2,3], is becoming increasingly important in manufacturing. Advances in AM over the last decade have seen it evolve from a prototyping technology to the point where it is transforming the way products are designed, developed and manufactured, and with improved properties and performance [4]. In this work the varied parameters were laser scanning speed (500–1700 mm/s) and the laser power (250–370 W). We analyze and discuss how these two parameters affect the surface topography, roughness, porosity, microstructure and hardness, as well as their anisotropy for the top and side surfaces in during selective laser melting (SLM) using a single AM machine and printing strategy.

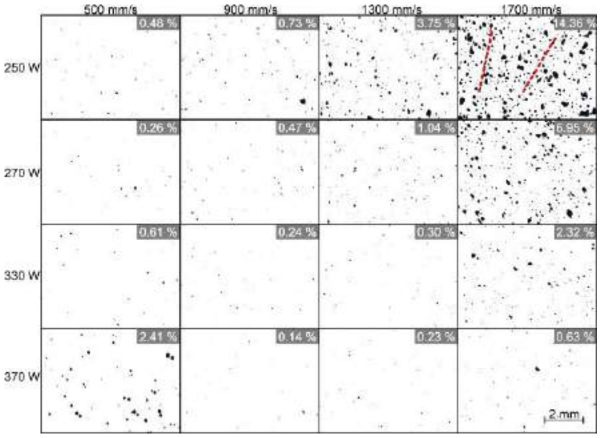


Figure 1. Surface porosity of top printed polished specimens with AM processing parameters.

With a high laser power and a slow scanning speed, top surfaces become flatter. An increase in the scanning speed, scanned paths become more distinguished with increased height and with less power, the balling effect becomes predominant, causing waviness and larger gaps in between scanning lines. Side surfaces are mostly comprise made up of adhered powder particles, caused by thermal conductivity or laser dispersion and are more predominant at lower energy densities. The surface porosity of the printed specimens show circular gas pores formed in the region at higher energy densities, which have circular shape. On the other hand, a lack of fusion pores, with irregular shapes, filled with powder particles, are present at lower energy density. The heat-affected zones in microstructure at the boundaries are comprised of three regions, where the area is increasing with energy density. With a decrease in the energy density the cellular dendritic microstructure is becoming smaller. On side surfaces the dendrites have columnar geometries instead of cellular.

References

[1]. G. Miao, M. Moghadasi, M. Li, Z. Pei, C. Ma, *Binder Jetting Additive Manufacturing*, **2022**, 4-7.
[2] L. zhi Wang, S. Wang, J. jiao Wu, *Opt Laser Technology*, **2017**, 88–96.
[3] I. Koutiri, E. Pessard, P. Peyre, O. Amlou, T. De Terris, *Mater Process Technology*, **2018**, 536–546.
[4] Q. Yan, B. Song, Y. Shi, *Mater Sci Technology*, **2020**, 199–208.

Tailoring the functional and mechanical properties of Nitinol via PBF-EB

B. Wahlmann[1*], A. Fink[1], C. Körner[1]

[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, Materials Science and Engineering for Metals, Germany
*benjamin.wahlmann@fau.de

Nitinol, a binary alloy of Ni and Ti, is the most widely used shape memory alloy (SMA). It is used in medical technology as well as engineering applications such as thermally triggered micro-actuators. The shape memory effect relies on a reversible, stress- or thermally induced transformation from austenite to martensite. SMAs are typically produced as sheets or wires with a pronounced texture resulting from the manufacturing process. The texture strongly influences the deformation behavior, the mechanical properties, and the extent of the shape memory effect [1,2].

Electron beam powder bed fusion (PBF-EB) is a promising alternative to the established thermo-mechanical processing methods as it allows near-net-shape production with minimal impurity pick-up. However, the build process induces directional solidification, evaporation, and internal stresses, all of which may affect the functional properties [3,4]. In this study, we investigate the effects of the beam power on the microstructure and the mechanical properties, as well as the influence of the build orientation on superelasticity and the shape memory effect of Ti-rich Nitinol. The material is processed on a freely programmable *Freemelt One* PBF-EB machine.

First, a processing window is rapidly established using only in situ electron optical imaging (ELO [5]) of the build surfaces. The effect of the heat input is examined by systematically varying the area energy. Increasing energy input causes the formation of Ti_2Ni precipitates due to the evaporation of Ni. These precipitates increase the stiffness and reduce the ductility.

Samples built standing (0°, cf. Fig. 1), flat (90°), and at 45° orientation were tested under tension and cyclic compression using a *Gleeble 3500*. The load direction relative to the build direction markedly influenced the mechanical strength. Furthermore, the percentage of recoverable strain under cyclic load was similarly affected, ranging from about 50 % for 45° relative orientation to 95 % for loading parallel to the build direction. Therefore, the strength of the shape memory effect shows a pronounced dependence on the texture. In the future, controlling the texture may enable the design of components with locally tailored shape memory properties.

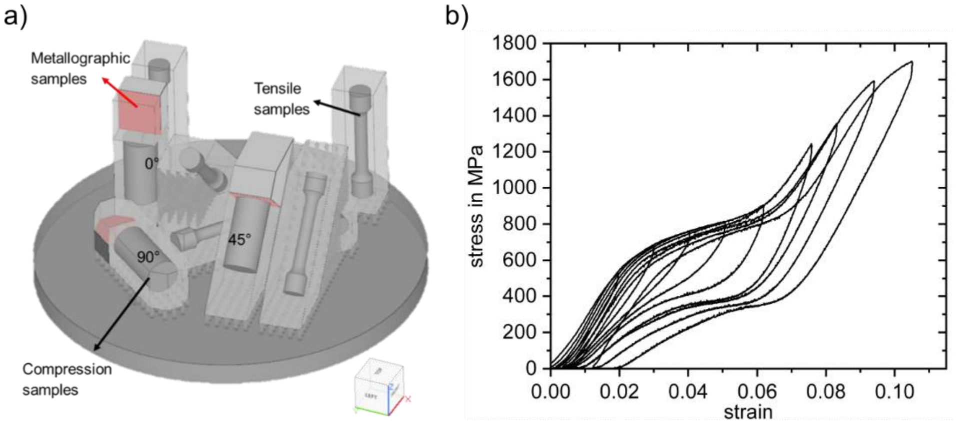
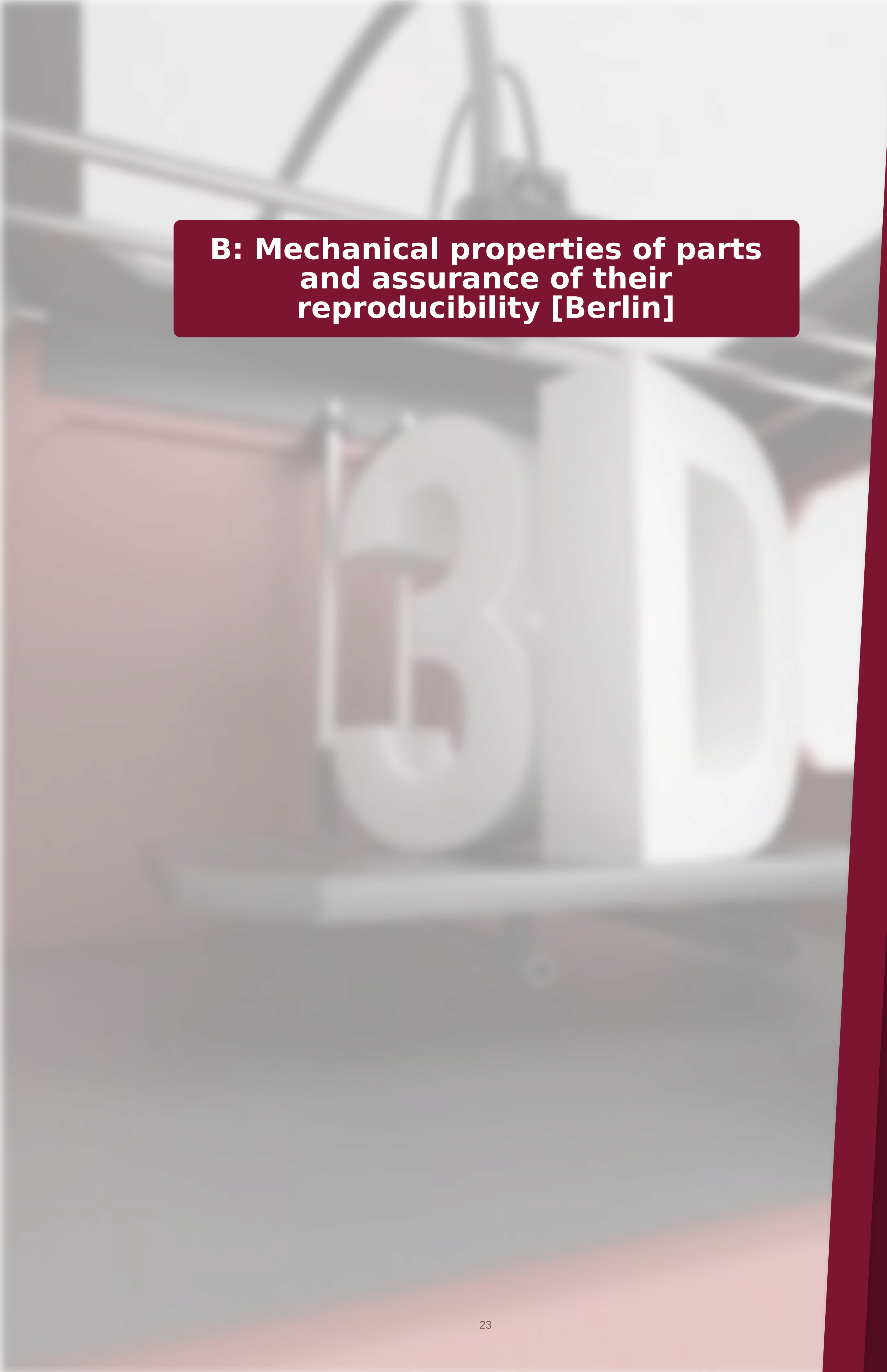


Figure 1. a) PBF-EB build setup. b) Superelastic compression cycling of a specimen loaded parallel (0°) to the build direction.

References

[1] B. Sun, *Materials Science and Engineering A*, **2021**, *809*, 140779.
[2] G. Laplanche, *Acta Materialia*, **2017**, *127*, 143-152.
[3] I. Ferreto; *Materials & Design*, **2023**, *229*, 111928.
[4] A. Fink, *Materialia*, **2023**, *30*, 101823.
[5] C. Pobel, *Materials Letters*, **2019**, *249*, 70-72.

B: Mechanical properties of parts and assurance of their reproducibility [Berlin]



Additive Manufacturing of High Strength Al-Mg-Si Alloys with DED-Arc

A. Pittner[1*], R. Winterkorn[1], Ç. Fabry[1*], M. Rethmeier[1]

[1] Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin
*andreas.pittner@bam.de

Direct energy deposition additive manufacturing technologies that utilize an electric arc have great potential for generating large volume metal components. However, selecting process parameters that yield the desired near net shape design and requested mechanical component behavior is not a trivial task due to the complex relationship between all process parameters and material characteristics (Fig. 1). This presentation exemplifies the application of a newly developed solid welding wire doped with TiB to enhance grain refinement in the deposited metal for additive manufacturing based on DED-Arc of high-strength precipitation hardening AlMgSi-aluminum alloys. It is worth noting that the solid wire is the result of our preliminary metallurgical studies on grain refinement in aluminum weld metal [1].

Consequently, research focuses on the correlation between process parameters and component quality to understand the underlying mechanisms. This is crucial for evaluating a robust process parameter space that yields component quality in line with corresponding standards which are mainly taken from welding technology.

Specifically, we examine component quality by analyzing pore size and distribution, as well as grain morphology. To enhance the mechanical properties of the deposited metal, a post-weld heat treatment was conducted, comprising of solution treatment, quenching, and artificial aging. The study also evaluates the effects of various heat treatment strategies on the final mechanical properties of the material.

To demonstrate the applicability of 3D metal printing of high-strength aluminium alloys, a more complex demonstrator was created. It has been shown that DED-Arc can produce high-volume aluminium parts with the same quality as the corresponding subtractive processing strategy.

Additionally, the entire additive manufacturing chain has been digitally integrated, enabling traceability of all relevant process steps, which is essential for reliable subsequent quality assessment.

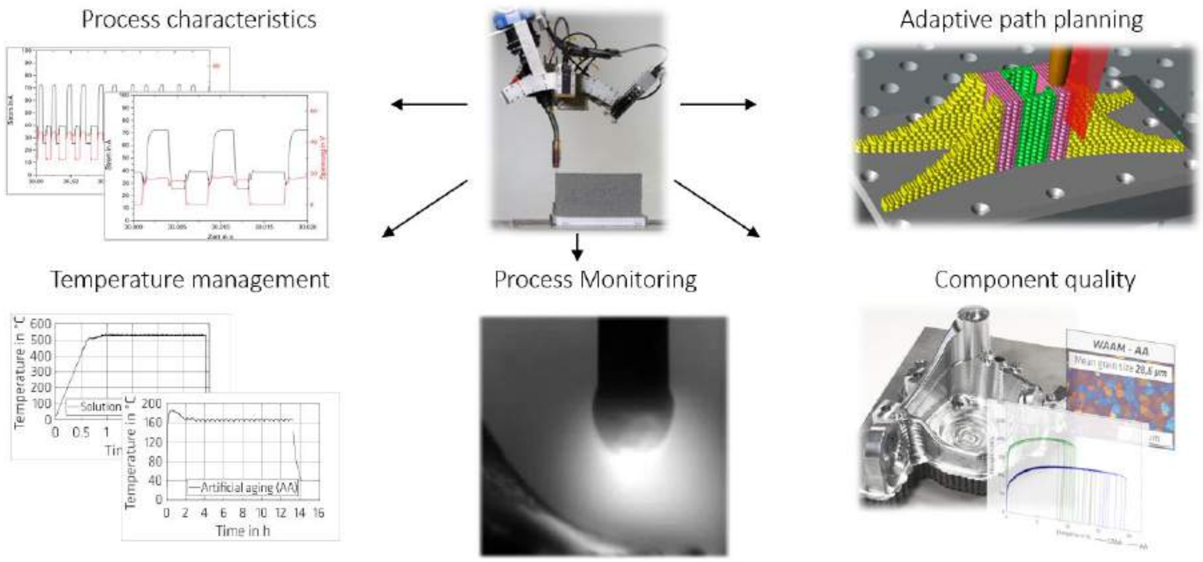


Figure 1. Additive manufacturing chain at BAM to print large volume metals parts utilizing DED-Arc processes.

[1] Schempp, P., Cross, C.E., Pittner, A. et al. Influence of Solute Content and Solidification Parameters on Grain Refinement of Aluminum Weld Metal., *Metall Mater Trans A*, **2013**, *44*, 3198–3210, https://doi.org/10.1007/s11661-013-1649-3

Additive manufacturing of high-strength steel components using gas metal arc welding based direct energy deposition

K. Wandtke[1*], L. Engelking[1], D. Schroepfer[1], R. Scharf-Wildenhain[2], A. Hälsig[2], A. Kromm[1], T. Kannengiesser[1], J. Hensel[2]

[1] Bundesanstalt für Materialforschung und -prüfung,
[2] Technische Universität Chemnitz, Professur Schweißtechnik
*karsten.wandtke@bam.de

Additive manufacturing processes such as direct energy deposition-arc (DED-Arc) or Wire Arc Additive Manufacturing (WAAM) enable the efficient production of weight-optimized near-net-shape components in modern steel constructions [1,2]. Further increased efficiency can be achieved by using high-strength steels, which leads to significant cost, time, and resource savings. While commercial filler metals for arc welding processes are available, their industrial application is hindered by a lack of guidelines and quantitative knowledge of the welding stresses during production and operation limit their industrial application. In a joint project of BAM and Chemnitz University of Technology, the main influences and complex interactions of material, production process, design and processing steps on the residual stress level are investigated. The aim is to develop processing recommendations and a cold cracking test for economical processing and stress-related design of high-strength steels with DED-arc.

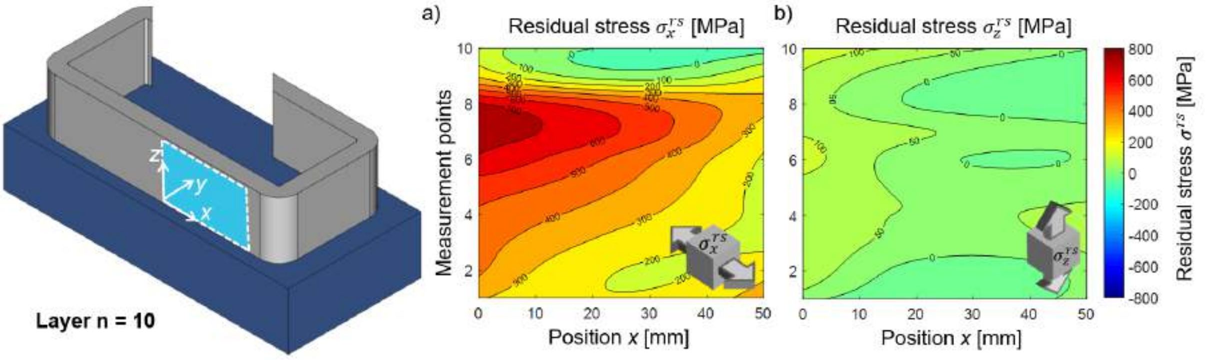


Figure 1. Residual stress analysis using neutron diffraction, a) residual stress map in x-direction (welding direction), b) residual stress map in z-direction (build-up direction)

The project focused on hardness and microstructure analysis as well as residual stress analysis using X-ray diffraction on the surface and neutron diffraction in the bulk. Reference specimens (open hollow cuboids) were fully automatic manufactured using a robot welding system. Systematic variation of the heat control and design was used to analyze the influences on heat input and interpass temperature, as well as geometric influences such as component length, height, and wall thickness. Figure 1 shows that the residual stresses in the WAAM specimens within the project are predominantly one-dimensional in welding direction (cf. [3]). Furthermore, the results reveal that the residual stresses are significantly influenced by the heat input. Low heat input and high cooling rates lead to high average residual stresses. The analysis of the variation of the component design indicates that the component height, in contrast to component length and wall thickness, significantly influences the level of residual stresses.

References

[1] J., Plangger; P., Schabhuettl; T. Vuherer; N. Enzinger CMT Additive Manufacturing of a High Strength Steel Alloy for Application in Crane Construction, Metals, **2019**, 9, doi:10.3390/met9060650.
[2] W. E., Frazier Metal Additive Manufacturing: A Review, Journal of Materials Engineering and Performance, **2014**, 23, 1917-1928, doi:10.1007/s11665-014-0958-z.
[3] Q. Wu, et al. Residual stresses in wire-arc additive manufacturing – Hierarchy of influential variables, Additive Manufacturing, **2020**. 35

Development of representative test specimens by thermal history transfer in laser powder bed fusion

G. Mohr[1*], M. A. Chaudry[1], N. Scheuschner[1], S. Blasón González[1], M. Madia[1], K. Hilgenberg[1]

[1] Bundesanstalt für Materialforschung und -prüfung,
*gunther.mohr@bam.de

The use of components manufactured by laser powder bed fusion (PBF-LB/M) and subjected to fatigue loading is still hampered by the uncertainty about the homogeneity of the process results [1, 2]. Numerous influencing factors including the component's geometry contribute to the risk of process instability and resulting inhomogeneity of properties. This drastically limits the comparability of different built parts and requires expensive full component testing [3, 4]. The thermal history as the spatiotemporal temperature distribution has been identified as a major cause for flaw formation [5]. Therefore, it can be hypothesized that a similar thermal history between components and test specimens enhances their comparability. Following this assumption, a strategy is developed to transfer the intrinsic preheating temperature as a measure of comparability of thermal histories from a region of interest of a complex component to a simple test specimen. This transfer concept has been successfully proved by the use of FEM-based macroscale thermal simulations, validated by calibrated infrared thermography. An adoption of the specimen manufacturing process by the adjustment of the inter layer times was established to manufacture specimens which are representatives of a specific region of a large-scale component in terms of the thermal history similarity criterion. The concept is schematically illustrated in Figure 1 and was demonstrated using a pressure vessel geometry from the chemical industry.

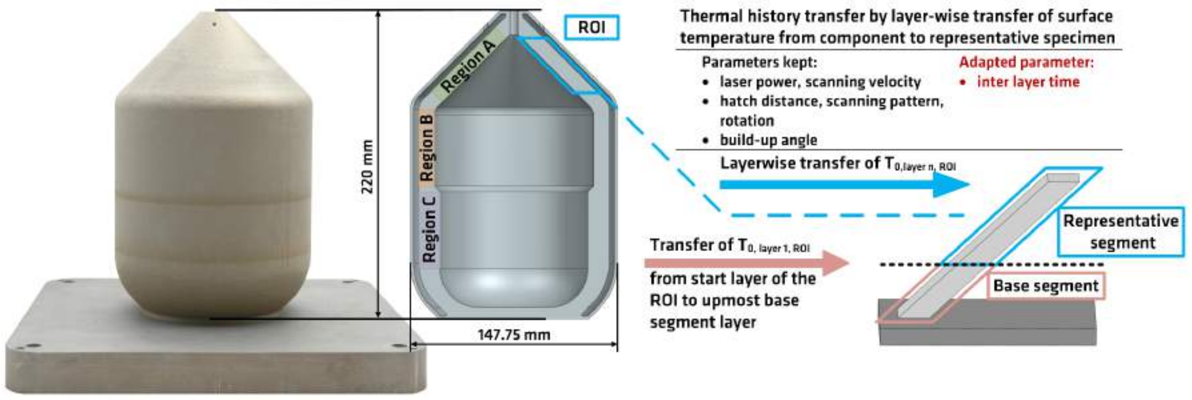


Figure 1. Schematic illustration of the concept of thermal history transfer from a demonstrator to a representative specimen.

References

[1] U. Zerbst, G. Bruno, J.-Y. Buffiere, T. Wegener, T. Niendorf, T. Wu, X. Zhang, N. Kashaev, G. Meneghetti, N. Hrabe, M. Madia, T. Werner, K. Hilgenberg, M. Koukolíková, R. Procházka, J. Džugan, B. Möller, S. Beretta, A. Evans, R. Wagener, K. Schnabel; Progress in Materials Science, **2021**, 121, 100786.

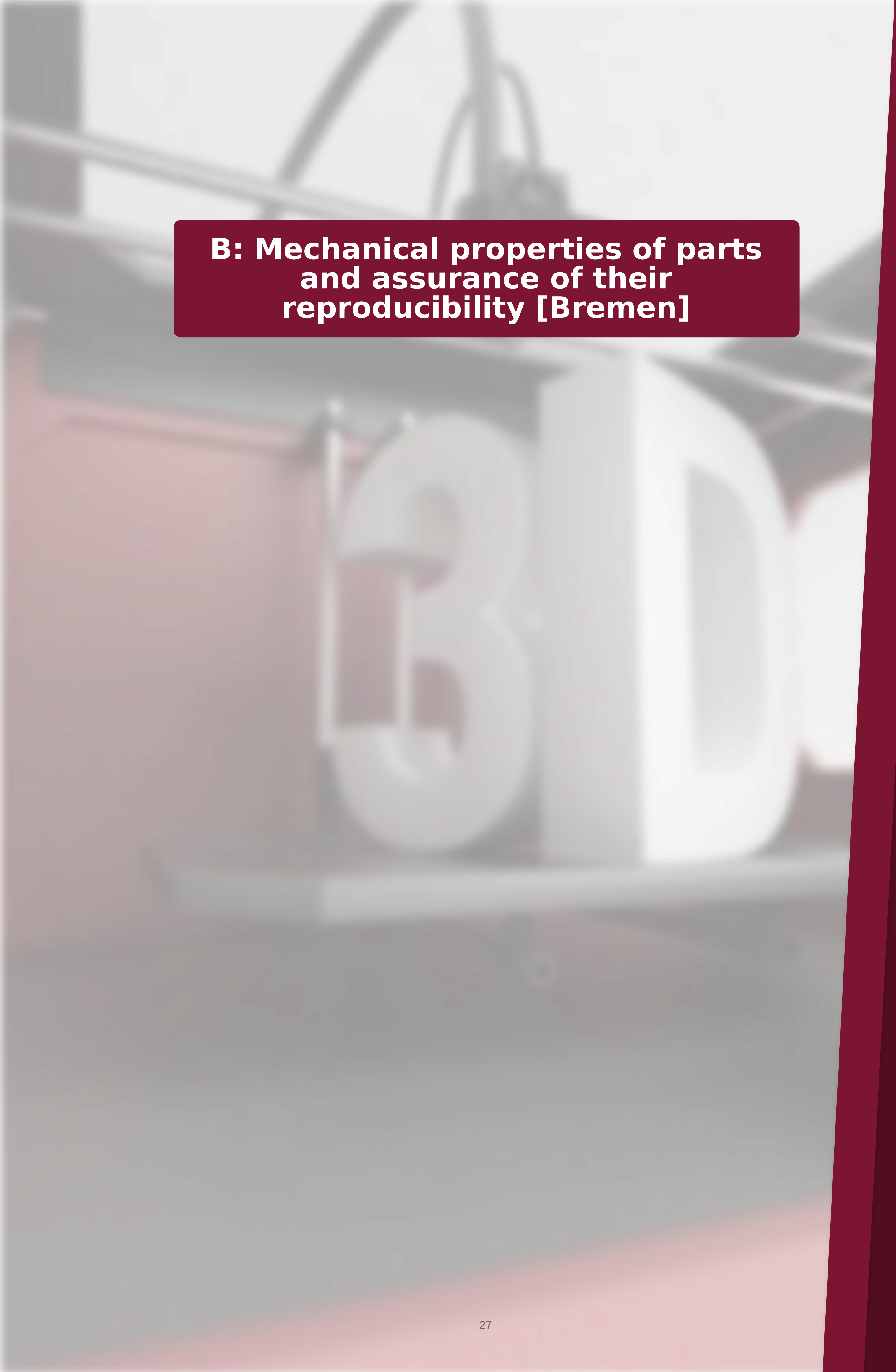
[2] F. Venturi, R. Taylor; Journal of Materials Engineering and Performance, **2023**, 32, 6589-6609.

[3] N. Sanaei, A. Fatemi, N. Phan; Materials & Design, **2019**, 182, 108091.

[4] G. Mohr, S.J. Altenburg, K. Hilgenberg; Journal of Laser Applications, **2023**, 35.

[5] A. Riensche, B.D. Bevans, Z. Smoqi, R. Yavari, A. Krishnan, J. Gilligan, N. Piercy, K. Cole, P. Rao; Materials & Design, **2022**, 224.

B: Mechanical properties of parts and assurance of their reproducibility [Bremen]



Title: Characterisation and Testing of 3D-printed PM-parts with novel Thermo-Optical-Measuring application

Dr. Andreas Diegeler*
Director Center of Device Development
Fraunhofer Institute for Silicate Research, Bronnbach 28, 97877 Wertheim
Germany

Abstract

Thermo-optical measurement devices have been developed at the Fraunhofer ISC during the last 20 years - recently also with atmospheric control (TOM-AC). This technique will be used to test and inspect additive manufactured PM-parts during the whole temperature cycle inside the furnace to evaluate full functionality. This method allows to follow changes of sample shape (up to 50mm in diameter) with an accuracy of nearly 0.3 micron by contact-less measurement. Due to the purely optical detection samples of any shape can be monitored inside the furnace. A sophisticated algorithm detects the contour of samples - and thus dimensional changes. Possible applications include simply measuring the shrinkage or shape distortions. By a computer-controlled program we realized full atmospheric control, i.e. changing the gas atmosphere inside the furnace (inert gas at different pressures, forming gas or vacuum) during the sintering process.

Main focus according additive manufactured PM-parts lies on quality and quality control during production process, and on characterization of behavior under thermal or other stress application. Thermo-Optical Measurement technique offers a wide range of contactless, optical detection of complex shaped PM-parts with very high resolution. Additional modules as load-, balance- or gas-analysis - module are appliable to the TOM system to detect in-situ creep, crack or degasing character of the parts during heat treatment. This data is highly needed for the optimization of production process and only available with innovative TOM-Technique.

Keyword

Additive Manufacturing, 3D-Printing, Thermo-Optical Measuring Technique, Characterization of sintering behavior, Quality control in production process, Quality testing

Biography

Dr. Andreas Diegeler with doctoral degree in applied Physics and Associate professor for Applied Science works as Director of the Center of Device Development of the Fraunhofer Institute for Silicate Research ISC in Wuerzburg and Wertheim, Germany since 2004. He is Specialist on Applied Physics with focus on software development, image analysis with implementation of KI-algorithms and ML-routines. Main focus of his thesis at University of Cologne, Germany was the development of new optical methods and devices to characterize Advanced Materials, finalized in 1999.

As an Expert in software development and image analysis, he works from 1999 until 2004 in the industry sector on high performed electronic material and changes in 2004 to the Fraunhofer Institute ISC.

Effects of extended shielding gas coverage on component contour accuracy in Wire Arc Additive Manufacturing

C. Kehm[1*], E. Wasilewski[1], R. Ossenbrink[1], H. Seidlitz[2,3]

[1] Brandenburg University of Technology Cottbus - Senftenberg
Department of Joining and Welding Technology
*Kehm@b-tu.de

[2] Brandenburg University of Technology Cottbus - Senftenberg
Department of Polymer-based Lightweight Design

[3] Fraunhofer Institute for Applied Polymer Research - IAP

Producing near-net-shape components with Wire Arc Additive Manufacturing (WAAM) is a challenging task. Compared to laser-based additive manufacturing technologies, WAAM is characterized by a lower contour accuracy with higher surface roughness and more uneven surface profiles. Therefore, the WAAM requires a high degree of post-processing (machining) which reduces economic efficiency and increases material consumption. Therefore, topics such as process optimization with regard to the component contour are increasingly in the focus of research. This study presents the application of an extended shielding gas coverage in the WAAM process of steel to improve part contour accuracy.

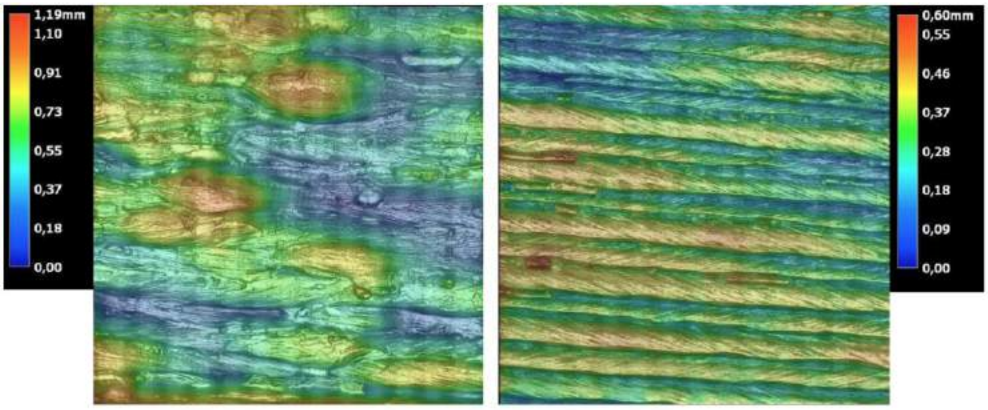


Figure 1. Measured surface profile (25x25 mm, digital microscope,100x magnification): (left) with standard and (right) with extended shielding gas coverage

A specially adapted shielding gas coverage was manufactured with laser powder bed fusion and following used to study the influence on the resulting component contour and properties in comparison to standard shielding gas nozzles. The investigations include the analysis of temperature profiles, shape deviations, hardness and porosity in the component. In addition, process parameters such as gas flow rate and nozzle geometry were varied in order to evaluate their influence on the accuracy of the component contour. The extended shielding gas coverage reduces the average deviation from the target contour significantly by a degree of 49,44%. In addition, the maximum of the occurring deviation height could be decreased by 42,39%. The results show an improvement in the dimensional accuracy of the contour and the surface quality, resulting in higher reproducibility and less post-processing effort.

Inconel 718 Mechanical Properties for Fabricate to Multi Material Impeller by Wire Arc Additive Manufacturing

S. Ejiri[1*]

[1] Nikkiso Co., LTD.
*shinichiro.ejiri@nikkiso.co.jp

Many studies have been conducted to evaluate the mechanical properties of laminations by wire arc additive manufacturing (WAAM), However, these studies do not guarantee that the moldability of laminations during industrial applications is taken into account. Especially when fabricating complex shapes such as turbomachinery impeller blades, heat input from arc welding can cause defects in the lamination process, so it would be industrially useful to clarify the mechanical properties under conditions where formability is guaranteed. Therefore, in this study, the mechanical properties of WAAM laminations were evaluated under conditions in which axial-flow impellers can be fabricated by WAAM and machining. In particular, since WAAM can improve the fabrication process of difficult-to-machine materials, Inconel 718, a typical difficult-to-machine material, was targeted.

First, an axial-flow impeller was fabricated using WAAM and machining. The shape of the axial-flow impeller was based on the fan type inducer developed in a previous study [1], and the blade shape was designed as a DAE airfoil shape to study complex shapes. In addition, for the purpose of upgrading the manufacturing of the impeller, a multi-material impeller was designed with Inconel 718 for the blade and SUS304 for the hub. The blade shape was fabricated using WAAM with Inconel 718 equivalent welding wire, on a JIS SUS304 round bar as the base material. WAAM conditions are, current: 196 A, voltage: 17 V, wire feed: 9 m/min, torch feed: 600 mm/min. Then, the blades were finished to their final shape by machining. Next, the axial-flow impeller fabricated on an industrial centrifugal pump was installed as an inducer to measure pump performance and confirmed to function soundly.

To evaluate mechanical propertiy, a wall was fabricated using WAAM under the same conditions as those used in the fabrication of the blades. After cutting the specimen shape from the wall, the specimen was finished to ISO6892-2 Annex B1. The direction of cutout from the wall is perpendicular to the lamination direction. The stress-strain diagrams obtained from the tensile tests are shown in Fig. 1. Tensile strength: 786 MPa, 0.2% proof strength: 541 MPa and elongation: 35% were obtained as the average values from 3 tests. Compared to the results of butt-welded joints of Inconel 718 without heat treatment performed by Sonar et al. under room temperature conditions [2], the tensile strength was approx. 80 MPa lower, the 0.2% proof stress was similar and the elongation was approx. 7 points higher.This difference can be attributed to the different welding / WAAM conditions.

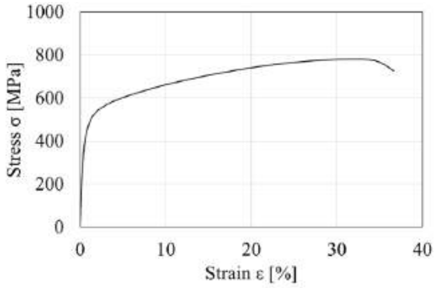
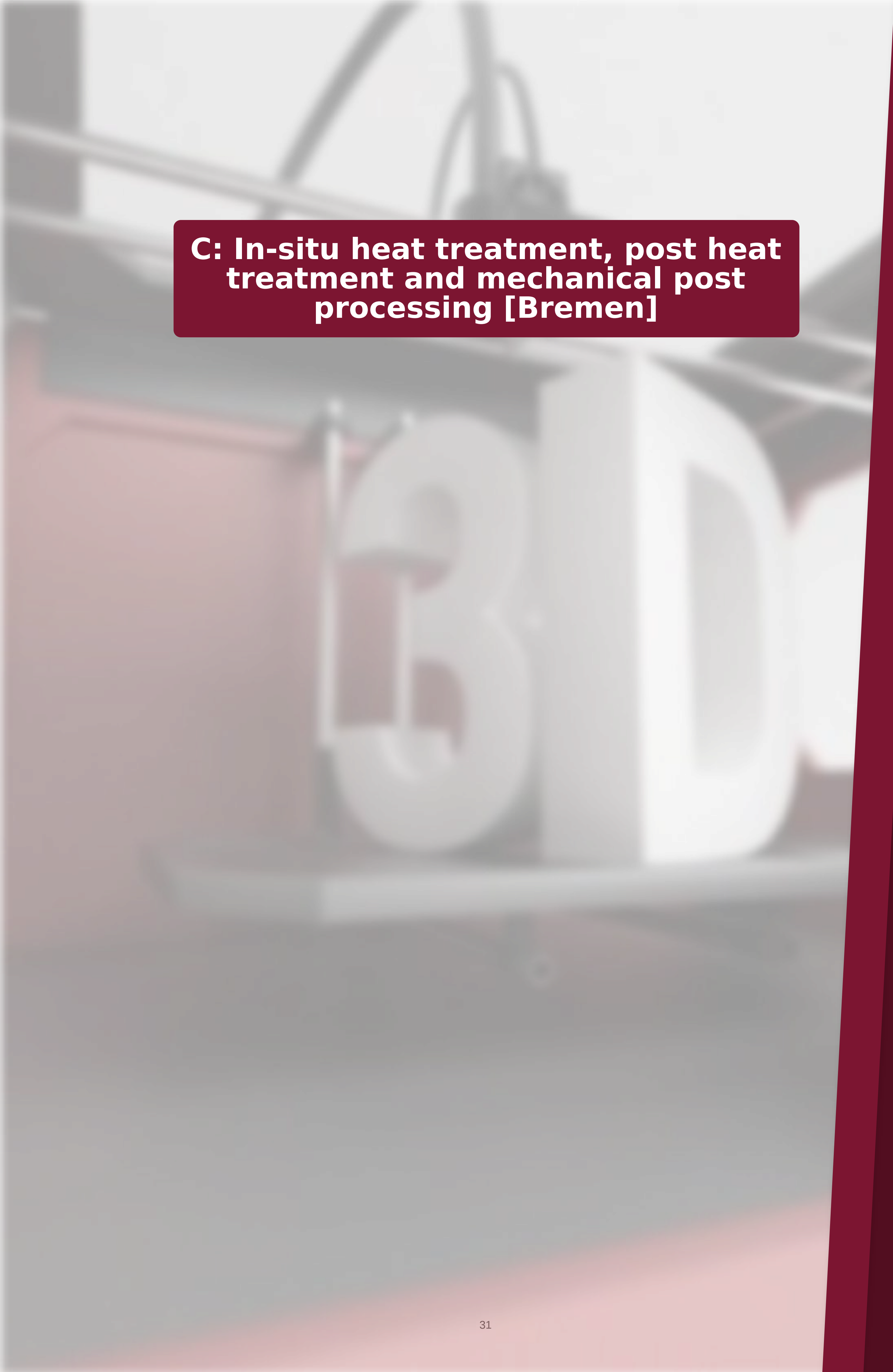


Figure 1. Tensile test results of Inconel 718 specimen fabricated by WAAM

References

[1] S. Ejiri *International Journal of Fluid Machinery and Systems*, 2023, 16-2, pp.184-191.
[2] T. Sonar, et. al, *Materials Characterization*, 2021, 174, 110997.



C: In-situ heat treatment, post heat treatment and mechanical post processing [Bremen]

Enhancing Structural Integrity in 42CrMo4 Steel (AISI 4140) Manufactured by Electron Beam-Based Powder Bed Fusion of Metals

T. Pham[1*], T. Wegener[1], J. Richter[1], T. Niendorf[1]

[1] University of Kassel, Institute of Materials Engineering - Metallic Materials, Mönchebergstr. 3, 34125 Kassel, Germany
*pham@uni-kassel.de

Quenched and tempered (Q&T) steels are known for relatively high strength, hardness and wear resistance combined with a comparatively good toughness. One of the most used Q&T steels is the low-alloyed structural steel grade 42CrMo4 (AISI 4140), as it offers a wide range of applications, representing one of the most universal grades for the Q&T heat treatment. In this context, near-net shape additive manufacturing (AM) processes represent promising candidates to overcome prevailing limitations, e.g. for small series, as these processes enable a considerable reduction in costs, as subsequent machining steps can be significantly reduced. For processing of metallic materials, the focus is particularly on powder bed-based AM processes such as laser-based powder bed fusion of metals (PBF-LB/M) and electron beam-based powder bed fusion of metals (PBF-EB/M). However, with respect to manufacturing of the low-alloyed Q&T steel 42CrMo4 by powder bed-based AM techniques, studies employing the PBF-EB/M process are still limited. The present study, thus, focuses on assessing the structural integrity of Q&T steels manufactured via PBF-EB/M technique.

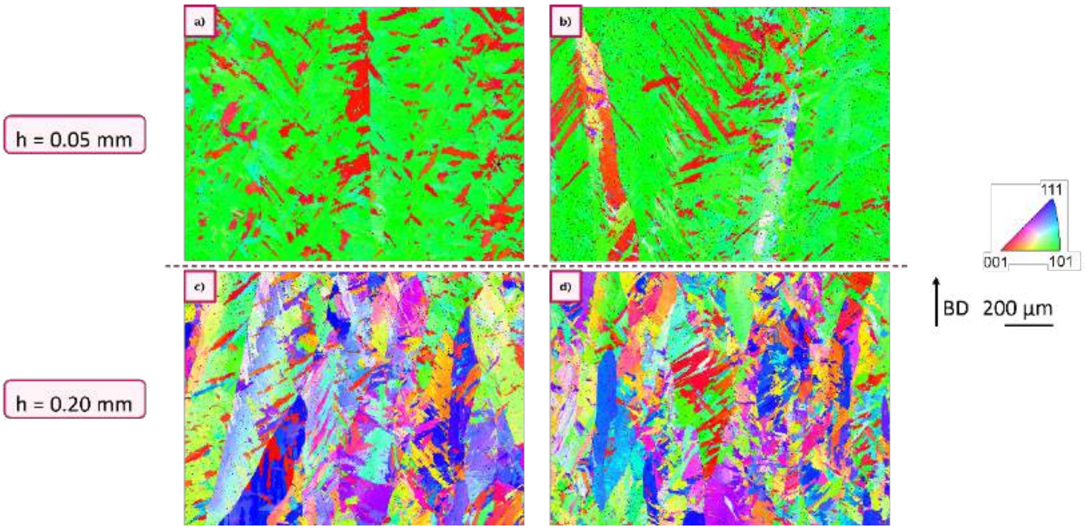


Figure 1: Inverse pole figure maps of PBF-EB/M Q&T steel 42CrMo4 (AISI 4140) manufactured with different parameter sets: a) v = 4000 mm/s, h = 0.05 mm, E = 60 J/mm³, b) v = 5000 mm/s, h = 0.05 mm, E = 48 J/mm³, c) v = 1000 mm/s, h = 0.20 mm, E = 60 J/mm³ and d) v = 2000 mm/s, h = 0.20 mm, E = 30 J/mm³. All specimens were manufactured with a beam current of 10 mA.

Near-fully dense components were fabricated by optimizing key process parameters, such as beam current, scanning speed (v) and hatch distance (h), aiming on an enhanced microstructure and mechanical properties. For mechanical characterization, hardness and quasi-static mechanical properties in both, as-built and heat-treated conditions, were assessed in order to examine the effects of post-processing routes. In direct comparisons with conventionally manufactured 42CrMo4 steel, the PBF-EB/M material revealed that tailored properties can be achieved. This work demonstrates the potential of PBF-EB/M to produce high-strength, wear-resistant steel components with the added benefits of design flexibility and reduced efforts in post-processing, making 42CrMo4 suitable for demanding engineering applications.

F. Keil, J. Schubnell, S. Fliegener, A. Heiss, D. Tiberto, U.E. Klotz

Enhancing the fatigue strength of AM materials via mechanical surface treatment

Additive manufacturing (AM) processes, such as powder-based or sintering methods, offer a high degree of flexibility to produce parts with complex geometries, even for structural applications that typically require a high strength of the components. However, the poor surface quality of as-built parts results in a low fatigue strength compared to conventionally manufactured components. Thus, the use cases for metallic AM components in safety relevant applications such as aviation and transport are currently limited. Reasons for the poor fatigue strength are the high surface roughness and defects such as pores and lack-of-fusion (LOF) near the surface layer. These notch-like features act as crack initiators. To improve the fatigue strength of the surface layer, mechanical surface treatment (MST) methods offer great potential, e.g. shot peening or deep rolling are widely used for post-treatment of conventionally manufactured components. However, relatively few studies exist for AM materials. In the ongoing IGF project 22833N "AM Oberfläche", MST methods such as shot peening and deep rolling are investigated to improve the properties of additively manufactured AlSi10Mg and 316L parts. In addition to experimental investigations to characterize the surface layer and the fatigue strength of different material states, the MST process is modelled via finite-element-based process simulation. A strain-rate dependent cyclic plasticity model with kinematic hardening is applied to account for the material behavior during the shot peening and deep rolling processes. As a perspective within the project, the developed methodology will also be applied to demonstrator components, considering the MST in a dimensioning scheme similar to the FKM guidelines widely used in the industry.

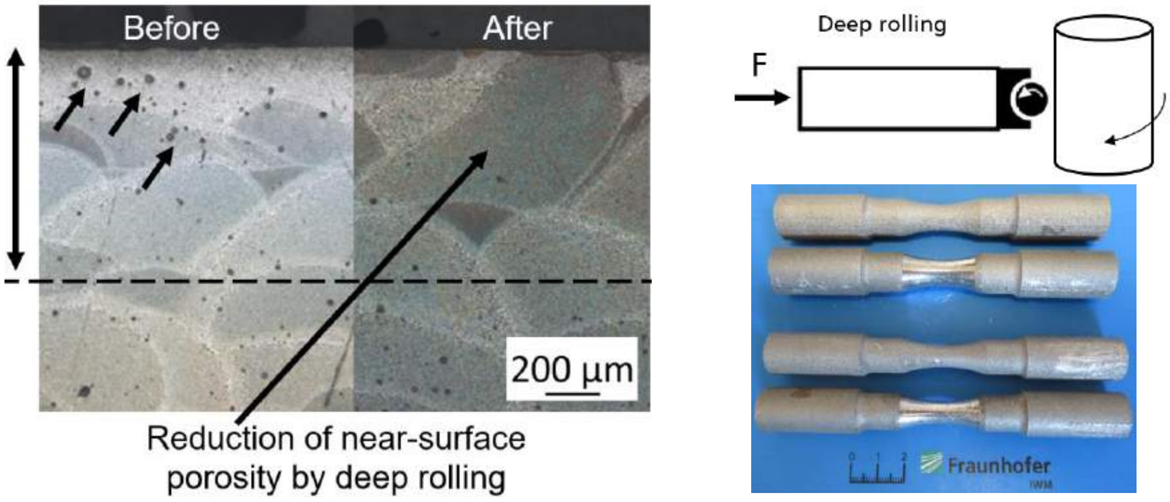


Fig. 1: Reduction of the near-surface porosity by deep rolling of additively manufactured AlSi10Mg samples

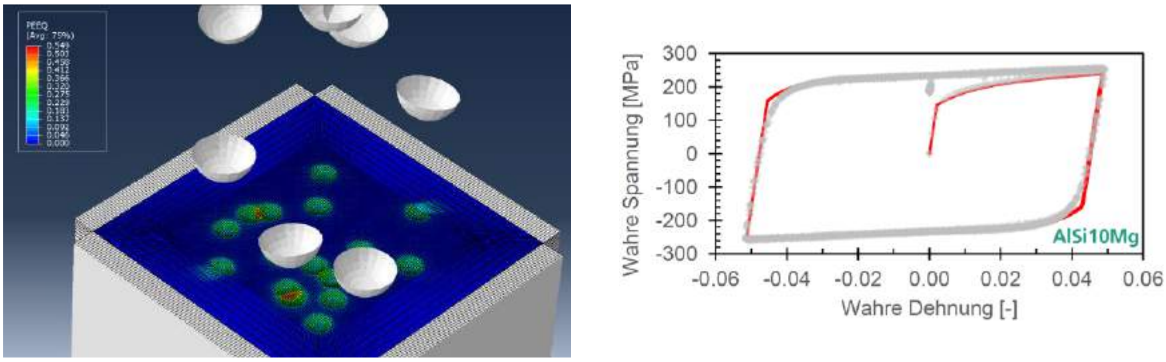


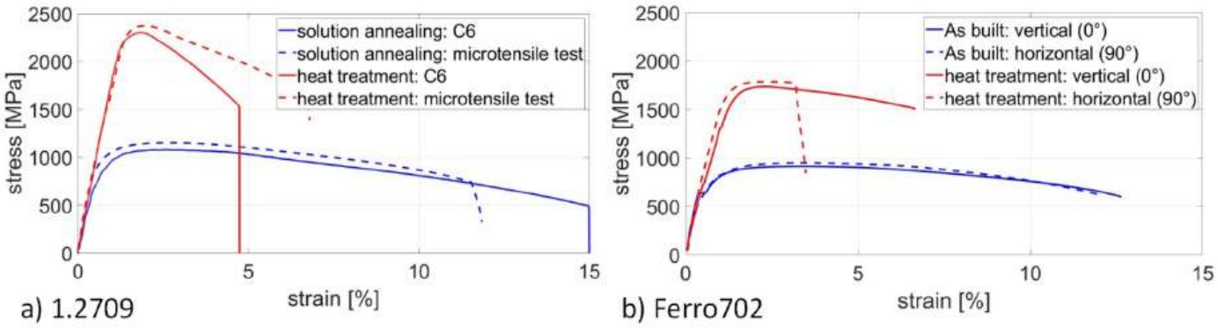
Fig. 2: Simulation of the shot peening process and plasticity model with kinematic hardening for AlSi10Mg material

Evaluation of the mechanical properties of LMD processed and heat-treated maraging steel (Ferro 702)

M. Fichtl[1*], A. Prihodovsky[1]
[1] Technische Hochschule Deggendorf
*maximilian.fichtl@th-deg.de

The increasing demands placed on components in the industrial environment, such as tool and mould making, require the use of high-strength steels. Maraging steels have very good machinability in the solution-annealed condition and achieve maximum strength combined with high toughness through suitable heat treatment. The combination with a good weldability makes these steels suitable for additive manufacturing and the maraging steel 1.2709 is widely used in laser powder-bed fabrication (LPBF). Laser metal deposition (LMD) is another laser-based process with increasing importance for tools and moulds. This process can be used for manufacturing of large-volume components and moulds repair.

The aim of the present study is the investigation of the mechanical properties of LMD-built samples made of the powder material PLASWeld Ferro702 (Ferro702) [1] and the comparison to the properties of commercially available material 1.2709. The chemical compositions of both materials are very similar. The mechanical properties are characterised by means of tensile and hardness tests in combination with the microstructure analysis. The shape of the micro tensile specimens used in this study [2] is more suitable for additive processes as it requires much smaller build-up volume. The influence of the specimen size on the measured values is initially evaluated by comparing the testing results obtained for the conventionally produced material 1.2709 with the standard specimen shape C6 [3] and the corresponding micro tensile specimens [2]. (Figure 1a) The final mechanical characterisation for different heat treatments is then carried out using micro tensile tests of 1.2709 and the additively manufactured Ferro702. (Figure 1b)



a) 1.2709 b) Ferro702

Figure 1. Comparison of the mechanical properties during the heat treatments carried out between a) the two sample forms from 1.2709 and b) the build-up direction from Ferro702

For the "as built" and heat-treated conditions (6 hours at 490 °C) the influence of the build-up orientation (0° and 90°) is also analysed. For the conventional material the heat treatment conditions (solution annealing at 850 °C with quenching; 6 hours at 490 °C) have been applied. The results show that the respective tendencies of the measured mechanical properties after heat treatment of 1.2709 and Ferro702 are similar. However, the achievable mechanical properties of the Ferro702 with the same heat treatment conditions are lower, so that further optimisation of the post treatment parameters for the LMD processed material is required.

References

[1] https://www.voestalpine.com/welding/de-de/produkte/produktsuche/metallpulver/#PTALaserPulverUTP accessed at 19.02.2024

[2] K. Kumar, A. Pooleery, K. Madhusoodanan, R.N. Singh, J.K. Chakravartty, B.K. Dutta, R.K. Sinha, 1. International Converence on Structural Integrity, 2014, 899 - 909

[3] DIN 50125

Metallography analysis of AISI316L austenitic steel processed via direct energy deposition technology and hot isostatic pressing technology

D. Bricín[1*], Z. Špirit[1], J. Zavitkovská[1]

[1] Centrum výzkumu Řež s.r.o.
*David.bricin@cvrez.cz

Our study aimed to describe microstructural changes associated with the processing of AISI316L powdered austenitic steel by direct energy deposition (DED) in combination with annealing (A), and hot isostatic pressing (HIP). A thick wall plate was prepared by direct energy deposition technology in dimensions of 250x250x35 mm. Annealing of the plate was done at 1090 °C with a holding time of 1 hour in vacuum furnace. HIP was done at 1100 °C, holding time 2 hours, and pressure 100 MPa. Metallography analysis was done by light optical microscopy and scanning electron microscopy in different locations of the plate and extracted samples. Metallography analysis aimed to determine changes in the presence of porosity, inclusions, grain morphologies, chemical homogeneity, and hardness associated with sample heat treatment. Our results show that during the printing of thick wall parts porosity could arise in some regions of the part. A lack of fusion and keyholing [1] type of pores was found in the high of 1/3 of the plate in the Z direction. The Pore's surface was covered with oxide envelopes, see Fig. 1. Annealing of the samples did not affect the presence of porosity. HIP treatment led to the closing of porosity. Their complete closure was then prevented by oxide films on the surface of the pores. The porosity of the plate was about 0.3±0.2 % in the annealed state and about 0.06±0.03 % for HIP-treated samples. The grain shape after the annealing and HIP treatment consisted of polygonal austenitic grains with a random orientation spread in almost all cases and with similar grain sizes in different parts of the evaluated thick plate. The difference in grain size for annealed and HIP-treated samples was not observed. Hardness was about 167±8HV1 for annealed samples and 157±5HV1 for HIP-treated samples. Our results then show that HIP technology is necessary in the case of the application of additively manufactured parts for thick parts used in the energy sector. Its application led to the closing of internal pores and increasing the homogeneity of printed parts. That could lead to an increase in fatigue life, stress corrosion cracking resistance, and creep resistance of thick parts. Our next research will focus on experiments with additively prepared ferrous and nonferrous materials that are in use or are in development for new types of power plants.

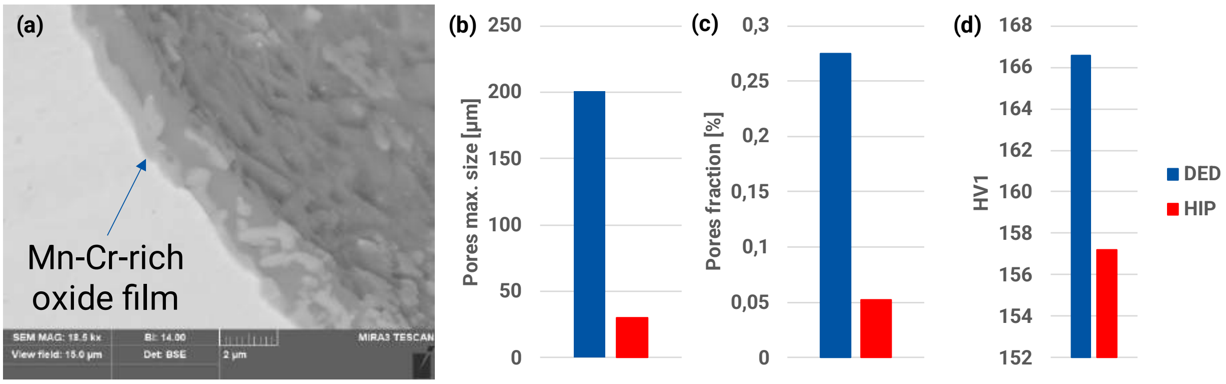


Figure 1. (a) Pore interface covered with oxide film; (b) Comparison of maximum pore sizes; (c) Comparison of pores fraction; (d) Comparison of hardness value

References

[1] D. Svetlizky; et al. *Materials Today*, **2021**, *49*, pp. 271–295

Modelling of Precipitation Strengthening during In-situ and Post-heat treatment of Scalmalloy and Scancromal

M.S. Mohebbi[1]*and V. Ploshikhin[1]

[1] ISEMP, University of Bremen
*mohebbi@isemp.de

Scalmalloy and Scancromal are among new alloys which have been specifically designed for additive manufacturing processes such as Powder Bed Fusion using Laser Beam (PBF-LB). The precipitation of nanoscale Sc-rich particles plays a significant role in the microstructure and mechanical properties of these alloys. Precipitation hardening can potentially contribute to the final material strength during the built-up process, which is referred to as intrinsic heat treatment (IHT), as well during the post-heat treatment (PHT).

In this work, we develop a precipitation model based on classical nucleation and growth theories (CNGTs) [1] and adapt it to both alloys. For Scalmalloy, homogeneous precipitation of small and coherent Al_3Sc phases is modeled. For Scancromal, a multi-component multi-phase approach is employed to account for mutual precipitates of types Al_3Sc and Al_7Cr. The model is coupled with arbitrary temperature-time data corresponding to either IHT or PHT. Temperature history during the PBF-LB process is predicted using a multi-scale thermal simulation. Different temperature profiles for various PBF-LB conditions are analysed to evaluate the impact of IHT to the precipitates number density, volume fraction and average size, as well as the resulting strength of the as-built parts. Experimental data from our own work as well as literature sources such [2–4] are used for validation of the model. The results including particle size distribution and strength are compared with common PHT conditions for the two alloys. Accordingly, IHT can be as effective as PHT, given that the inter-layer temperature sufficiently supports the nucleation and growth of particles. This can be attained primarily through active platform heating, short inter-layer times, and high energy density.

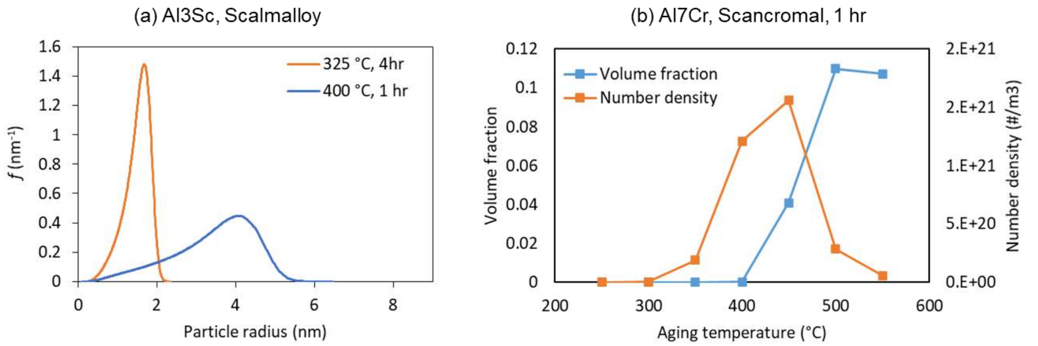


Figure 1. (a) Examples of Al_3Sc precipitate size distribution for Scalmalloy, and (b) volume fraction and number density of Al_7Cr precipitates by heat treatment of Scancromal.

References

[1] R. Kampmann, R. Wagner, Materials Science and Technology 5 (1991).
[2] A.B. Spierings, K. Dawson, P.J. Uggowitzer, K. Wegener, Mater. Des. 140 (2018) 134–143.
[3] A.B. Spierings, K. Dawson, T. Heeling, P.J. Uggowitzer, R. Schäublin, F. Palm, K. Wegener, Mater. Des. 115 (2017) 52–63.
[4] D. Schimbäck, L. Kaserer, P. Mair, M.S. Mohebbi, P. Staron, V. Maier-Kiener, I. Letofsky-Papst, T. Kremmer, F. Palm, I. Montes, H.W. Höppel, G. Leichtfried, S. Pogatscher, Mater. Sci. Eng. A (2024) 146102.

Post-treatment of additively manufactured high-alloy steel samples by particle blasting and/or plasma electrolytic polishing

K. Navickaitė[1,2,*], S. Langenhan[3], K. Nestler[2], A. Weidner[3], A. Sherstneva[4], J. Köckritz[1], R. Szlosarek[1], M. Wendler[4], O. Volkova[4], M. Kröger[1], H. Biermann[3], H. Zeidler[1,2]

[1] Technische Universität Bergakademie Freiberg, Faculty of Mechanical, Process and Energy Engineering, Institute for Machine Elements, Design and Manufacturing, Agricolastr.1, 09599, Freiberg, Germany;
[2] Beckmann-Institute for Technology Development e.V., Annabergerstr. 73, 09111, Chemnitz, Germany;
[3] Technische Universität Bergakademie Freiberg, Faculty of Material Science and Technology, Institute of Materials Engineering, Gustav-Zeuner-Straße 5, 09599, Freiberg, Germany;
[4] Technische Universität Bergakademie Freiberg, Faculty of Material Science and Technology, Institute of Iron and Steel Technology, Leipziger Straße 34, 09599, Freiberg, Germany;
* kristina.navickaite@imkf.tu-freiberg.de

Extended abstract. The analysed samples made of high-alloy, austenitic X2CrMnNi16-7-4.5 [1,2] steel were produced using electron beam powder bed technology (PBF-EB/M). The surface quality of all additively manufactured parts is very poor by nature. Therefore, a post-processing step is required to improve their surface integrity. Although a variety of post-processing technologies exist, not all are suitable for additively manufactured parts as they are geometrically limited or too labour- and/or time-intensive. For this reason, this study focuses on two polishing techniques that are particularly suitable and efficient for treating such parts. These are particle blasting (PB) and plasma electrolytic polishing (PEP) [3,4]. The analysed samples were treated either with the two-step PEP process or with the combination of PB and PEP. The surface roughness of the samples was measured before and after the treatment using the MahrSurf confocal microscope. The material removal rate, *MRR*, was also determined. The final surface quality depends very strongly on the initial surface roughness, therefore the PBF-EB/M parameters were also optimised to improve the surface quality of the samples in as-build condition. The surface roughness of the investigated non-optimised and optimised samples in the as-built condition varied between Sq = 50.8 µm and Sv = 243.0 µm and Sq = 40.0 µm and Sv = 167.3 µm. While the PBF-E/M parameter optimisation effect on the surface roughness parameter Sq is not significant, it resulted in smaller and fewer defects in subsurface region of the samples was well as lower absolute height of the highest pit Sv. In addition, a lower final surface roughness was achieved in the samples with optimised PBF-EB/M parameters compared to the non-optimised samples. The analysed samples were treated with PB for a total of 15 min and finally with PEP for 30 min. The process parameters were 9000 RPM, 7000 RPM and 4000 RPM for 5 min each for PB and DC voltage at U = 330 V and/or U = 300 V and an electrolyte temperature of 75 °C for PEP. The resulting surface roughness was Sq = 15.7 µm and Sv = 188.8 µm and Sq = 37.8 µm and Sv = 137.8 µm for the samples with non-optimised and optimised PBF-EB/M parameters, respectively. The greatest reduction in surface roughness was achieved for the sample with non-optimised PBF-EB/M parameters, which was polished using the two-step PEP process. However, the total duration of the treatment was 60 min, while the sample with the optimised PBF-E/M parameters was PEP-treated for only 30 min. The final surface roughness of the sample with non-optimised PBF-E/M parameters that was polished using a combination of PB and PEP was Sq = 21.0 µm and Sv = 248.5 µm.

Acknowledgement. This measure is co-financed by tax funds on the basis of the budget approved by the Saxon state parliament. The project number is 100649753.

References

[1] M. Wendler, M. Hauser, O. Fabrichnaya, L. Krüger, A. Weiß, J. Mola, *Materials Science and Engineering: A*, **2015,** *645*, 28–39
[2] C. Quitzke, Q. Huang, H. Biermann, O. Volkova, M. Wendler, *Materials*, **2021,** *14*, 6502
[3] E. V. Parfenov, V.R. Mukaeva, R.G. Farrakhov, *Materials. Technologies. Design*, **2019,** *1*, 34–41
[4] S.A. Kusmanov, A. V. Zhirov, I.A. Kusmanova, P.N. Belkin, *Surface Engineering*, **2019,** *35*, 507–511

Surface characterisation of electron beam melted Alloy 718 and the effect of varied pre-treatments

L. George Thomas[1*], T. Grund[1], S. Joshi[2], T. Lampke[1]

[1] Materials and Surface Engineering Group, Institute of Materials Science and Engineering, Chemnitz University of Technology, D-09125, Germany, [2] Department of Engineering Science, University West, 46186 Trollhättan, Sweden
*linto.george-thomas@mb.tu-chemnitz.de

Electron beam melted (EBM) 718 superalloys have earned significant attention from the industrial and academic domains. The attention is primarily owing to the high performance of AM-built critical parts suitable for advanced industrial systems exposed to high thermal or chemical load in combination with mechanical demands by virtue of the design freedom, and with reduced material wastage. However, the very nature of EBM processing can potentially result in surface flaws that can ultimately affect the fatigue life of EBM-built parts [1] and their subsequent functionalization. As a result, the imperfections and extreme roughness on the surface of such parts demand the investigation of potential approaches that can be applied to enhance surface attributes and, thereby, functional performance [2].

The present work entails a comprehensive assessment of the near-surface characteristics of EBM Alloy 718 in its original state by using various microscopic techniques and porosity evaluation methods. Further, the as-built surfaces are subjected to three different surface pre-treatment methods, which are grit blasting (GB), electrochemical pickling (PCK), and laser surface texturing (LST). All surfaces were evaluated for their topographical features (2D and 3D) and morphology. In addition, the effect of different surface pre-treatments on the variation of structural defects, pores and surface roughness is contrasted and evaluated in comparison with the as-built state.

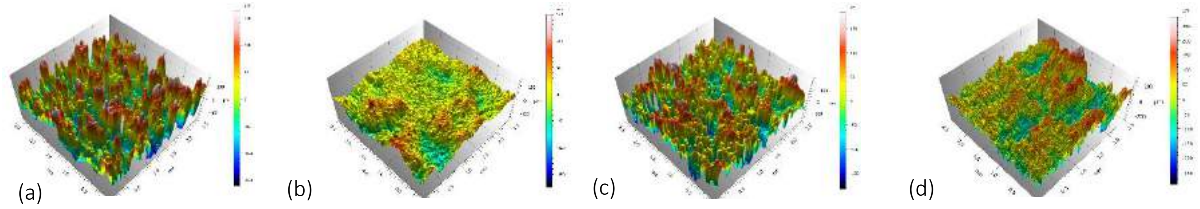


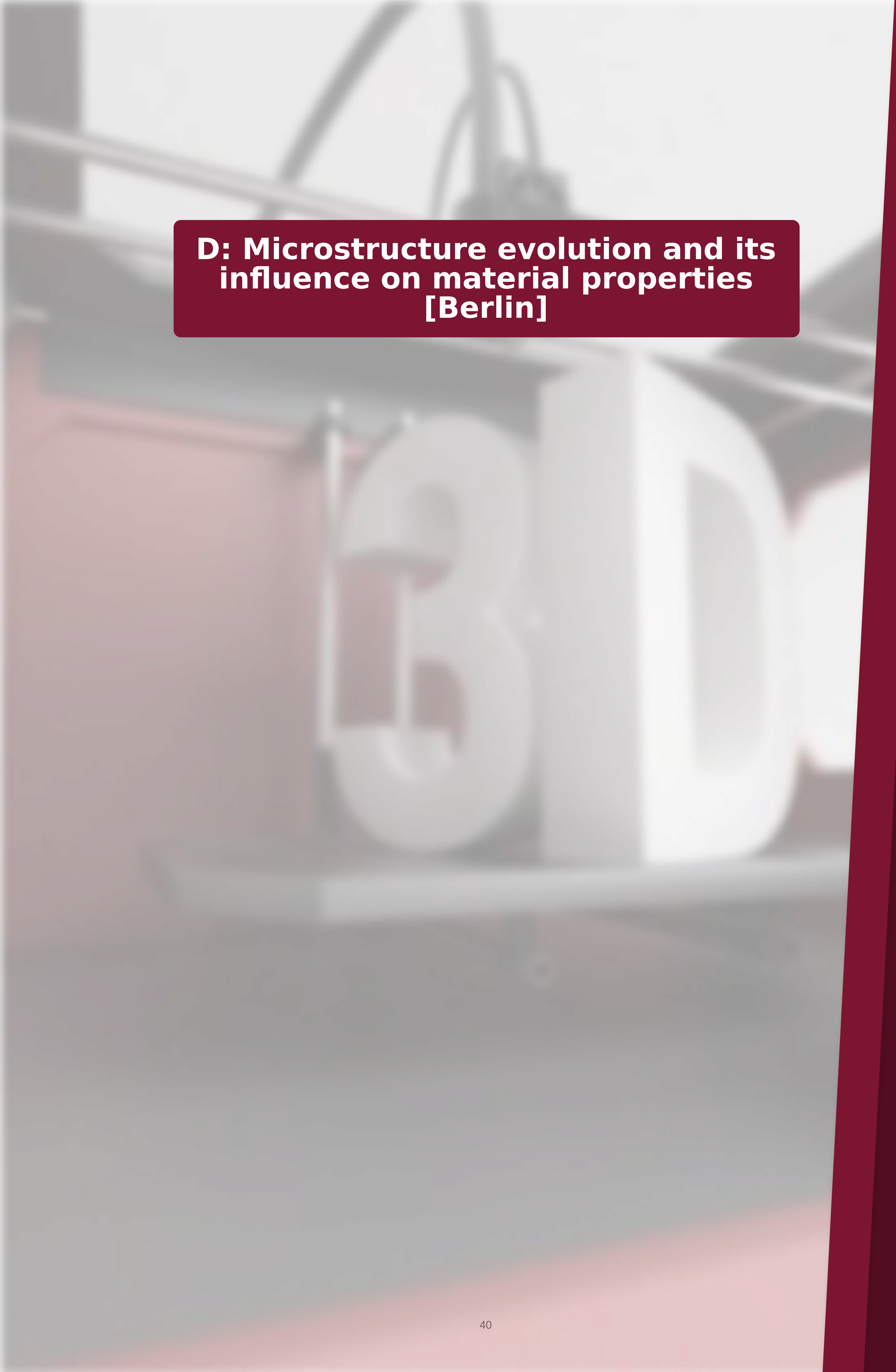
Figure 1. 3D digital surface topography of EBM Alloy 718 (a) surface as built (SAB), (b) grit blasted (GB), (c) electrochemical pickled (PCK), (d) laser surface textured (LST)

Results show variations in the surface characteristics of the as-built condition obtained from various regions of an EBM-built rod structure, particularly with regard to lack of fusion, open and closed porosity in the near-surface region, as well as topographical surface features. Further, it is observed that LST and GB pre-treatments improved the surface quality of the as-built condition by eliminating near-surface imperfections. In contrast, the PCK state does not significantly reduce the average roughness, *Ra* of the as-built specimens. PCK process etched only a minimal amount of material from the surface of the EBM built substrate. This information provided a comprehensive insight into the effectiveness of various pre-treatments for enhancing the surface functionalities in EBM Alloy 718 and laid a foundation for deciding on pre-coating surface treatments for EBM-built parts.

References

[1] S. Goel, A. Sittiho, I. Charit, U. Klement, S. Joshi; Effect of post-treatments under hot isostatic pressure on microstructural characteristics of EBM-built Alloy 718, Additive Manufacturing, 2019, 28, 727-737.
[2] M. Alehojat, R. Jafari, P. Karimi, E. Sadeghi; Electron beam-powder bed fusion of Alloy 718: Effect of hot isostatic pressing and thermal spraying on microstructural characteristics and oxidation performance, Surface and Coatings Technology, 2020, 404, 126626.

D: Microstructure evolution and its influence on material properties [Berlin]



Effect of heat treatment on the hierarchical microstructure and properties of 316L stainless steel produced by Laser Powder Bed Fusion (PBF-LB/M).

P. Suárez Ocano[1], L. A. Ávila Calderón[*1], B. Rehmer[1], G. Mohr[1], A. Evans[1], B. Skrotzki[1].
[1]Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany
*patricia.suarez-ocano@bam.de

Laser Powder Bed Fusion (PBF-LB/M) of AISI 316L stainless steel has gained popularity due to its exceptional capacity to produce complex geometries and hierarchical microstructures, which can increase the yield strength while maintaining good ductility [1]. Nevertheless, owing to high thermal gradients encountered during the process, the as printed 316L stainless steel often exhibit microstructural heterogeneities and residual stresses, which can limit its performance in demanding environments [2]. Hence, employing heat treatments which balance the reduction of residual stresses while retaining improved static strength may be beneficial in various scenarios and applications [3,4]. This study investigates the impact of post-processing heat treatments on the microstructure of 316L stainless steel manufactured via PBF-LB/M, along with its correlation with micro-hardness properties. To this end, 6 different heat treatments, *i.e.*, 450 °C for 4h, 700 °C for 1h, 700 °C for 3h, 800 °C for 1h, 800 °C for 3h, and 900 °C for 1h, were applied to different specimens and Vickers hardness measurements (HV1) were performed in all states.

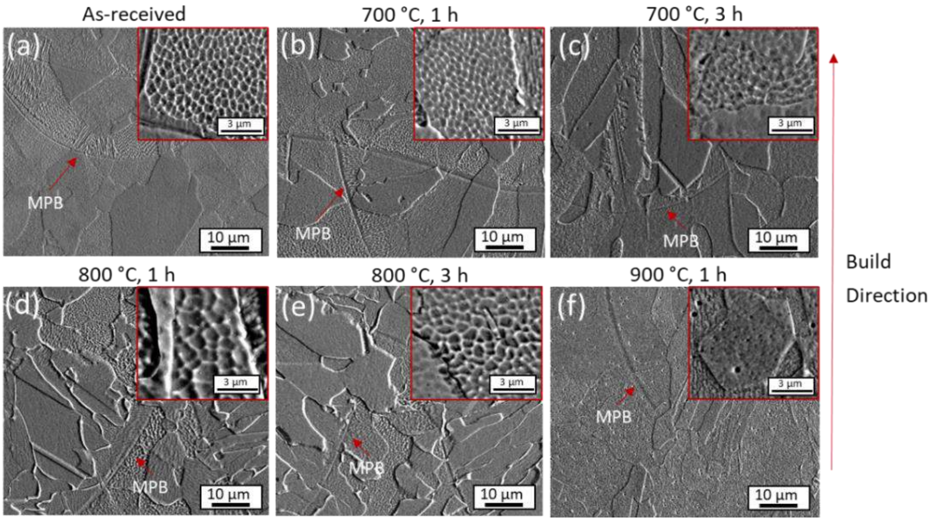


Figure 1. SEM micrographs after etching of the heat treated 316L stainless steel manufactured by Laser Powder Bed Fusion (PBF-LB/M/316L) at (a) 450 °C for 4 h, (b) 700 °C for 1 h, (c) 700 °C for 3 h (d) 800 °C for 1 h, (e) 800 °C for 3 h, and (f) 900 °C for 1 h, showing the evolution of the cellular structure at different heat treatments.

Figure 1 shows representative SEM micrographs of the heat-treated samples, highlighting the primary impact of the applied heat treatments, particularly on the cellular subgrain structure visible due to local chemical segregation. At 800 °C, although the cellular structure appears to be retained, there is an observable increase in cellular size. However, while treatments exceeding 900 °C indicate no significant grain growth compared to other conditions, the cellular structure is entirely dissolved (Figure 1f), which leads to a reduced Vickers hardness. The effect of the heat treatments on other microstructural features such as grain size and morphology, melt pool boundaries (MPB), crystallographic texture, chemical segregation, dispersoids and phase stability are also discussed in the present work.

References

[1] Y. Morris Wang *et al.; Nature Materials, **2017**,* 17, 63-71.
[2] T. Kurzynowski *et al*.; *Materials Science and Engineering: A, **2018***, 718*,* 64-73.
[3] T. Voisin *et al*.; *Acta Materialia, **2021***, 203, 116476.
[4] M. Sprengel *et al*.; *Metall Mater Trans A*, ***2021***, 52, 5342–5356.

Formation of Creep Damage of 316L produced by Laser Powder Bed Fusion

A. Ulbricht[1*], L. A. Ávila C.[1], K. Sommer, G. Mohr[1], A. Evans[1], B. Skrotzki[1], G. Bruno[1]

[1] Bundesanstalt für Materialforschung und –prüfung, Deutschland
*alexander.ulbricht@bam.de

Laser powder bed fusion (PBF-LB/M) tends to produce unique microstructures arising from rapid, directional cooling. These microstructures impact the damage mechanisms of PBF-LB/M-components differently compared to conventionally manufactured variants of the same alloy. In particular, we present results of a study of the evolution of creep damage in stainless steel 316L specimens produced by PBF-LB/M. We used X-ray computed tomography to unravel the influence of the process-specific microstructure from the contribution of the initial void distribution on creep damage mechanisms. Therefore the void distribution of specimens tested at 600 °C and 650 °C was analyzed before the creep test, after an interruption, and after rupture. We conclude that the formation of damage is not connected to the initial void distribution. Instead, an accumulation of damage at grain boundaries resulting from extensive intergranular cracking is observed. We compared this creep induced intergranular damage of PBF-LB/M/316L to hot rolled 316L. [1,2]

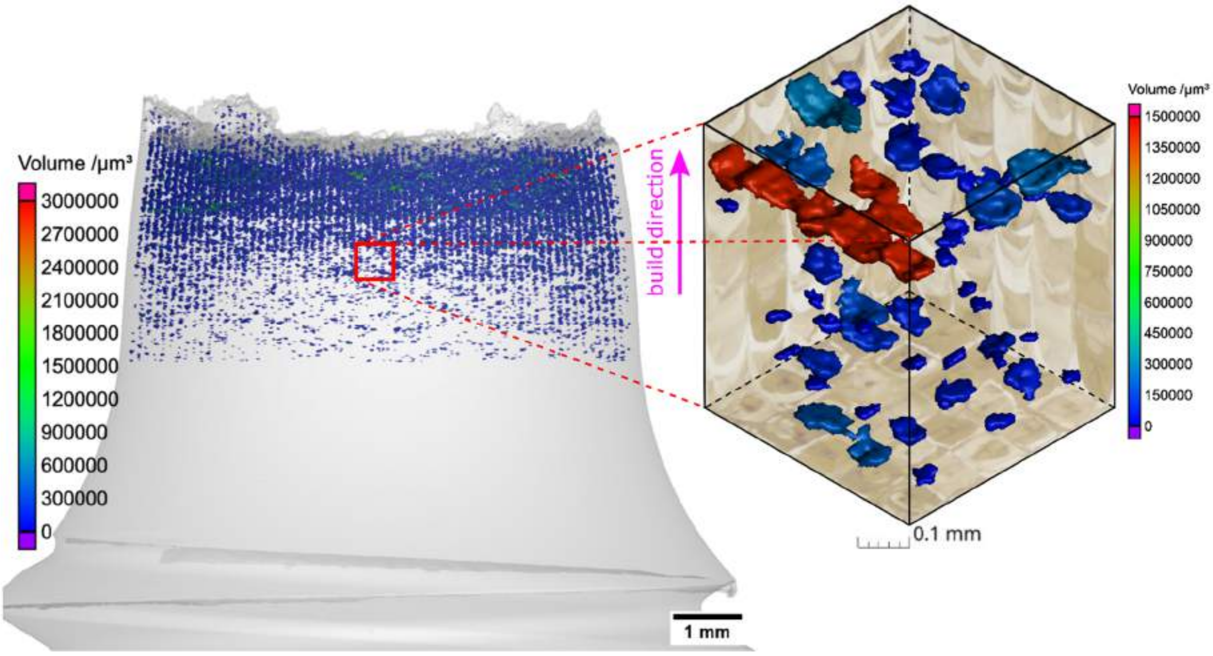


Figure 1. Segmented XCT reconstruction of a broken creep specimen. Magnified damage is combined with microscopy images. [2]

References

[1] L.A. Ávila Calderón, B. Rehmer, S. Schriever, A. Ulbricht, L. Agudo Jácome, K. Sommer, G. Mohr, B. Skrotzki, A. Evans, Materials Science and Engineering: A, 2022, Volume 830, 142223

[2] A. Ulbricht, L.A. Ávila Calderón, K. Sommer, G. Mohr, A. Evans, B. Skrotzki, G. Bruno, Adv. Eng. Mater., 25, 2023, 2201581.

Heat treatment, microstructure and properties of precipitation hardening stainless steel produced by powder bed fusion

P. Rosemann[1,*], S. Roßberg[1], P. Jakob[1], L.D. Kukuk[1], H.-W. Theobald[2]

[1] Leipzig University of Applied Science, Faculty of Engineering, Research Group Material Science
[2] 3D-Metall Theobald, Leipzig

*paul.rosemann@htwk-leipzig.de

The mechanical properties and the corrosion resistance of additively manufactured stainless steels are influenced by their alloy composition, processing and heat treatment. In the case of components that are manufactured using powder bed fusion, the initial state after 3D-printing is crucial in order to adjust the mechanical properties and corrosion resistance through the subsequent heat treatment. This applies in particular to the high-alloy, high-strength and corrosion-resistant maraging steel 1.4542 (X5CrNiCuNb16-4), which is used in the aerospace industry. The alloy concept of this steel will be presented in the lecture, followed by the properties of 3D-printed components and the effect of further heat treatments. It is shown that a subsequent heat treatment can achieve tensile strengths of up to 1.500 MPa and notch impact values of up to 50 J.

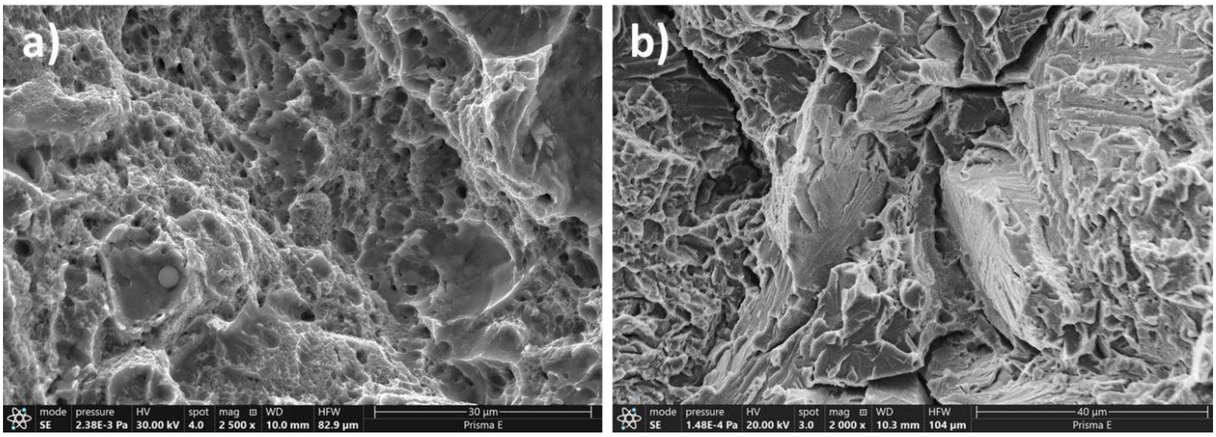


Figure 1. SEM of the fracture surfaces of 1.4542 manufactured by powder bed fusion and examined with charpy impact tests **a)** in the as-printed state with 50 J and ductile fracture **b)** after aging at 480 °C for 1 h with 3 J and brittle fracture

To analyse the structure-property-relationship, the fracture surfaces of the notched bar impact test and the corresponding microstructure are analysed by light and scanning electron microscopy. The pitting corrosion resistance is also determined using potentiodynamic polarization tests. All results are compared to classic austenitic stainless steels 1.4404 (316L) in order to fully reflect the property profile. The extensive results show that the maraging steel 1.4542 (X5CrNiCuNb16-4) is an excellent material for 3D printing by powder bed fusion and achieves outstanding properties by suitable heat treatment. The heat treatment allows to adept the material properties of the maraging steel 1.4542 (X5CrNiCuNb16-4) to the specific requirements of different applications.

Microstructure evolution during plasma nitriding of metallic materials produced by additive manufacturing

M. Godec[1*], Č. Donik[1], B. Podgornik[1], A. Kocijan[1], D. Skobir Balantič[1]

[1] Institute of Metals and Technology, Ljubljana, Slovenia
*matjaz.godec@imt.si

Additive manufacturing (AM) is an innovative technology that has revolutionised the manufacturing industry. It has opened up new possibilities for producing parts with unprecedented customisation, intricate designs, and advanced functionalities. One of the most notable techniques in AM is Laser Powder Bed Fusion (LPBF), which can manufacture metallic parts with complex geometries and refined microstructures. However, AM produces materials with unique microstructural characteristics and surface finishes, which are significantly different from those produced through conventional manufacturing methods. These variations, such as finer grain structures, porosity, and residual stresses, can significantly affect the material properties [1].

Applying surface plasma nitriding [2] can markedly enhance the wear and corrosion resistance of AM-produced parts, in some cases making them superior to conventionally manufactured equivalents. This presentation will explore the corrosion characteristics and other mechanical and tribological properties of various metallic materials produced through AM, such as stainless steel, maraging steel, tool steel and nickel alloy, compared to their traditionally manufactured counterparts [3]. Additionally, the presentation will examine the effects of various heat treatments on nitride layer formation and present corrosion and wear testing results to underscore the significance of our findings. All the results will be linked to the microstructure itself and microstructure evolution during heat treatments and plasma nitriding in relation to specific AM microstructure features.

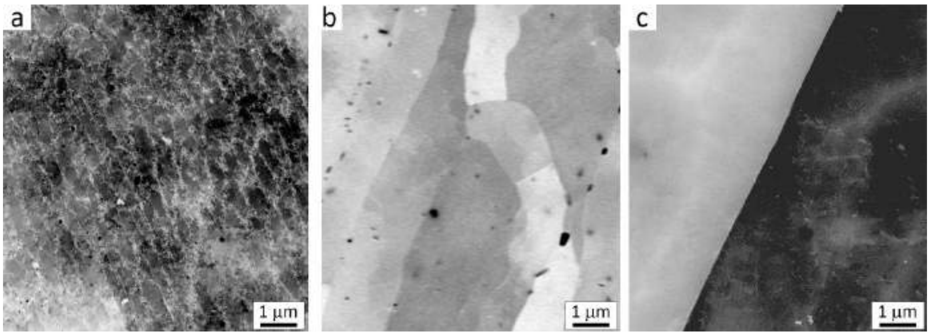


Figure 1. ECCI images of AM stainless steel: a) LPBF produced, b) LPBF and solution-treated, and c) conventionally produced.

The presentation will illustrate the connection between additive manufactured (AM) metals' unique microstructures and their properties, highlighting how surface plasma nitriding significantly boosts their corrosion and wear resistance. This discussion highlights the significance of AM-specific microstructures in enhancing material performance and demonstrates the effectiveness of surface treatments in improving the durability of AM metals.

References

[1] P. Bajaj, A. Hariharan, A. Kini, P. Kuernsteiner, D. Raabe, E.A. Jaegle; *Mater. Sci. Eng. A*, 2020, *772*, 138633.
[2] M. Berg, C.V. Budtz-Jorgensen, H. Reitz, K.O. Schweitz, J. Chevallier, P. Kringhoj, J. Bottiger; *Surf. Coat. Technol.,* 2000, *124*, 25-31.
[3] M. Godec, Č. Donik, A. Kocijan, B. Podgornik, D.A. Skobir Balantič; *Addit. Manuf.,* 2020, 32, 101000.

Microstructure-based Study on the Low-Cycle-Fatigue Behavior of Stainless Steel 316L manufactured by Laser Powder Bed Fusion

L. A. Ávila Calderón*[1], B. Rehmer[1], T. Werner[1], A. Ulbricht[1], G. Mohr[1], B. Skrotzki[1], A. Evans[1]
[1]Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany
*luis.avila@bam.de

Due to the advantages of Laser Powder Bed Fusion (PBF-LB), i.e., design freedom and the possibility to manufacture parts with filigree structures, and the considerable amount of knowledge available for 316L in its conventional variant, the mechanical behavior, and related microstructure-property relationships of PBF-LB/316L are increasingly subject of research [1]. However, many aspects regarding the - application-relevant - mechanical behavior at high temperatures are not yet fully understood. Here, we present the results of an experimental study on the LCF behavior of PBF-LB/316L featuring a low defect population, which makes this study more microstructure-focused than most of the studies in the literature. The LCF tests were performed between room temperature (RT) and 600 °C. The mechanical response is characterized by strain-life curves, and hysteresis and cyclic deformation curves. The damage and deformation mechanisms are studied with X-ray computed tomography, and optical and electron microscopy. The PBF-LB/M/316L was heat treated at 450 °C for 4 h, and a hot-rolled (HR) 316L variant with a fully recrystallized equiaxed microstructure was tested as a reference. Besides, selected investigations were performed after a subsequent heat treatment at 900 °C for 1 h.

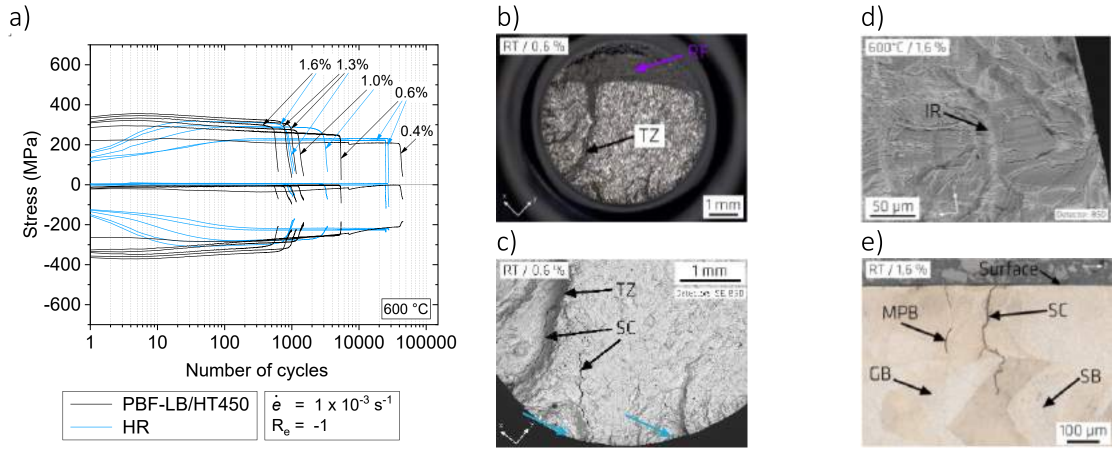


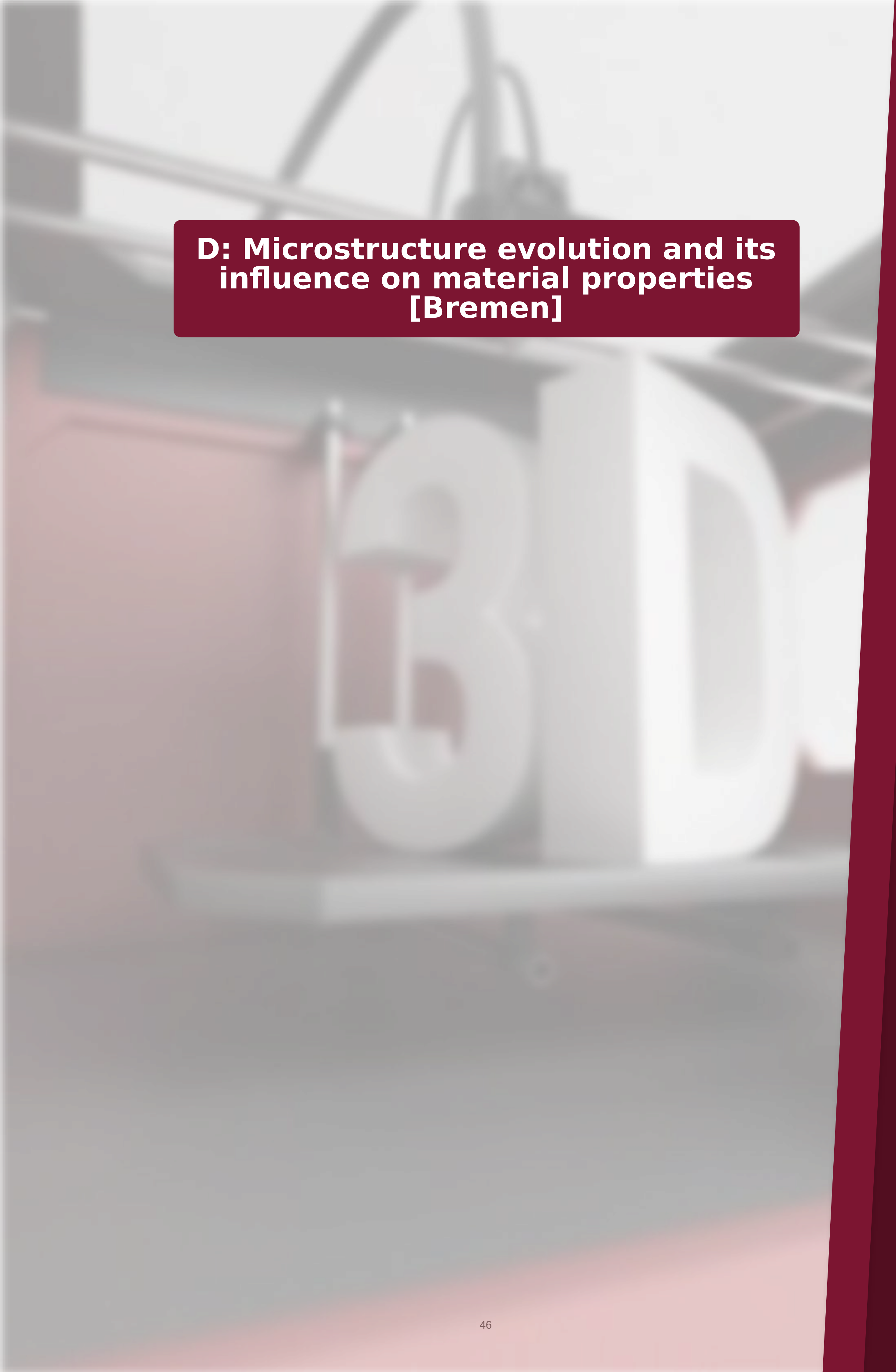
Figure 1. Selected results. a) Cyclic deformation behavior of PBF-LB/M/316L, b)-d) representative fracture characteristics at selected test parameters, e) cut section showing secondary cracking (SC). TZ: Transition Zone, RF: Residual fracture, IR: Intercolumnar Region, MPB: Melt Pool Boundary, GB: Grain Boundary, SB: Slip Band. Images taken from [2].

The PBF-LB/316L exhibits higher cyclic stresses than HR/316L for most of the fatigue life, especially at room temperature. At the smallest strain amplitudes, the fatigue lives of PBF-LB/M/316L are markedly shorter than in HR/316L. The main damage mechanisms are multiple cracking at slip bands (RT) and intergranular cracking (600 °C). Neither the melt pool boundaries nor the gas porosity have a significant influence on the LCF damage mechanism. The cyclic stress-strain deformation behavior of PBF-LB/M/316L features an initial hardening followed by a continuous softening. Depending on testing parameters and microstructure, crack initiation, and propagation can be inter- or transgranular. The additional heat treatment at 900 °C for 1 h led to decreased cyclic stresses, and a longer fatigue life. Overall, the solidification cellular structure seems to be the most relevant underlying microstructural feature determining the cyclic deformation behavior.

References

[1] M. Laleh et al.; *Progress in Materials Science*, **2023**, 133.
[2] L. A. Ávila Calderón; Technische Universität Berlin, **2024**.

D: Microstructure evolution and its influence on material properties [Bremen]



Applicability of spattered powder in laser-based powder bed fusion process – Fatigue life of additively manufactured structures

J. Richter[1*], C. J. J. Torrent [1], M. Krochmal[1], T. Wegener[1], M. Vollmer[1], T. Niendorf[1]

[1] University of Kassel, Institute of Materials Engineering, Metallic Materials, Germany
*julia.richter@uni-kassel.de

Process-inherent high cooling rates and intrinsic heat treatments of additive manufacturing techniques lead to unique microstructures with concomitantly tempting mechanical properties. However, these process-inherent properties also possess drawbacks such as the formation of pores being crucial for the applications of components under fatigue loading. In the present studies, non-optimal feedstock material, i.e., spattered commercially pure iron powder particles, were employed in the laser-based powder bed fusion of metals. After production, the microstructure and defect distribution were analyzed via electron-backscattered diffraction and micro-computed tomography. The mechanical properties were tested under quasi-static loading and fatigued in the low cycle regime and compared to material manufactured utilizing optimal powder conditions. With respect to defect distribution and grain morphology, it was shown that the between the optimal and non-optimal process conditions only slight differences are prevailing, however, under quasi-static loading a different behavior was found. Most characteristically, the specimens built using the spherical powder exhibit a pronounced yield point and a higher strength as compared to the material built from the spattered powder. These differences can be rationalized by microstructural differences with respect to the chemical composition of the initial powders. Based on the analysis of fatigue life, it could be revealed that the specimens built using spattered powder are competitive to the ideal counterparts with respect to stress response and number of cycles to failure. Taking all results obtained into account, the utilization of spattered powders in additive manufacturing is thought to be robustly feasible such that spattered powders can be considered to be qualified for processing. [1]

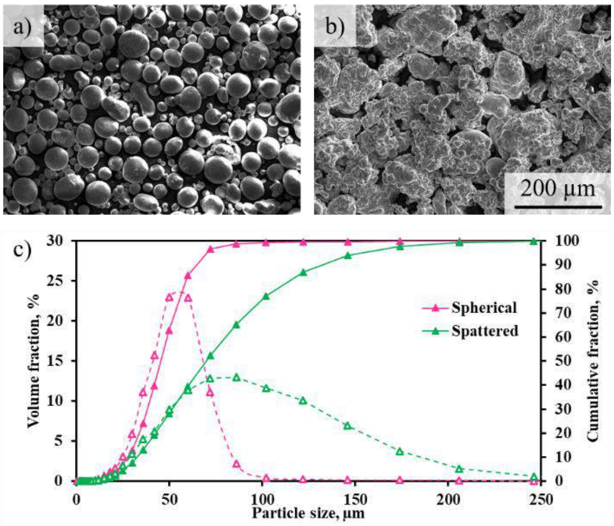


Figure 1. Secondary electron images of the spherical (a) and the spattered powder (b) considered in the study as well as the corresponding particle size distributions (c). Hollow dots correspond to the volume fraction, filled dots depict the cumulative fraction. [2]

References

[1] J. Richter, C. Torrent, M. Krochmal, T. Wegener, M. Vollmer, T. Niendorf; *International Journal of Fatigue*, **2022**, 27, 107468.
[2] J. Richter, On the impact of non-optimal parameters in additive manufacturing -from microstructure to mechanical properties, kassel university press, Kassel, Hess, **2024**.

Dispersion strengthening of NiCu Alloy 400 for LPBF – an overview

Jan-Philipp Roth[1*] (J.-P. Roth), Ulrich Krupp[2] (U. Krupp), Katrin Jahns[1] (K. Jahns)

[1] Faculty of Engineering and Computer Science, Osnabrück University of Applied Sciences, Osnabrück, Germany
[2] Steel Institute IEHK, RWTH Aachen University, Aachen, Germany
*j.roth@hs-osnabrueck.de

The incorporation of nanoscaled particles into a ductile alloy matrix is commonly referred to as dispersion strengthening (DS). During laser powder bed fusion (LPBF), the accumulation of these nanoparticles along the interdendritic cell walls takes place and may result in superior mechanical performance in comparison to unmodified material. The reason for this is a suppression or obstruction of the dislocation movement, which significantly increases both, the ultimate tensile strength and the creep resistance. Feasibility of DS in the present NiCu-based Alloy 400 during LPBF was demonstrated for various modification routes already, e.g. based on (i) gas atomization reaction synthesis (GARS, Figure 1 left, [1]) and (ii) the addition of nanoparticles to the base alloy during the powder feedstock preparation process (Figure 1 right), respectively. The present work gives a broad overview of multiple DS modification processes for Alloy 400, not only highlighting promising ones, but also presenting the reason for drawbacks of unsuccessful processes. Nanoparticle incorporation into both powders and parts is characterized and evaluated. Ultimately, a determination of mechanical properties is carried out, leading to a decision on whether or not the particular modification route can be considered a potential candidate for DS enhancement of Alloy 400.

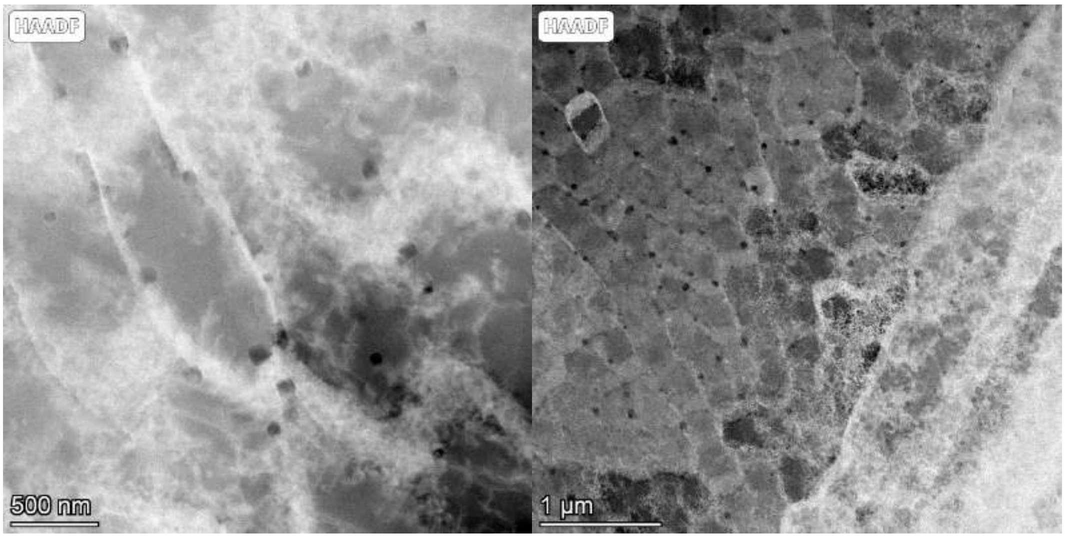


Figure 1. DS modified LPBF parts, enriched with TiN (left) and Y_2O_3 (right) nanoparticles throughout the base alloy matrices.

References

[1] J.-P. Roth et al., The dispersion-strengthening effect of TiN evoked by in situ nitridation of NiCu-based Alloy 400 during gas atomization for laser powder bed fusion, *Materials Science and Engineering: A*, **2024**, 146129.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958192.

Electron microscopy of additively manufactured AlSi3.5Mg2.5 alloy: *sample preparation and microstructural analysis*

M. Alhakim[1], T. Yallew[1], H. Wang[1,4*], Y. Sakalli[2], K. Solanki[3], J. Müller[1], B. Butz[1], C. Zinn[3], A. von Hehl[3]

[1] Lehrstuhl für Mikro- und Nanoanalytik, Universität Siegen, [2] Gerätezentrum für Mikro- und Nanoanalytik MNaF, Universität Siegen, [3] Lehrstuhl für Materialkunde und Werkstoffprüfung, Universität Siegen, [4] Lehrstuhl Werkstoffwissenschaft, Ruhr-Universität Bochum

*hongcai.wang@uni-siegen.de

Additive manufacturing of Al alloys is considered a promising manufacturing method for the critical automotive, aerospace, military components. Recently, many efforts have been made to manufacture Al-Si alloys using Laser Powder-Bed Fusion, due to benefits such as fabricating lightweight parts with complex geometries [1].

To understand structure formation and mechanical properties, comprehensive micro- and nanoanalytical characterization of those material states is crucial due to the complex, highly inhomogeneous microstructure. Here, we aim at preparing quality specimens for microscopic investigation from a rod-shaped standardized specimens of Laser Powder-Bed fused AlSi3.5Mg2.5 (Fig. 1a). In this study systematic parameter optimization was carried out to obtain high quality specimens by mechanical polishing (Fig. 1b,c), after etching (Fig. 1d), and after electropolishing (Fig. 1e) for microscopical analysis. This comprehensive approach allows for addressing the correlation between microstructure and hardness variations along the build direction (Fig.1f) and provides valuable insights to tailor the microstructure and mechanical properties of additively manufactured Al alloys.

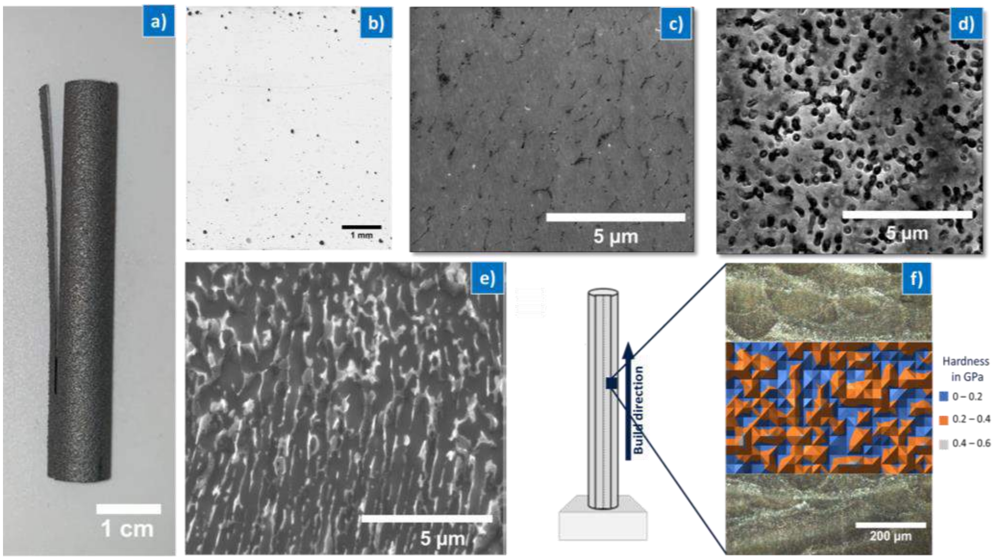


Figure 1. a) as-built rod-shaped specimen, b) pores present in the specimen, c) SEM image of specimen before etching d) SEM image of specimen after etching e) SEM image after electropolishing f) hardness map by nano-indentation along the build direction.

References

[1] H.R. Kotadia, G. Gibbons, A. Das, and P.D. Howes *Additive Manufacturing* ,**2021,**46, 102155

The authors acknowledge Dr. Daniel Knoop from Leibniz-IWT in Bremen for providing the specimens and extend the gratitude to the support and resources provided by ZGH at Ruhr-University Bochum. Part of this work was performed at the DFG-funded Micro- and Nanoanalytics Facility (MNaF) of the University of Siegen (INST 221/131-1).

Industry based material science for AM: Development and characterization of steels and superalloys

C. Aumayr[1*], K. Leitner[1], C. Turk[1]

[1] voestalpine BÖHLER Edelstahl GmbH & Co KG
*Christin.Aumayr@bohler-edelstahl.at

Additive Manufacturing (AM) holds great promise for producing complex components with tailored properties in the aerospace, automotive, and medical industries. However, the successful implementation of AM relies heavily on the availability of suitable materials with tailored properties to meet the demanding requirements of specific applications. In 2016 voestalpine BÖHLER Edelstahl GmbH & Co KG started its journey in the world of AM by installing its first AMPO powder production unit. Since then, intensive research focuses on the development and characterization of steels and superalloys for AM processes. Through a systematic approach combining alloy design, powder metallurgy, and advanced characterization techniques, the microstructure and mechanical properties of AM-produced parts will be optimized to enhance performance and reliability. Special emphasis will be placed on understanding the effects of alloy composition, process parameters, and post-processing treatments on the resulting microstructure and properties. The findings of this study will contribute to the advancement of materials science for AM, enabling the fabrication of high-performance components with enhanced structural integrity and mechanical properties.

Influence of cooling rate and oxygen content on WAAM-produced Ti-6Al-4V

A. Meermeier[1], S. Berbalk[2], T. Meyer[2], H. W. Höppel[1]

[1] Friedrich-Alexander-Universität Erlangen-Nürnberg, [2] HEGGEMANN AG
*annalena.meermeier@fau.de

Minimizing the buy-to-fly ratio of aircraft structural parts made from milled Ti-6Al-4V is an important step in reducing the environmental impact of the aerospace industry. One possible way to achieve this goal is through wire and arc additive manufacturing (WAAM), an additive manufacturing technique based on arc welding. It is a cost-effective process with a minimal lead-time and significantly reduces material waste through near-net-shape manufacturing. In previous investigations, we determined the most relevant WAAM-process parameters and developed an in-depth understanding on the process-parameter-microstructure-properties correlation [1-3] with a focus on understanding the thermal management and its influence on the intrinsic heat treatment.

Due to titanium's low heat conduction, heat accumulates and further reduces the cooling rate. This leads to elongated β-grain growth and thus anisotropic properties. Additionally, titanium's affinity to oxygen has to be taken into account during the manufacturing process to avoid α-case formation. In this work, samples with two different cooling rates achieved by using air curtains as well as three further samples produced with different residual oxygen content (see Figure 1) are investigated. The aim is to establish a correlation between process parameters, microstructure and mechanical properties. The samples were analyzed in terms of their microstructure and mechanical properties using Scanning Electron Microscopy, tensile and compression tests as well as nanoindentation.

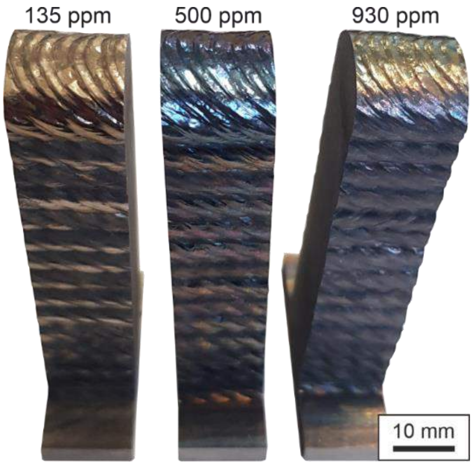


Figure 1. Variations in color of samples fabricated with different residual oxygen contents during the manufacturing process.

Effects of the varying cooling rates as well as the impact of higher residual oxygen contents on the microstructure and mechanical properties were evaluated. These results highlight the importance of comprehensively understanding the impact of both thermal management and atmosphere on the production of Ti-6Al-4V components.

References

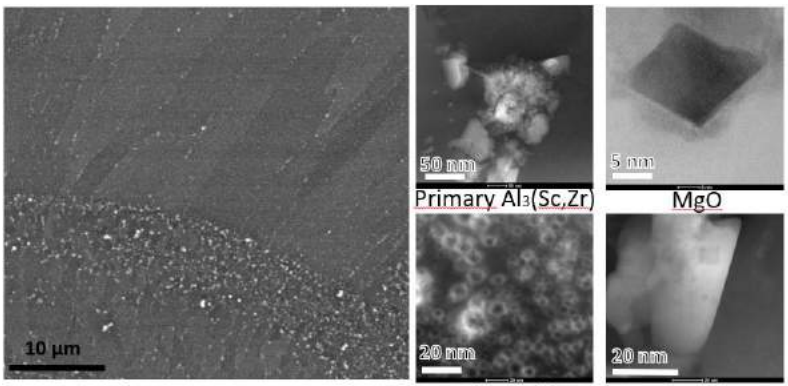
[1] D. Elitzer et al. *MATEC Web of Conferences*, **2020**, *321*, 03037.
[2] D. Elitzer et al. *Advanced Engineering Materials*, **2022**, *25*, 2201025.
[3] C. Fuchs et al. *Production Engineering*, **2023**, *17*, 703-714.

Microstructure characteristics of an Al-Mg-Sc-Zr-Mn alloy prepared using SLM

S. Nagy[1*], M. Mohebbi[2], Z. Hajovska[1], V.N. Trembosova[1], M. Nosko[1]

[1] Institute of Materials and Machine Mechanics v.v.i. SAS, 845 11 Bratislava, Slovakia
[2] Airbus Endowed Chair for Integrative Simulation and Engineering of Materials and Processes
(ISEMP), University of Bremen, Am Fallturm 1, 28359, Bremen, Germany,
*nagy.stefan@savba.sk

The precipitation of Al3(Sc,Zr) primary phase in aluminum alloys fabricated with Selective Laser Melting (SLM) can be influenced by various factors, including the alloy composition, processing parameters, and post-processing treatments. The Al3(Sc,Zr) phase is often desirable for its grain refinement (primary phase) and precipitation strengthening (secondary phase) effects. Primary Al3(Sc,Zr) in the melt act as potent nucleation sites for aluminium grains with warious morphology characteristics wich is dependent of cooling rate. However, the Al3(Sc,Zr) particles at the grain boundaries have similar sub-structures also. [1,2]



Primary $Al_3(Sc,Zr)$ MgO

CG and FG structure Secondary $Al_3(Sc,Zr)$ Mn-Fe phase

Figure 1. SEM and STEM microstructure details of CG, FG zones and precipitation

The secondary Al3(Sc,Zr) is an ordered intermetallic compound that can provide precipitation hardening and contribute to the improvement of mechanical properties in the alloy. The size, distribution, and density of these precipitates significantly impact the alloy's final mechanical properties. Understanding the characteristics of secondary Al3(Sc,Zr) precipitates is crucial for optimizing heat treatment processes and designing aluminum alloys with enhanced mechanical performance for various applications. [3]

This study investigates the microstructure of an Al-Mg-Sc-Zr-Mn alloy using SEM and STEM. The general microstructure consists of an equiaxial ultrafine-grained (FG) band at the melt pool boundary and a relatively columnar and coarse-grain (CG) region at the melt pool core. Primary precipitation is evident in the grains and grain boundaries with other phases according to alloying elements (Mg, Mn) and impurities (Fe). The secondary spherical Al3(Sc,Zr) with the L12 phase, after heat treatment, can be observed and identified.

References

[1] K.B. HYDE *Acta mater.*, **2001**, *49*, 1327-1337.
[2] Y. SUN *Materials Characterization*, **2020**, *169*.
[3] KUN V. YANG *Scripta Materialia*, **2018**, *145*, 113-117.

Notch Embrittlement in different build orientations of IN718 manufactured with Laser Powder Bed Fusion

S. Megahed[1,2*], K.M. Krämer[1,2], C. Kontermann[1], R. Herzog[3], A. Udoh[4], S. Weihe[4], M. Oechsner[1,2]

1 Technical University of Darmstadt, Institute for Materials Technology, Grafenstr. 2, 64283 Darmstadt, Germany
2 Technical University of Darmstadt, Additive Manufacturing Center, Ottilie-Bock-Straße 1, 64287 Darmstadt, Germany
3 MAN Energy Solutions, ETM - Material Technology, Steinbrinkstr. 1, 46145 Oberhausen, Germany
4 University Stuttgart, Materials Testing Institute, Pfaffenwaldring 32, 70569 Stuttgart, Germany

*sandra.megahed@tu-darmstadt.de

Abstract

Metal Laser Powder Bed Fusion (PBF-LB/M) allows for high degrees of freedom and the manufacture of high temperature materials. The PBF-LB/M microstructure is dependent on process parameters, component geometry and build orientation among others. The large number of process parameters and the constantly changing thermal conditions during the build cause challenges regarding reliability and repeatability of the achieved component quality.

IN718 is one of the most frequently used nickel-based superalloys and is applied, for example, in the aerospace industry as a turbine disk material due to its good high-temperature strength and corrosion and oxidation resistance [1]. IN718 is characterized by very good weldability and is thus ideally suited for processing with PBF-LB/M [2]. The elimination or minimization of Nb segregations poses a major challenge in the manufacturing process of this alloy. In addition to macro-segregations, the microstructure after the casting, forging or the PBF-LB process can show an unfavorable degree of precipitation. By heat treating IN718 fabricated components, a reduction of residual stresses, segregations as well as phase formation and distribution can be modified. The proportion of hardening phases is reduced and the proportion of brittle phases (δ- and Laves phase) is increased [3].

It is generally accepted in literature that these brittle phases (δ- and Laves phase) are the root cause for the IN718 notch embrittlement. Figure 1 shows results of notched IN718 PBF-LB/M creep samples from this study. As can be seen in Figure 1, IN718 notch embrittlement is not affected by the scan strategy (P1-P4). Even different heat treatments (HTA, HTB) have a limiting effect in prolonging the creep life. Only an adjustment in creep testing parameters (reduction in applied normal stress) allowed for an increased notched creep life.

In this study, different build orientations (0°, 45° and 90°), print parameter settings, heat treatments and notch factors were considered and their effect on notched creep life was investigated in short term creep experiments. Since the manufacturing and thermal conditions between different build orientations differ, the microstructure is also expected to differ. Differences in oxygen content, grain size and phase distribution were found, which significantly affect notched creep life.

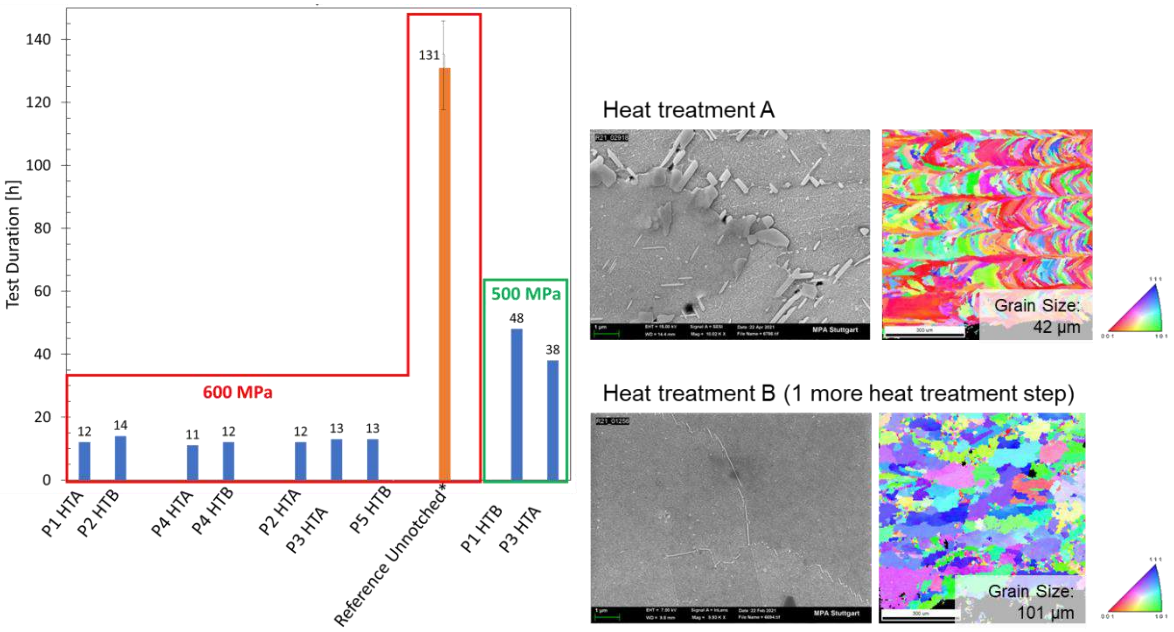


Figure 1. Notched creep life at 650 °C of PBF-LB/M IN718 samples in current study. Reference taken from Sanchez et al. [4]

References

[1] Huan Q. I., 2012,“Review of INCONEL 718 Alloy: Its History, Properties, Processing and De-veloping Substitutes,” Journal of Materials Engineering(8).

[2] Henderson M. B., Arrell D., Larsson R., Heobel M., and Marchant G., 2004,“Nickel based superalloy welding practices for industrial gas turbine applications,” Science and Technology of Welding and Joining, **9**(1), pp. 13–21.

[3] Carlson, R.G., Radavich, J.F., 1989,“Microstructural Characterization of Cast 718,” Superalloy 718-Metallurgy and Applications.

[4] Sanchez S., Hyde C. J., Ashcroft I. A., G.A. R., and Clare A. T., 2021,“Multi-laser scan strategies for enhancing creep performance in LPBF,” Additive Manufacturing, **41**(11), p. 101948.

Scale-bridging approach of microstructural analysis of an Al-Mg-Si Alloy produced by Laser Power-Bed Fusion

H. Wang[1,4*], M. Alhakim[1], T. Yallew[1], Y. Sakali[2], K. Solanki[3], J. Müller[1], B. Butz[1], C. Zinn[3], A. von Hehl[3]

[1] Lehrstuhl für Mikro- und Nanoanalytik, Universität Siegen, [2] Gerätezentrum für Mikro- und Nanoanalytik MNaF, Universität Siegen, [3] Lehrstuhl für Materialkunde und Werkstoffprüfung, Universität Siegen, [4] Lehrstuhl Werkstoffwissenschaft, Ruhr-Universität Bochum

*hongcai.wang@uni-siegen.de

Additive manufacturing (AM) of Aluminum (Al) alloys represents a revolutionary approach in metal fabrication, offering unparalleled design flexibility and material efficiency. However, achieving optimal performance relies heavily on understanding and controlling the microstructures. Microstructure analysis is crucial for assessing properties like grain morphology, size distribution, and phase constitute, which directly impact mechanical properties. By tailoring AM parameters and post-processing techniques based on microstructural insights, engineers can enhance the integrity and performance of Al alloy components. Careful microstructure analysis ensures that AM-produced parts meet stringent quality standards and reliability required by diverse industries, from aerospace to automotive and beyond.

Nevertheless, the rapid solidification and complex thermal histories inherent in AM-produced Al alloys result in microstructures that are far different from the conventional process routes (e.g. casting) and poses significant challenges in accounting for microstructural elements across differnt length scale [1]. In this study, a scale-bridging approach [2] combining multiple techniques in scanning electron microscopy (SEM) and transmission electron microscopy (TEM) was employed for microscopical analysis of an Al-Si-Mg alloy [3] produced by Laser Power-Bed Fusion (LPBF). Preliminary phase analysis was performed by combining energy dispersive x-ray spectrometry (EDS) and electron diffraction techniques (Figure 1). This comprehensive approach will provide valuable insights into the microstructural evolution of AM-produced Al alloys, facilitating further advancements in material design and process optimization.

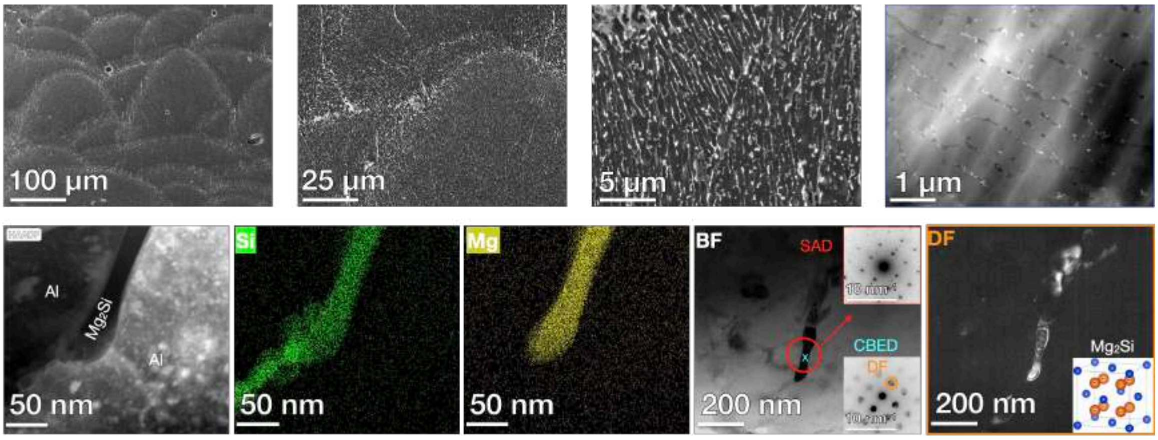


Figure 1. Scale bridging microstructure analysis of a AlSiMg alloy produced by LPBF. *Top:* microstructural details at different length scale in SEM and TEM; *Bottom:* Phase analysis by EDS and electron diffraction in TEM.

The authors acknowledge Dr. Daniel Knoop from Leibniz-IWT in Bremen for providing the specimens and extend the gratitude to the support and resources provided by ZGH at Ruhr-University Bochum. Part of this work was performed at the DFG-funded Micro- and Nanoanalytics Facility (MNaF) of the University of Siegen (INST 221/131-1).

References

[1] Z. Chaghazardi and R. Wüthrich *Journal of The Electrochemical Society*, **2022**, 169, 043510.
[2] H. Wang, C. Somsen, G. Eggeler, E. Detemple *Materwissenschaft und Werksttechnik,* **2018**, 49, 726–740.
[3] D. Knoop, A. Lutz, B. Mais, and A. von Hehl *Metals* **2020**, 10, 514.

Short-range ordering and its influence on mechanical properties in highly alloyed, additively manufactured, metallic materials

F. Oppermann[1*] F. Kies[2], J. Bernsmann[3], B. Hallstedt[4], C. Haase [1]

[1] Steel Institute, RWTH Aachen [2] Enrichment Technology Company, Jülich [3] Chair for Digital Additive Production, RWTH Aachen [4] Institute for Materials Applications in Mechanical Engineering, RWTH Aachen

*felix.oppermann@iehk.rwth-aachen.de

Additive manufacturing (AM) distinguishes itself in materials engineering by its exceptional capacity for processing metals under diverse conditions. This transformative technology allows for precise layer-by-layer fabrication of intricate metal structures directly from digital models. This uniqueness not only facilitates the creation of complex geometries but also enables tailored mechanical properties. To harness AM's ability to optimize metal structures under varying processing conditions enhances material efficiency and reduces waste, contributing to cost-effectiveness, is vital to reduce post processing steps such as heat treatments. Therefore, in this work we investigated the short-range ordering (SRO) phenomena in additively manufactured highly alloyed steels and multi-principal element alloys (MPEAs), with the objective of reducing the amount of post processing required, by optimizing as-built microstructure.

Using the DED-LB process, augmented by controlled substrate preheating, X110MnAl30-8 HMnS samples were manufactured. The additional layer of control over the process temperature, allowed for formation of κ-carbides, and thereby SRO, directly during deposition. This strategy eliminates the need for separate heat treatment steps and enables tailored control over the distribution and morphology of κ-carbides, thereby improving the mechanical properties. Furthermore, the occurrence of the strain-age-cracking mechanism, commonly seen in Ni-based alloys, was observed during manufacturing, posing challenges but also opportunities for increased robustness in AM processes.

In similar fashion, SRO phenomena in the CoFeMnNiAlC MPEA were investigated during the PBF-LB process. MPEAs present a unique combination of elements that can exhibit complex ordering phenomena at the atomic scale. Our work sheds light on the intricate atomic arrangements within the alloy matrix and their correlation with the mechanical properties. The findings provide valuable insights into tailoring the SRO in CoFeMnNiAlC alloys through additive manufacturing, offering a pathway for optimizing material performance for applications in advanced structural components. In this case high solid solution strengthening, high dislocation density and SRO resulted in an as-built single phase fcc material, boasting 1.1 GPa in tensile strength, while retaining 13% total elongation. Both results display interesting and promising avenues for furthering the potential of additively manufactured alloy systems by incorporating microstructure design down to atomic scale.

The Effects of Process Parameters on the Microstructure and Mechanical Properties of Additively Manufactured Metals

N. Tsuchiya[1*], N. Tsushima[1], R. Higuchi[1], T. Yokozeki[1]

[1] University of Tokyo
*nasatsuchiya1919@g.ecc.u-tokyo.ac.jp

Additively Manufactured (AM) metals exhibit unique microstructure in its melt pools, crystallographic characterization, and specifically in AlSi10Mg components, Si distribution, which affect its mechanical properties.[1] This microstructure is heavily influenced by the process parameters during AM. [2] Two crucial process parameters, laser power (LP) [W] and layer thickness (LT) $[\mu\mathrm{m}]$ were investigated in this study. Components of AlSi10Mg were built under four different parameter conditions, LP200/LT30, LP370/LT10, LP370/LT30, and LP370/LT200. Three-point bending tests, Surface Roughness Measurements, Scanning Electron Microscope (SEM) observation, and Electron Back Scattered Diffraction Pattern (EBSD) analysis were conducted to understand how the two parameters affect the mechanical properties (Young's modulus, Yield stress, and ductility), void characterization, and hierarchical microstructure of the manufactured material.

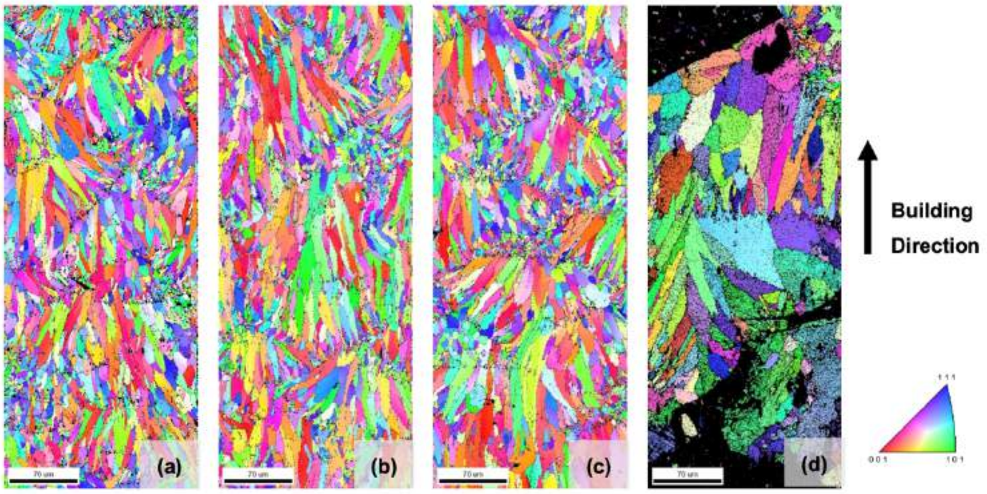
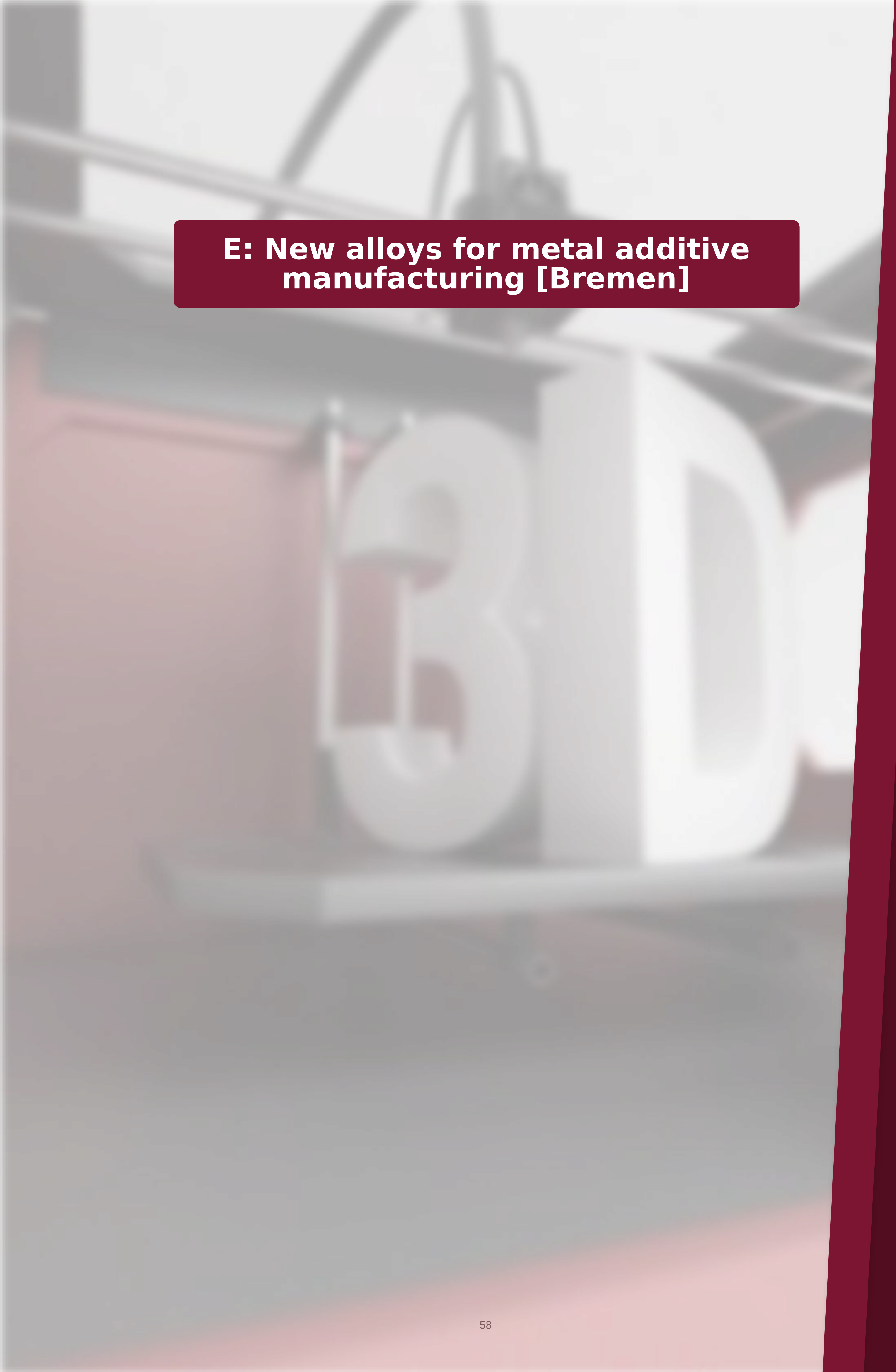


Figure 1. Results of EBSD analysis (a) LP200/LT30, (b) LP370/LT10, (c) LP370/LT30, (d) LP370/LT200

When laser power was increased from 200 [W] to 370 [W], surface voids decreased, the crystallographic grain size and micro α-Al cell size increased, and the nano-size Si precipitates decreased. Higher Young's modulus and yield strength were observed at 370 [W] most likely due to the increased density of the component. When layer thickness was increased from 10 $[\mu\mathrm{m}]$ to 30 $[\mu\mathrm{m}]$, there was a slight increase in voids, the crystallographic grain and micro α-Al cell size increased, the Si-rich eutectic network showed thinner walls, and the nano-size Si precipitates decreased. Young's Modulus and yield strength remained the same, whereas fracture strength and ductility were higher at 10 $[\mu\mathrm{m}]$. This may have been due to a stronger Orowan strengthening mechanism of the nano-sized Si precipitates impeding dislocation motion.[3] When layer thickness was increased to 200 $[\mu\mathrm{m}]$, the fine microstructure typical to AM materials was lost. The crystallographic grain size and micro α-Al cell size were significantly larger, the Si-rich eutectic network was degraded, and nano-size Si precipitates could not be observed. The mechanical properties deteriorated significantly, likely as a result of a notable increase in porosity.

References

[1] R. E. Gite and V. D. Wakchaure; *Materials Today: Proceedings,* **2023**, *Volume 72*, pp. 966-986.
[2] X. Liu et al.; *Materials and Design,* **2019**, *Volume 168*,
[3] A. Hadadzadeh et al.; *Additive Manufacturing,* **2019**, *Volume 28*, pp. 1-13



E: New alloys for metal additive manufacturing [Bremen]

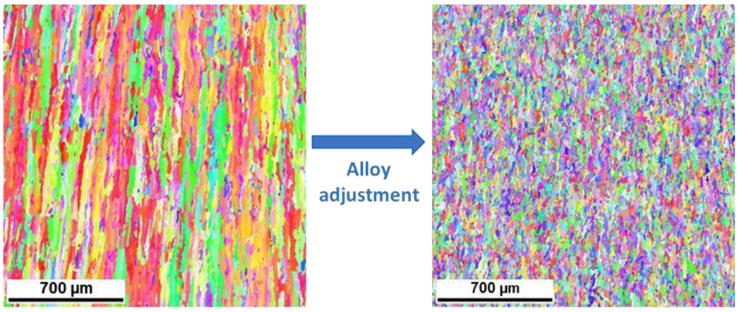
Alloy adjustment for fine-grained and texture-free microstructure of AISI 304L in electron beam melting

C. Burkhardt[1*], M. Wendler[2], R. Lehnert[1], M. Hauser[2], P. Clausnitzer[1], O. Volkova[2], H. Biermann[1], A. Weidner[1]

[1] Institute of Materials Engineering, Technische Universität Bergakademie Freiberg, Germany
[2] Institute of Iron and Steel Technology, Technische Universität Bergakademie Freiberg, Germany
* Christina.Burkhardt@iwt.tu-freiberg.de

Powder-bed based processing of austenitic stainless steels often results in a columnar microstructure with strong texture caused by a directed solidification of the melt, because of the strong temperature gradient from the heat source perpendicular to the build platform. The resulting anisotropic mechanical properties are undesirable for the majority of applications. In order to avoid columnar grain growth, it is usually attempted to adjust the beam parameters to limit the direction of heat flow parallel to the build direction. Another approach to interrupt epitaxial grain growth is to specifically adapt the alloy to the process conditions.

Günther et al. [1] and Seleznev et al. [2] already observed on EB-PBF manufactured high-alloy austenitic CrMnNi steels with a similar chemical composition, but a slightly different nickel content contrary microstructures and attributed this to the different solidification behaviour of the steels. While the microstructure of CrMnNi steel with lower nickel content was fine-grained and texture-free, the CrMnNi steel with higher nickel content showed a columnar microstructure with a strong texture in build direction. Based on these findings new modified steel variants of steel AISI 304L were developed with the aim to suppress columnar grain growth during the EB-PBF process and produce a fine-grained and texture-free microstructure by changing the chromium and nickel equivalent (Cr_{eq}/Ni_{eq}) of this steel (see Fig. 1). The resulting material properties are discussed on the base of the solidification behaviour by means of thermodynamic calculations as well as microstructural investigations and are compared with steel AISI 304L in its standard composition as well as the properties of the CrMnNi-steel mentioned before. Finally, this work presents requirements for the alloy design of austenitic steels to suppress epitaxial grain growth during the EB-PBF process.



Columnar grain structure of steel AISI 304L in standard composition

Fine-grinaed microstructure of modified steel 304L

Figure 1. Transition from a columnar to a fine-grained microstructure of steel 304L through special alloy design.

References

[1] J. Günther et al., *Scientific Reports*, **2018**, *8.*
[2] M. Seleznev et al., *Additive Manufacturing*, **2021**, 47.

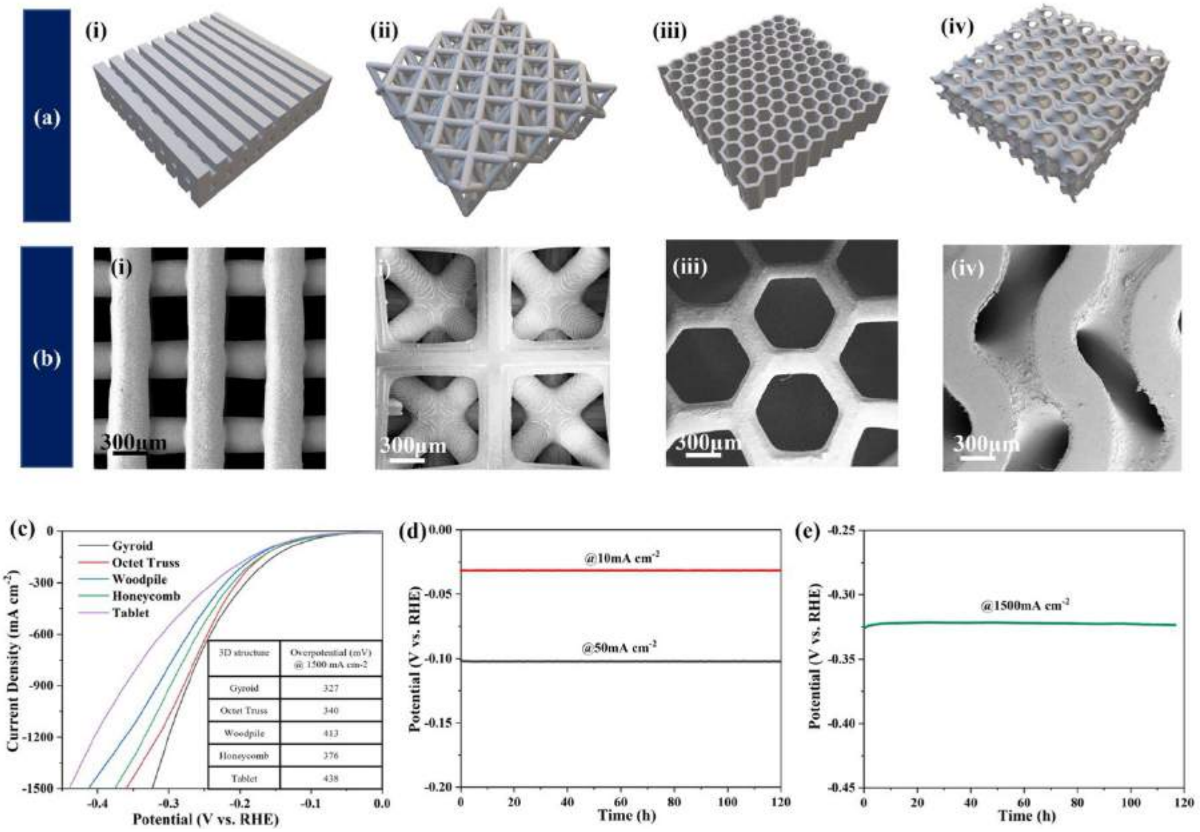
DLP-Printed Ni-Mo catalysts for high-performance HER at a high current density

Yanran Xun[1], **Jun Ding**[1]

1- Department of Materials Science and Engineering, National University of Singapore, Singapore 117574

Main author email address:
msedingj@nus.edu.sg
xunyanran@u.nus.edu

Developing efficient water splitting at high current density (>500 mA cm^{-2}) is essential for its scalability. [1] Electrochemical water splitting is one of the most promising technological approaches for producing green hydrogen, and it plays a crucial role in achieving carbon neutrality. [2] In the meantime, additive manufacturing as a simple and facile method has attracted researchers' interest for the past decades, and a couple of outstanding works about using 3D printing to fabricate electrodes for water-splitting have been done. [3]–[5] Here, we reported a series of monolithic 3D-printed Ni-Mo alloy electrodes for highly efficient water splitting at high current density (1500 mA cm^{-2}) with excellent stability and bubble removal behavior, which provides a solution to scale up Ni-Mo catalysts for HER to industry use. All possible Ni-Mo metal/alloy phases were achieved by tuning the atomic composition and heat treatment procedure, and they were investigated through both experiment and simulation, and the optimal NiMo phase shows the best performance. Density functional theory (DFT) calculations elucidate that the NiMo phase has the lowest H_2O dissociation energy, which further explains the exceptional performance of NiMo. In addition, the microporosity was modulated via controlled thermal treatment, indicating that the 1100 °C sintered sample has excellent catalytic performance, which is attributed to the high electrochemical surface area (ECSA). Finally, the 4 different macrostructures were achieved by 3D printing, and they further improved the catalytic performance. The gyroid structure exhibits the best catalytic performance of driving 500 mA cm^{-2} at a low overpotential of 228 mV and 1500 mA cm^{-2} at 325 mV as it maximizes the efficient bubble removal from the electrode surface, which offers the great potential for high current density water splitting (shown in Figure 1).



3D structure	Overpotential (mV) @ 1500 mA cm-2
Gyroid	327
Octet Truss	340
Woodpile	413
Honeycomb	376
Tablet	438

Figure 1. (a) 3D models created from Blender. (i) woodpile structure. (ii) octet truss structure. (iii) honeycomb structure. (iv) gyroid structure. (b) SEM images of Ni-Mo electrodes with different 3D architectures. (i) woodpile structure. (ii) octet truss structure. (iii) honeycomb structure. (iv) gyroid structure. (c) HER polarization curves of different 3D architecture electrodes (53 at. % Mo) in 1M KOH solution at 1 mV s^{-1} with 85% iR-compensations: gyroid, octet truss, woodpile, honeycomb, and plate. (Inset: overpotential at 1500 mA cm^{-2}) (d) Time-dependent potential curves with 85% iR-compensations for the 3D-printed Ni-Mo electrode at 10 and 50 mA cm^{-2}. (e) Chronoamperometric measurements with 85% iR-compensation of the HER at high current densities of 1500 mA cm^{-2} for the 3D-printed Ni-Mo electrode.

[[1] Y. Luo, Z. Zhang, M. Chhowalla, and B. Liu, “Recent Advances in Design of Electrocatalysts for High-Current-Density Water Splitting,” *Adv. Mater.*, vol. 34, no. 16, p. 2108133, (2022)

[2] X. Liu, M. Gong, S. Deng, T. Zhao, J. Zhang, and D. Wang, “Recent advances on metal alkoxide-based electrocatalysts for water splitting,” *J. Mater. Chem. A*, vol. 8, no. 20, pp. 10130–10149, (2020)

[3] S. Chang *et al.*, “Conductivity Modulation of 3D-Printed Shellular Electrodes through Embedding Nanocrystalline Intermetallics into Amorphous Matrix for Ultrahigh-Current Oxygen Evolution,” *Adv. Energy Mater.*, p. 2100968, (2021)

[4] R. A. Márquez *et al.*, “Tailoring 3D-Printed Electrodes for Enhanced Water Splitting,” *ACS Appl. Mater. Interfaces*, p. acsami.2c12579, Sep. (2022)

[5] I. Sullivan *et al.*, “ 3D Printed Nickel–Molybdenum-Based Electrocatalysts for Hydrogen Evolution at Low Overpotentials in a Flow-Through Configuration,” *ACS Appl. Mater. Interfaces*, vol. 13, no. 17, pp. 20260–20268, (2021)

Development of Ti-Cu alloy by mixing for medical applications in the PBF-LB/M process

A. L. Strauch[1*], A. Toenjes[1,2]

[1] Leibniz-Institut für Werkstofforientierte Technologien – IWT, Bremen
[2] University of Bremen, Bremen
*strauch@iwt-bremen.de

An antibacterial effect is essential for medical applications, but around 40,000 endoprostheses are replaced in Germany every year, with bacterial infection being the cause in around 20 % of cases [1,2]. Titanium alloys, for example Ti-6Al-4V, are used to manufacture artificial joints and surgical devices [3-6] but has poor antibacterial properties [7]. This can be achieved by adding copper (Cu), which has an antibacterial effect [8-11] and is also a trace element that is well tolerated by human cells and contributes to the formation of new bone [12,13]. Ti6Al4V-xCu powder is not commercially available, so its clinical suitability is unknown. The literature describes that processability problems arise with Ti-Cu alloys with > 6 wt.% Cu [14-16], but that an antibacterial effect only occurs with at least 5 wt.% Cu [8-10,17].

Alloy development and production for the laser powder bed fusion process (PBF-LB/M) is complex, costly, time-consuming and, above all, energy-intensive. In order to make the alloy development steps more sustainable, the approach of mixing pre-alloyed and/or pure elemental powders is used in presented work. This allows the exact amount required for this application or property-oriented alloy development to be mixed in order to perform first tests, initial characterizations and investigations of the mixed alloy. Due to the flexible variance of the mass % of Cu in the mixture, the Cu content can be increased step by step and the processability in the process can be ensured and the antibacterial effect in the sample can be investigated afterwards.

With this approach it can already be shown that a mixture of Ti6Al4V with 10 mass.% Cu can be processed in the PBF-LB/M process and dense samples (> 99.99 %) with fully melted Cu microstructures can be produced (Figure 1).

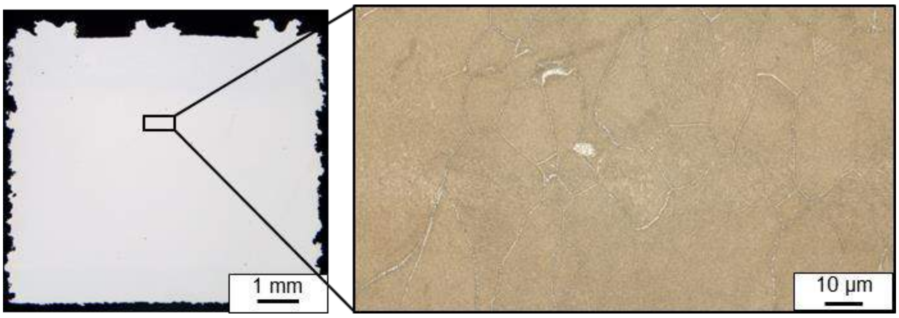


Figure 1. Overview image for density determination (left) and microstructure (right) of a Ti6Al4V mixture with 10 Ma.% Cu

References

[1] Melvin, J.S.; Karthikeyan, T.; Cope, R.; Fehring, T.K. Early failures in total hip arthroplasty -- a changing paradigm. *J Arthroplasty* **2014**, *29*, 1285-1288, doi:10.1016/j.arth.2013.12.024.

[2] Wengler, A.; Nimptsch, U.; Mansky, T. Hip and knee replacement in Germany and the USA: analysis of individual inpatient data from German and US hospitals for the years 2005 to 2011. *Dtsch Arztebl Int* **2014**, *111*, 407-416, doi:10.3238/arztebl.2014.0407.

[3] Zhang, L.C.; Chen, L.Y. A Review on Biomedical Titanium Alloys: Recent Progress and Prospect. *Advanced Engineering Materials* **2019**, *21*, doi:10.1002/adem.201801215.

[4] de Viteri, V.S.; Fuentes, E. Titanium and Titanium Alloys as Biomaterials. In *Tribology - Fundamentals and Advancements*, Gegner, J., Ed.; IntechOpen: Rijeka, 2013; pp. 155-181.

[5] Vu, N.B.; Truong, N.H.; Dang, L.T.; Phi, L.T.; Ho, N.T.-T.; Pham, T.N.; Phan, T.P.; Pham, P.V. In vitro and in vivo biocompatibility of Ti-6Al-4V titanium alloy and UHMWPE polymer for total hip replacement. *Biomedical Research and Therapy* **2016**, *3*, 567-577, doi:10.7603/s40730-016-0014-8.

[6] Österle, W.; Klaffke, D.; Griepentrog, M.; Gross, U.; Kranz, I.; Knabe, C. Potential of wear resistant coatings on Ti–6Al–4V for artificial hip joint bearing surfaces. *Wear* **2008**, *264*, 505-517, doi:10.1016/j.wear.2007.04.001.

[7] Han, X.; Ji, X.; Zhao, M.; Li, D. Mg/Ag ratios induced in vitro cell adhesion and preliminary antibacterial properties of TiN on medical Ti-6Al-4V alloy by Mg and Ag implantation. *Surface and Coatings Technology* **2020**, *397*, doi:10.1016/j.surfcoat.2020.126020.

[8] Liu, J.; Li, F.; Liu, C.; Wang, H.; Ren, B.; Yang, K.; Zhang, E. Effect of Cu content on the antibacterial activity of titanium-copper sintered alloys. *Mater Sci Eng C Mater Biol Appl* **2014**, *35*, 392-400, doi:10.1016/j.msec.2013.11.028.

[9] Zhang, E.; Zheng, L.; Liu, J.; Bai, B.; Liu, C. Influence of Cu content on the cell biocompatibility of Ti-Cu sintered alloys. *Mater Sci Eng C Mater Biol Appl* **2015**, *46*, 148-157, doi:10.1016/j.msec.2014.10.021.

[10] Liu, R.; Memarzadeh, K.; Chang, B.; Zhang, Y.; Ma, Z.; Allaker, R.P.; Ren, L.; Yang, K. Antibacterial effect of copper-bearing titanium alloy (Ti-Cu) against Streptococcus mutans and Porphyromonas gingivalis. *Sci Rep* **2016**, *6*, 29985, doi:10.1038/srep29985.

[11] Chan, Y.-H.; Huang, C.-F.; Ou, K.-L.; Peng, P.-W. Mechanical properties and antibacterial activity of copper doped diamond-like carbon films. *Surface and Coatings Technology* **2011**, *206*, 1037-1040, doi:10.1016/j.surfcoat.2011.07.034.

[12] Dupont, C.L.; Grass, G.; Rensing, C. Copper toxicity and the origin of bacterial resistance--new insights and applications. *Metallomics* **2011**, *3*, 1109-1118, doi:10.1039/c1mt00107h.

[13] Ahrens, H.; Gosheger, G.; Streitbürger, A.; Gebert, C.; Hardes, J. Antimikrobielle Silberbeschichtung von Tumorprothesen. *Der Onkologe* **2006**, *12*, 145-151, doi:10.1007/s00761-005-1007-1.

[14] Vilardell, A.M.; Yadroitsev, I.; Yadroitsava, I.; Albu, M.; Takata, N.; Kobashi, M.; Krakhmalev, P.; Kouprianoff, D.; Kothleitner, G.; Plessis, A.d. Manufacturing and characterization of in-situ alloyed Ti6Al4V(ELI)-3 at.% Cu by laser powder bed fusion. *Additive Manufacturing* **2020**, *36*, doi:10.1016/j.addma.2020.101436.

[15] Guo, S.; Lu, Y.; Wu, S.; Liu, L.; He, M.; Zhao, C.; Gan, Y.; Lin, J.; Luo, J.; Xu, X.; Lin, J. Preliminary study on the corrosion resistance, antibacterial activity and cytotoxicity of selective-laser-melted Ti6Al4V-xCu alloys. *Mater Sci Eng C Mater Biol Appl* **2017**, *72*, 631-640, doi:10.1016/j.msec.2016.11.126.

[16] Krakhmalev, P.; Yadroitsev, I.; Yadroitsava, I.; de Smidt, O. Functionalization of Biomedical Ti6Al4V via In Situ Alloying by Cu during Laser Powder Bed Fusion Manufacturing. *Materials (Basel)* **2017**, *10*, doi:10.3390/ma10101154.

[17] Ma, Z.; Ren, L.; Liu, R.; Yang, K.; Zhang, Y.; Liao, Z.; Liu, W.; Qi, M.; Misra, R.D.K. Effect of Heat Treatment on Cu Distribution, Antibacterial Performance and Cytotoxicity of Ti–6Al–4V–5Cu Alloy. *Journal of Materials Science & Technology* **2015**, *31*, 723-732, doi:10.1016/j.jmst.2015.04.002.

Fatigue Resistance Enhancement of an Aluminium Standard Alloy for Additive Manufacturing by Zirconium Addition

J. Schmidt[1*], L. Langer[2], H.W. Höppel[3], U. Tetzlaff[1]

[1] Technische Hochschule Ingolstadt, [2] Fraunhofer IGCV, [3]Friedrich-Alexander-Universität Erlangen-Nürnberg
*janina.schmidt@thi.de

AlSi10Mg is a widely recognized standard alloy in additive manufacturing, offering several advantages such as excellent printability, affordability, and ease of transferring printing parameters between systems. These characteristics make it a suitable choice, particularly for prototyping purposes. However, it does have certain drawbacks, such as inferior mechanical properties compared to cast parts [1]. Consequently, it is not suitable for most automotive applications beyond prototype manufacturing. To address this issue, various approaches have been proposed, including optimization of the printing process and exploring different alloy systems. For instance, APPWORX has promoted Scandium-modified options that exhibit superior mechanical properties [2,3,4,5]. The drawback is that these concepts often come with increased costs, making them economically unfeasible for high volume applications. Finding a way to improve additive manufacturing through the addition of an economically viable element would pave the way to greatly expand its industrial usage. The main objective of this study was to enhance fatigue resistance properties by modifying the alloy system with varying amounts of Zirconium, without the need for additional heat treatments or extensive optimization of printing parameters. In order to understand the changes occurring in the mechanical properties, the microstructure of both the new and standard alloys was examined. Additionally, comprehensive mechanical testing, including tensile and cyclic fatigue testing, was conducted. The addition of Zirconium has been demonstrated to enable the creation of a more isotropic microstructure, addressing one of the problematic aspects arising from the LBPF process. Moreover, only minor adjustments to the standard printing parameters are required, if any. In room temperature cyclic fatigue tests, alloys with Zirconium exhibit significantly higher cycle numbers. However, the beneficial effect cannot be indefinitely enhanced by increasing the Zirconium content, as it reaches its maximum at a specific weight proportion. Beyond this point, embrittlement occurs, rendering the material more susceptible to defects induced by the additive manufacturing process.

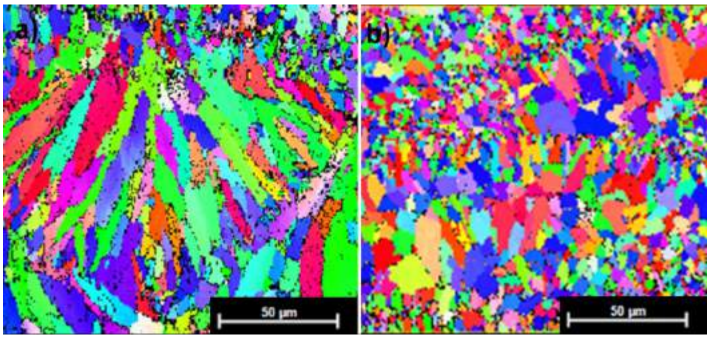


Figure 1. EBSD analysis of a) AlSi10Mg and b) AlSi10Mg with addition of Zirconium, showing significant grain refinement.

References

[1] N.T. Aboulkhair, *Materials & Design*, **2016**, *104*, 174-182
[2] A. Yadollahi, *International Journal of Fatigue*, **2017**, *98*, 14-31
[3] M. Raab; *Journal of Materials Processing Technology*, **2023**, *311*, 117811
[4] F. Palm, *PM2010 World Congress – PM Aluminium and Magnesium 2*, **2010**
[5] D. Schimbäck, *International Journal of Fatigue*, **2023**, *172*, 107592

Harnessing new material for superior quality and faster injection molds production using AM

Vishal Katoch[1]
Dr. Horst Hill[2]

[1] AddUp GmbH, [2] Deutsche Edelstahl Werke (Swiss steel group)
Vishal.katoch@addupsolutions.com
Horst.Hill@swisssteelgroup.com

In the realm of injection molding the quality and performance of mold inserts are of paramount importance to ensure durability and longevity of molds and for high end parts production. The creation of tailored materials with optimal mechanical properties, wear resistance, and corrosion resistance for adoption on metal AM system open doors for innovation of complex parts by exploiting the design freedom of AM, which is not possible by conventional manufacturing approaches.

Tool steels with high hardness (>52HRC), crack & wear resistance and corrosion resistance are fixed specifications for injection molding applications. Printdur HCT, has been developed based on conventional std. tool steel 1.2083/AISI420 by Swiss Steel Group in partnership with AddUp which has exactly these features and can be built up excellently on the FormUp350 with part density of over 99.95%.

Figure 1. 60mm*30mm*60mm (L*W*H) sample after polishing showing mirror finish, printed in Printdur HCT on FormUp350.

A hurdle for tool makers while adopting additive manufacturing is the crack issue in the parts and many tool steels are challenging to print due to the massive spatters and in-process pollution caused upon laser interaction with the powder. This can create additional porosity in molds which will lower the quality of the end part. Results using Printdur HCT have shown to build crack-free and denser parts with low porosity and smaller pores. The AddUp GmbH team has been able to print using this material with pores under 100 µm. Printdur HCT was used to print a benchmark part (figure 1) to test when extreme polishing would be required. Many tooling applications require machining and/or polishing after printed and pore size and porosity are magnified through this process. The benchmark in firgure1 shows a 60mm by 60mm L-shaped part after being polished to a mirror finish to further demonstrate the capabilities of Printdur HCT. Additionally, Printdur HCT does not consist of nickel and cobalt, preventing from significant damage to operators and the environment.

AddUp would like to deliver a short presentation with DEW (Swiss Steel Group) where they show together the current status of the development and adapation of the new material on FormUp 350. In the presentation, light would be shed on the technical aspects of the material and its asoption phases on FormUp based on the requirements from a consortium of industry partners in the tooling industry.

Influence of process parameters of High-speed Laser Directed Energy Deposition on material properties in the context of Rapid Alloy Development

M.-N. Bold[1*], J. H. Schleifenbaum[1]

[1] RWTH Aachen university – Digital Additive Production
*marie.bold@dap.rwth-aachen.de

New, application-specific materials are becoming increasingly important in Additive Manufacturing (AM) of highly stressed components. The number of customized materials that are manufacturable (crack-free) with laser-based AM and/or make targeted use of AM-typical process conditions, such as high cooling rates (up to 10^7 K/s), to achieve specific microstructures and properties is still very limited [1]. To accelerate alloy development, which takes years traditionally, both simulative and experimental approaches have been pursued. Simulations usually cannot predict microstructures of laser-AM fabricated samples accurately because of the high cooling rates. Experimental methods of powder-bed based processes are usually limited to one alloy composition per build job, demanding a high amount of metal powder with the alloy composition and considerable time.

High-speed Laser Directed Energy Deposition (HS DED-LB) has the potential to investigate new material systems quickly and resource-efficiently. In contrast to powder-bed based processes, the alloy composition can be changed within a few seconds and less metal powder is needed for sample production due to the local powder supply. Cooling conditions can be varied over a wide range by adjusting the process parameters, reaching those of the laser-based powder bed fusion (PBF-LB/M). [2,3]

As of today, the exact relationships between the process parameters in HS DED-LB (e.g. laser power, process speed, powder mass flow, and gas flows) and solidification conditions, microstructural parameters, and mechanical properties are not known. To use the HS DED-LB process for the alloy development of a range of melt-based manufacturing processes (such as PBF-LB/M), these correlations must be determined.

In this work, the first findings on the main factors influencing the HS DED-LB process on solidification cell size (as an indirect means for solidification conditions), hardness, and change in chemical composition due to processing of 316L are presented. The parameters with the greatest influence on the investigated material properties are then explored in more detail.

With the established correlations of process parameters and material properties, HS DED-LB processes can be easily adapted to emulate solidification conditions of other melt-based processes such as PBF-LB/M to accelerate alloy development. Additionally, existing HS DED-LB/M processes can be fine-tuned with regards to desired microstructure, hardness and change in chemical composition more quickly

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´ s Excellence Strategy – EXC-2023 Internet of Production – 390621612.

References

[1] B. Poorganji et al. *JOM*, 2020, *72*, 561–576
[2] S. Koss et al., *AMR*, 2021, *1161*, 13-25
[3] K. Büßenschütt et al., *Addit. Manuf. Lett.,* 2024, *8*, 100188

Innovative Fabrication of High Hardness High Entropy Alloy via Wire Arc Additive Manufacturing

Anatoliy Zavdoveev[1*], Dmytro Vedel[2], Andrej Klapatyuk[1], Magdalena Speicher[3]

[1] Paton electric welding institute, NASU, Kyiv, Ukraine
[2] I.M. Frantsevich Institute of Problems of Materials Science NASU, st. Krzyzanowski, 303142, Kyiv, Ukraine
[3] Materials Engineering and Metallurgy Faculty of Mechanical Engineering University of Applied Sciences Kempten Bahnhofstraße 61 87435 Kempten (Allgäu) Germany
*avzavdoveev@gmail.com

High-entropy alloys (HEAs) represent a modern category of materials formed through a multi-component approach, wherein alloying elements are combined to create a supersaturated solid solution. HEAs typically consist of equal proportions of these elemts. Notably, these materials exhibit outstanding mechanical characteristics, including high strength, ductility, corrosion resistance, and wear resistance.

Integrating Wire Arc Additive Manufacturing (WAAM) with High-Entropy Alloys (HEAs) presents numerous benefits. Foremost among these advantages is the ability to efficiently and cost-effectively produce large-scale components. To successfully implement WAAM for HEAs manufacturing, a crucial component is the presence of a filament with a specific chemical composition, such as a welding wire. While for softer HEAs like Cantor alloys, solid wire or multi-component wire cords can be utilized, the challenge arises with high-hardness alloys where fabricating a solid wire with the required composition becomes impractical. Addressing this intricate technological challenge forms the focal point of the current study [1].

The proposed method revolves around Gas Metal Arc Welding (GMAW) employing Metal Powder-Cored Wires (MPCW). These wires are filled with powder components in equal proportions to each other. This approach offers several advantages compared to alternative methods such as vacuum or argon-plasma melting, primarily due to its dominance in the molten volume of the workpiece. The evolution of this method is elaborated upon using a high-hardness eutectic high-entropy FeCoNiAl alloying system doped with Ta as a case study. The resulting WAAMed alloy exhibits nearly zero plasticity, a characteristic that becomes pronounced following a specialized heat treatment procedure.

References

[1] A. Zavdoveev, A. Klapatyuk, T. Baudin, E. MacDonald, D. Mohan, J. Oliveira, A. Gajvoronskiy, V. Poznyakov, H.S. Kim, F. Brisset, M. Khokhlov, M. Heaton, M. Rogante, M. Skoryk, D. Vedel, R. Kozin, I. Klochkov, S. Motrunich, Addit. Manuf. Lett. (**2023**) 100124. https://doi.org/https://doi.org/10.1016/j.addlet.2023.100124.

Acknowledgements: “This project has received funding through the EURIZON project, Grant Agreement #EU-3027, which is funded by the European Union under grant agreement No.871072.”

Microstructure tailoring of a NiAl-based eutectic alloy via electron beam powder bed fusion

K. Titz[1*], J. Vollhüter[2], S. Neumeier[2], M. Göken[2], B. Wahlmann[1], C. Körner[1]

[1]Friedrich-Alexander-Universität Erlangen, Materials Science and Engineering for Metals, Erlangen, Germany
[2]Friedrich-Alexander-Universität Erlangen, Institute for General Materials Properties, Erlangen, Germany
* katharina.titz@fau.de

NiAl-based alloys are emerging as promising high-temperature materials, owing to their excellent properties such as a high melting point, exceptional oxidation behavior, and low density. However, low fracture toughness and low ductility at room temperature limit the application area. A eutectic microstructure consisting of fine cellular-lamellar phases can improve these properties [1]. Our newly developed alloy $Ni_{30.6}Al_{36}Cr_{31.4}Mo_2$ (at.%) in combination with electron beam powder bed fusion (PBF-EB) exhibits this favorable microstructure due to the eutectic composition and the high cooling rates present in additive manufacturing [2]. The elevated process temperature achievable by PBF-EB can be used for an in-situ heat treatment. Consequently, spinodal decomposition and discontinuous precipitation occur and therefore change the microstructural composition (see Figure 1). In addition, modifying material characteristics such as material density, phase volume fraction, phase thickness, and grain size is achievable by controlling the process parameters and thus the thermal conditions. In this contribution, we present dense, crack-free specimens of the eutectic $Ni_{30.6}Al_{36}Cr_{31.4}Mo_2$ alloy processed by PBF-EB and a detailed microstructural study including chemical composition analysis. Moreover, the experimental results are validated by CALPHAD calculations and literature data [3]. Considering these findings, we offer a deeper understanding of the relationship between energy input and microstructure and therefore, the possibility of tailoring the microstructure.

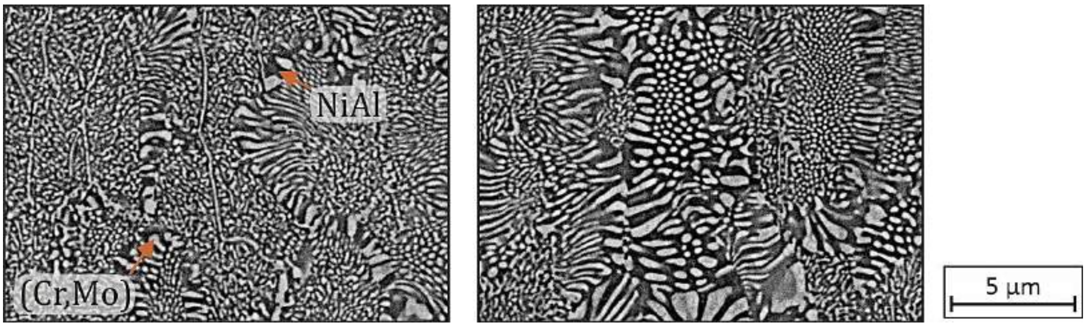


Figure 1. Microstructure of the eutectic NiAl-(Cr,Mo) in-situ composite with a low area of discontinuous precipitated (DP) regions (left) and a high amount of DP regions (right).

This work is funded by German Research Foundation (Project number 491441582).

References

[1] A. Förner, J. Vollhüter, A. Krapf, A. Jamjoom, D. Hausmann, B. Wahlmann, Z. Fu, C. Körner, S. Neumeier, M. Göken, *Adv. Eng. Mater.*, **2023**, *25*.
[2] K. Titz, J. Vollhüter, P. Randelzhofer, S. Neumeier, M. Göken, B. Wahlmann, C. Körner, *Design and Characterization of a Novel NiAl-(Cr,Mo) Eutectic Alloy: Manuscript submitted for publication* **2024**.
[3] C. Gombola, A. Kauffmann, G. Geramifard, M. Blankenburg, M. Heilmaier, *Metals*, **2020**, *10*, 961.

Rapid processing window development of Mo-Si-B alloy for electron beam powder bed fusion

Y. Chen[1*], B. Wahlmann[1], J. Böhm[2], J Schmelzer[3], M Krüger[3], C. Körner[1,2]

[1] Friedrich-Alexander University Erlangen-Nürnberg, Center of Advanced Materials and Processes, Dr.-Mack-Straße 81, 90762 Fürth, Germany, [2]Friedrich-Alexander University Erlangen-Nürnberg, Department of Materials Science, Chair of Materials Science and Technology for Metals, Martensstrasse 5, 91058 Erlangen, Germany, [3]Otto-von-Guericke-Universität Magdeburg, Institut für Werkstoff- und Fügetechnik, P.O. Box 4120, D-39016 Magdeburg, Germany
*yong.chen@fau.de

The alloy Mo-9Si-8B (at.%) exhibits an acceptable balance between creep and oxidation resistance at high temperatures as well as fracture toughness at ambient temperatures. Since it has a melting point of about 2000 °C, it is a promising ultra-high temperature material for turbine engines. [1] Mo-9Si-8B (at.%) is difficult to process by traditional manufacturing methods due to its brittleness at low temperatures. Additive manufacturing (AM), however, enables the production of complex near-net-shape bulk materials (e.g., turbine blades) in a single step. Electron Beam Powder Bed Fusion (PBF-EB), which is characterized by extremely high local processing temperatures and associated high powder bed temperatures (i.e.., above the brittle to ductile transition temperature of the material), is well-suited for producing refractory materials with complex geometries. [2]

In this work, the processing window of Mo-9Si-8B (at.%) was rapidly developed using novel strategies that combine high-throughput thermal modelling to predict the melt pool dimensions with in-situ Electron-optical imaging (ELO) for the first time (see Figure 1). High-density bulk Mo-9Si-8B (at.%) samples were successfully fabricated according to the established processing window, and the typical microstructure of the as-built samples was analyzed. This novel approach significantly reduced the effort required to generate processing windows, making it highly viable for developing stable processing conditions for new materials in PBF-EB.

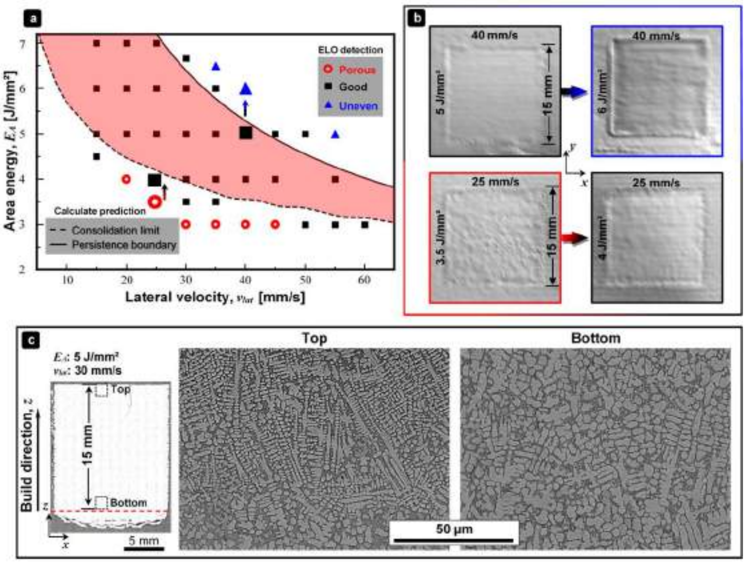
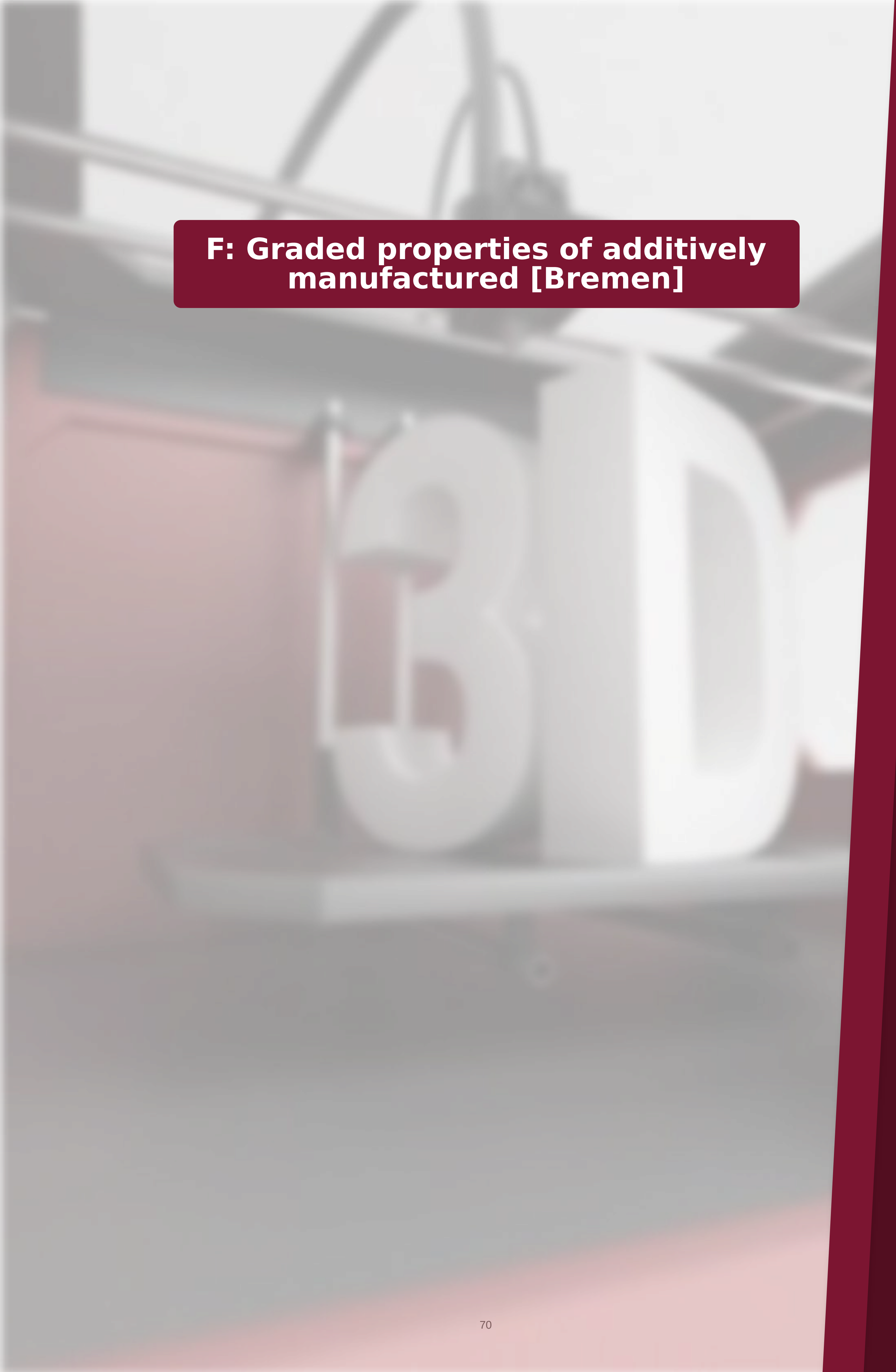


Figure 1. Generation of a PBF-EB Mo-9Si-8B (at.%) process map using calculated predictions with electron-optical imaging (ELO). a) processing window, b) ELO images of samples generated during processing, c) typical microstructure.

References

[1] M. Krüger, P. Jain, K.S. Kumar, M. Heilmaier; *Intermetallics*, 2014*, 48*, 10–18.
[2] Z. Fu, C. Körner; *European Journal of Materials*, 2022, *2(1)*, 54–116.



F: Graded properties of additively manufactured [Bremen]

Electron backscatter diffraction (EBSD) mapping of solidification grains, micro-twins, and building texture during laser additive manufacturing

F. Khodabakhshi[1,2*], A.P. Gerlich[3], M. Mohammadi[4], G. Wilde[2]

[1] School of Metallurgy and Materials Engineering, College of Engineering, University of Tehran, P.O. Box: 11155-4563, Tehran, Iran
[2] Institute of Materials Physics, University of Münster, Münster, 48149, Germany
[3] Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada
[4] Marine Additive Manufacturing Centre of Excellence (MAMCE), University of New Brunswick, 3 Bailey Drive, P.O. Box 4400, Fredericton, NB, Canada, E3B 5A1
*khodabak@uni-muenster.de

Closed-loop control of temperature and cooling rates during layer-upon-layer metal deposition of laser additive manufacturing (LAM) was implemented to design a solidification strategy and engineer the subsequent phase transformations and grain structure of stainless steels. Directed energy deposition (DED) of two grades of stainless steels, austenitic (316L) and martensitic (410L), without and with solid-state eutectoid austenite to ferrite phase transformation, were investigated to this end. In order to characterize the columnar grain formation and crystallographic texture generation along the building direction (BD) of deposited layers, large-scale electron backscatter diffraction (EBSD) mapping and focused ion beam/scanning transmission electron microscopy (FIB/STEM) analyses were employed. As a critical aspect, the impact of cooling rate on epitaxial growth or alignment of solidified grains during multi-layer deposition and its possible martensitic reversion assisted with micro-twining attributing to the subsequent solid-state phase transformation was explored.

In this research, the well-established algorithm and method for real-time monitoring and control of laser cladding was implemented for laser additive manufacturing in order to engineer the microstructural development and crystallographic orientation directionality during layer-upon-layer metal deposition [1, 2]. The successful accomplishment of the developed closed-loop route regarding the LAM construction by applying a constant cooling rate in deposition of each molten layer for two cases of 316L austenitic stainless steel and 410L martensitic stainless steel with and without solid-state eutectoid phase transformation, was studied in a previous studied by Farshidianfar *et al.* [3, 4]. In those Journal publications, the LAM deposition behaviour of these materials under two states of open- and closed-loop manufacturing was studied, followed by the examination of mechanical properties in correlation with the induced thermal history profiles. This project's leading innovation is comprised of the characterization of LAM deposited walls using electron backscatter diffraction (EBSD) mapping to possibly discuss the trends for solidification-induced grain evolution and the resulting main textural orientation development during multi-layer metal deposition and consolidation.

In Fig. 1, the ESBD microstructural maps in the case of 316L austenitic stainless steel show the inverse pole figure (IPF) of grains along the Y-direction and across the wall deposits for both states of open- and closed-loop laser additive deposition under varying processing parameters. As revealed, this alloy's solidification microstructure was preserved down to room temperature without a solid-state eutectoid transformation. In the case of open-loop laser additive manufactured walls, by applying a constant laser power of 800 W and changing the scanning speed in the three levels of 100 (316L_OL1), 200 (316L_OL2), and 300 mm/min (316L_OL3), as shown in Figs. 1a-c, microstructures seem heterogeneous with a random alignment of the solidified grains. Under such a processing state, although the operative processing parameters are conserved and fixed among all layers, the cooling rate can continuously change upon multi-layer deposition due to the role of pre-heating. By controlling and keeping this critical factor constant using an adaptive variation of laser traveling speed under a constant power, as accomplished under closed-loop LAM deposition, more aligned and identical solidification grains with building directionality were achieved, as characterized by EBSD mapping in Figs. 1d-f, for the three cooling rate magnitudes of 550 (316L_CL1), 1100 (316L_CL2), and 1750°C/sec (316L_CL3), respectively.

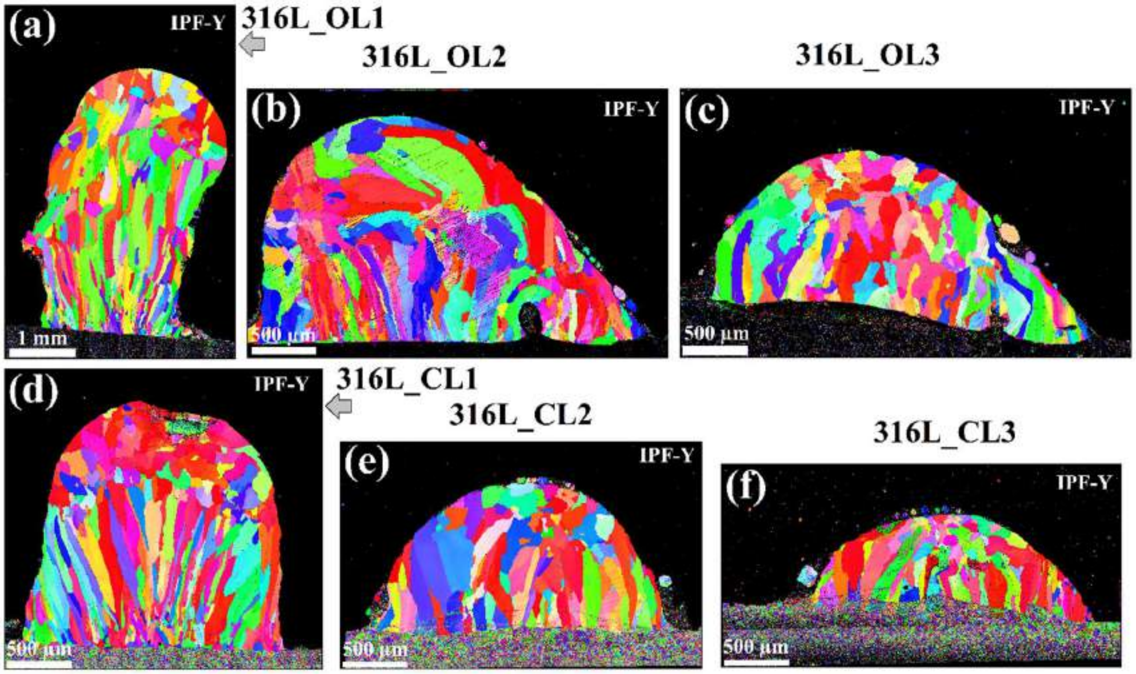


Figure 1. The EBSD IPF grain structural maps along the Y-direction for the LAM deposited 316L stainless steel walls under two different states of (a-c) open- and (d-f) closed-loop conditions. Variation in the laser scanning speed in the field of (a) 100, (b) 200, and (c) 300 mm/min under a constant power of 800 W and changing the cooling rate in the range of (d) 550, (e) 1100, and (f) 1750°C/sec.

In contrast, a martensitic transformation altered the above scenario regarding the other alloy (410L) involving the operative solid-state phase change by rapid cooling of LAM. Accordingly, the solidification microstructures disappeared, while the corresponding EBSD IPF-Y grain maps are illustrated in Fig. 2. The occurrence of the martensitic phase transformation assisted by micro-twinning along the boundaries had strong impact on controlling the built walls microstructures and was strongly dependent on LAM processing parameters. For the open-loop deposits of 410L_OL1, 410L_OL2, and 410L_OL3 from this steel alloy, as shown in Figs. 2a-c, with the same parameters as before for the 316L LAM consolidated walls, the progression of the martensitic phase transformation and micro-twinning across the borders from the bottom to the top layers seems different at the altered laser traverse speeds by changing the solidification cooling rate between the layers. The micro-twinning determined that the dominant transformation mechanism resulted in a very fine martensitic microstructure formation in the first layers with higher applied cooling rates. However, following the deposition of the following layers with lower cooling rates due to the pre-heating effect of previously solidified layers, the domains for martensitic shear transformation and micro-twinning were extended, resulting in the formation of coarser martensite laths surrounded with twins in the top part of the LAM deposits. Meanwhile, the closed-loop LAM strategy is applied through the persisting control of constant cooling rate among all layers (in this work, in the range of 550 to 1750°C/sec), as indicated in Figs. 2d-f for the constructed 410L walls of CL1, CL2, and CL3. This strategy produced a more homogenous microstructures from the martensitic laths and micro-twins in terms of population and size distribution. For a specific composition, such as 410L alloy in the present case, the cooling rate is the most critical parameter that can control and affect the above-mentioned non-diffusive phase transformations. Also, in comparison between 410L_CL1 to 410L_CL3 by increasing the cooling rate, the microstructure of the LAM built wall became more uniform with less gradients from bottom to top, which indicates the beneficial impact of closed-loop LAM, particularly at higher cooling rates.

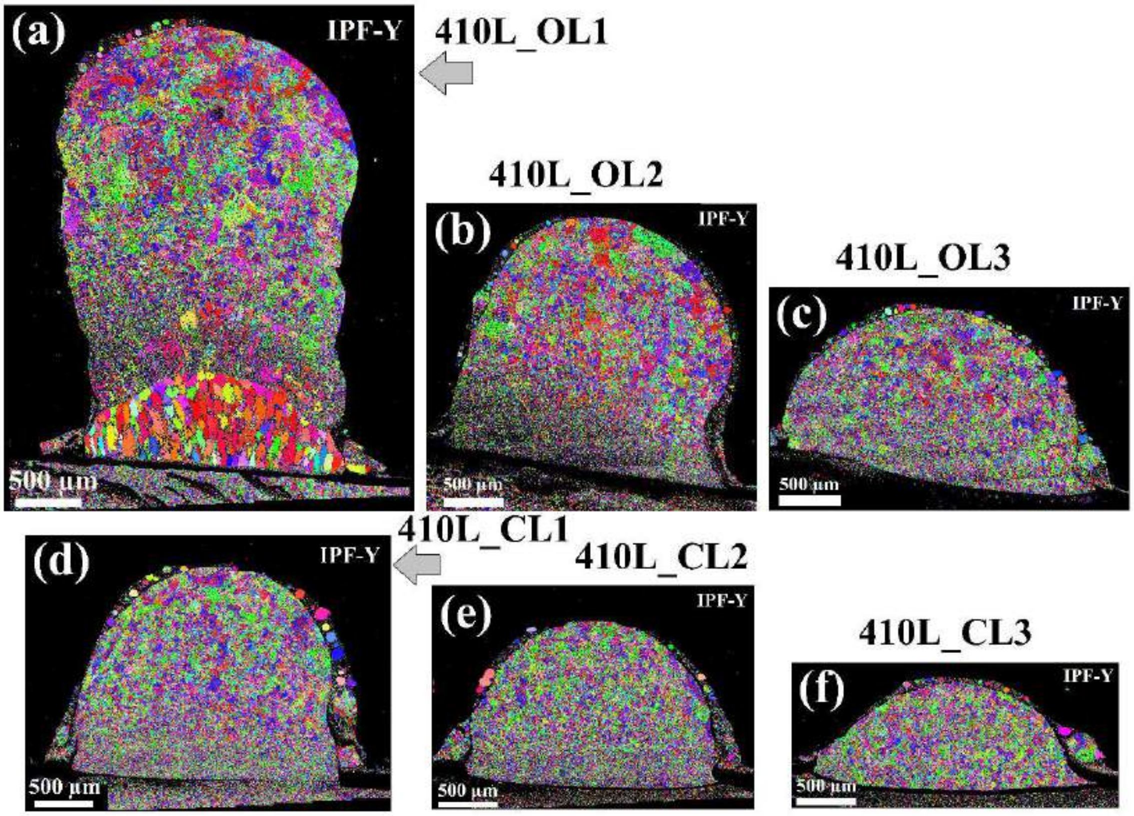


Figure 2. The identical EBSD IPF-Y microstructures for the laser additively manufactured 410L martensitic stainless steel walls for both states of (a-c) open-loop and (d-f) closed-loop LAM deposition: Structures of OL1 to OL3 with a constant power of 800 W and varying travel speed of (a) 100, (b) 200, and (c) 300 mm/min, and closed loop deposits of CL1 to CL3 with constant cooling rates of (d) 550, (e) 1100, and (f) 1750°C/sec.

References

[1] M.H. Farshidianfar; A. Khajepour; A.P. Gerlich; *Journal of Materials Processing Technology*, **2016**, *231*, 468-478.

[2] M.H. Farshidianfar; A. Khajepour; A. Gerlich; *International Journal of Advanced Manufacturing Technology*, **2016**, *82*, 1173-1186.

[3] M.H. Farshidianfar; F. Khodabakhshi; A. Khajepour; A.P. Gerlich; *Materials Science and Engineering: A*, **2021**, *803*, 140483.

[4] M.H. Farshidianfar; F. Khodabakhshi; A. Khajepour; A.P. Gerlich; Optics and Lasers in Engineering, **2021**, *145*, 106680.

Enhancing Fe-based Shape Memory Alloys through In-Situ Re-Alloying during Laser Powder Bed Fusion

J. Schmidt[1], M. Homfeldt[1], A. Toenjes[1,2*]

[1] Leibniz-Institute for Materials Engineering - IWT, [2] University of Bremen
*toenjes@iwt-bremen.de

Shape memory alloys (SMAs) exhibit unique properties that make them ideal for functionally integrated components, such as actuators. While commonly used Ni-Ti alloys are well-established, especially in biomedicine and aerospace, their high cost limits wider applications. Fe-based SMAs present an affordable alternative, suitable for diverse applications, with a larger thermal hysteresis but lower recovery strain [1,2]. Nonetheless, their functional properties can be enhanced through optimized processing methods like laser powder bed fusion and adjustments to their alloy composition [3,4]. However, attributing the functional improvements to individual factors is complex due to interdependency and inseparability of some factors.

In order to address this ambiguous state of literature, a novel approach for modifying the chemical composition of a FeMnSiCr-alloy will be presented. The technique allows in-situ re-alloying during laser powder bed fusion by locally applying a nanofluid containing the desired alloying element. This method offers a cost- and material-efficient high-throughput solution for alloy modification and functional grading (see Figure 1).

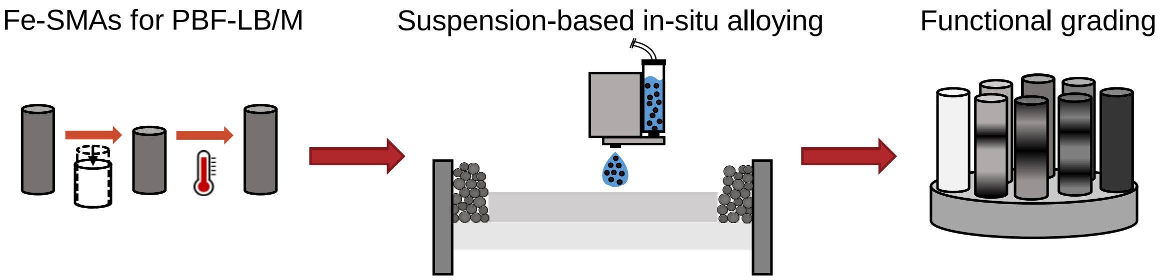


Figure 1. Schematic overview of the research outline.

Our current research focuses on utilizing this method to analyze the influence of interstitial atoms and carbide precipitates. For this purpose, specialized nanofluids for the flexible addition of necessary elements, such as carbon and niobium, were developed. Subsequently, the impact of the resulting compositional changes on the microstructure and the materials functional properties are analyzed.

The poster showcases the use of this novel re-alloying approach for the improvement of SMA composition and its possible application for functional grading.

References

[1] S. Miyazaki, H. Y. Kim in *Shape Memory and Superelastic Alloys*, **2011**, 15-42.
[2] T. Maruyama, H. Kubo in *Shape Memory and Superelastic Alloys*, **2011**, 141-159.
[3] I. Ferretto, D. Kim, N.M. Della Ventura, M. Shahverdi, W. Lee, C. Leinenbach, *Additive Manufacturing*, **2021**, *46*, 102071.
[4] H. Otsuka, H. Yamada, M. Tadakatsu, H. Tanahashi, S. Matsuda, M. Murakami, *ISIJ International*, **1990**, *30*, 674-679.

Evaluation of SLA-Based Additively Manufactured Oxide Ceramics for Biomedical Applications: A Comparative Study of Printability and Mechanical Properties

M.Vozárová[1*], F. Jelínek[2], M. Bordeus[2], L. Vály[1], M. Fedel[1], L. Sajti[1], M. Kitzmantel[1]

[1] RHP-Technology GmbH, Forschungs- und Technologiezentrum, A-2444 Seibersdorf, Austria
[2]ACMIT Gmbh, Viktor Kaplan-Straße 2, A-2700 Wiener Neustadt, Austria
*m.vo@rhp.at

This study delves into the advancement of oxide ceramics through stereolithography (SLA)-based additive manufacturing, with a primary focus on their suitability for biomedical applications. The objective is to comprehensively compare the printability and mechanical properties of diverse oxide ceramic materials, shedding light on their potential in fabricating intricate structures for biomedical purposes. The example of a demonstrator for an orthopaedic application prepared by SLA-based additive manufacturing using oxide ceramics is shown in Figure 1.

The research methodology involves the utilization of SLA technology to fabricate oxide ceramic samples using a variety of materials. The printability of each material is systematically assessed, considering factors such as layer adhesion, surface finish, and dimensional accuracy. Subsequently, a comprehensive investigation of mechanical properties, such as, hardness, and fracture toughness, is conducted to evaluate the structural integrity and overall performance of the printed ceramics.

The findings of this study aim to contribute valuable insights into the selection and optimization of oxide ceramic materials for biomedical additive manufacturing applications [1].

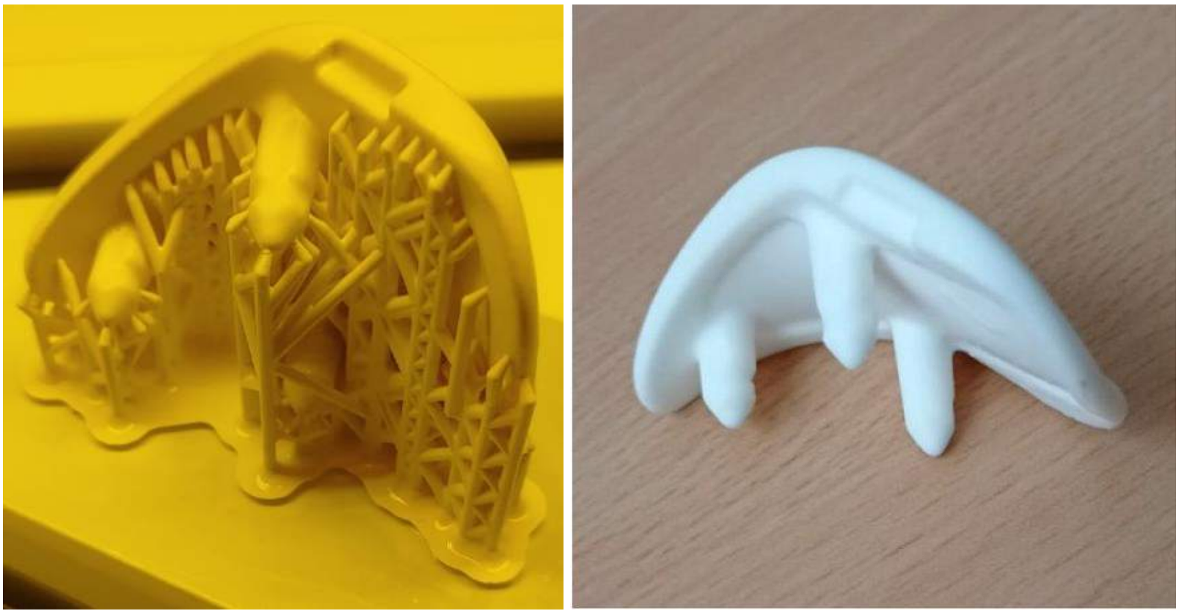


Figure 1. *A knee implant demonstrator for orthopaedic application prepared by SLA-based additive manufacturing using oxide ceramics*

References

[1] R. Dhanfapani et al.; Additive manufacturing of biodegradable porous orthopaedic screw; *Bioactive Materials*, **2020**, *5*, 458-467.

Functionally graded stiffness of magneto-active composites fabricated by laser powder bed fusion

K. Schäfer[1,6*], M. Lutzi[1,6], M. B. Khan[1,6], L. Schäfer[1,6], I. Dirba[1,6], S. Bruns[2,6], I. Valizadeh[3,6], O. Weeger[3,6], C. Hartmann[4,6], M. Kupnik[4,6], E. Adabifiroozjaei[5,6], L. Molina-Luna[5,6], K. Skokov[1,6], O. Gutfleisch[1,6]

[1]Functional Materials, TU Darmstadt, [2]Physical Metallurgy, TU Darmstadt, [3]Cyber-Physical Simulation Group, TU Darmstadt, [4]Measurement and Sensor Technology Group, TU Darmstadt, [5]Advanced Electron Microscopy, TU Darmstadt, [6]Additive Manufacturing Center, TU Darmstadt
*kilian.schaefer@tu-darmstadt.de

Inspired by biological structures like bones, wood and teeth, the production of artificial materials with site-specific and graded properties are under investigation [1]. Additive manufacturing technologies are especially promising for the fabrication of these materials since they allow the combination of complex geometries with locally adjusted properties [2]. Examples where precise geometry and tailored mechanical properties are required can be found in biomedical applications, for example, in airway stents [3].

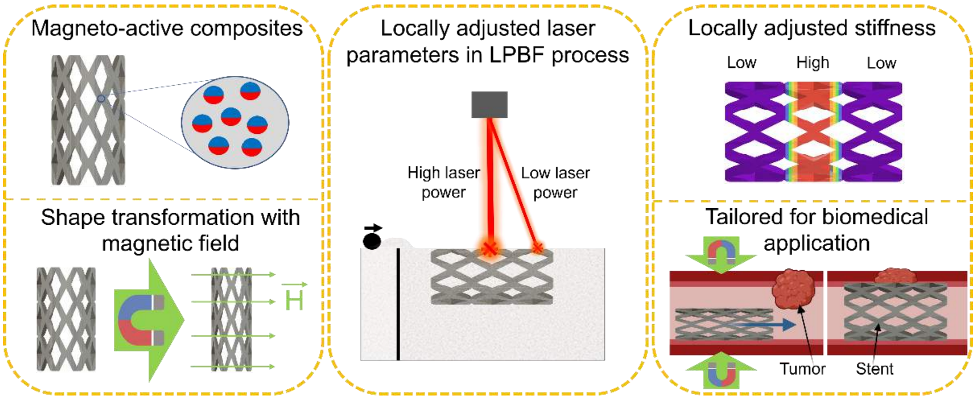


Figure 1. Graphical abstract: The work investigates the possibility of tailoring the mechanical properties of magneto-active composites locally [4].

Here we present a single-step laser powder bed fusion (LPBF) process that enables precise local adjustments of the mechanical stiffness within magneto-active composites [4]. By utilizing distinct laser parameters in specific regions of a composite containing thermoplastic polyurethane and atomized magnetic powder derived from hard magnetic Nd-Fe-B, the stiffness of the composite can be modified within the range of 2–22 MPa. The fabrication of graded mechanical properties is verified with nanoindentation of parts printed with different orientations toward the building direction. As an example of a biomedical application, a magnetically responsive airway stent with localized stiffness adjustment is presented. The position and diameter of the stent can be controlled remotely by an external magnetic field. Since the airway stent is fabricated with increased stiffness at the center, the structure is well adapted to the function of expanding force on a tumor. The proposed method using LPBF presents an approach for creating functionally graded materials, not only for magneto-active materials but also for various other structural and functional materials.

Acknowledgements

This work was financially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Project ID No. 405553726, TRR 270 and the RTG 2761 LokoAssist (Grant no. 450821862).

References

[1] Z. Liu, M. A. Meyers, Z. Zhang, and R. O. Ritchie. *Progress in Materials Science,* **2017***, 88,* 467–498.
[2] G. H. Loh, E. Pei, D. Harrison, and M. D. Monzón. *Additive Manufacturing,* **2018**, *23*, 34–44.
[3] L. Freitag, M. Gördes, P. Zarogoulidis, K. Darwiche, D. Franzen, *et al. Respiration*, **2017,** *94 no. 5*, 442–456.
[4] K. Schäfer, M. Lutzi, M. B. Khan, L. Schäfer, I. Dirba, S. Bruns, *et al. Additive Manufacturing*, **2024,** *79,* 103905,

Impact of Build Envelope and Ultrasonic Excitation on the Microstructure of 316L Stainless Steel Fabricated by DED-LB/P

F. Stredak[1*], N. Sommer1, C. Wolf[1], P. Mäckel[2], S. Böhm[1]

[1]University of Kassel, Institute of Production Technology and Logistics, Department for Cutting and Joining Manufacturing Processes, Kassel, Germany
[2]isi.sys GmbH, Kassel, Germany
*f.stredak@uni-kassel.de

The layer-wise deposition of materials by means of Additive Manufacturing (AM) enables the development and production of components with unparalleled complexity. Laser-based powder-bed fusion (PBF-LB) and direct energy deposition (DED-LB) are prominent examples of fabrication technologies in the field of metallic materials. Due to the repeated remelting of previously applied layers, these processes promote epitaxial grain growth, which can lead to the formation of long grains with a pronounced <001> texture. Particularly for the DED-LB, the insulating effect of the surrounding atmosphere only allows heat dissipation through the generated structure. The resulting temperature gradient further enhances the formation of a textured and columnar-grained microstructure with respect to the building direction. However, recent studies have shown that coupling ultrasonic excitation with the DED-LB processes is one of the most promising methods to counteract epitaxial grain growth during AM. In addition, this technology can also be used to systematically manipulate the microstructure of individual layers by triggering the ultrasonic excitation at specific points in time within the process. This represents a novel approach for AM of metallic materials and geometries with graded properties.

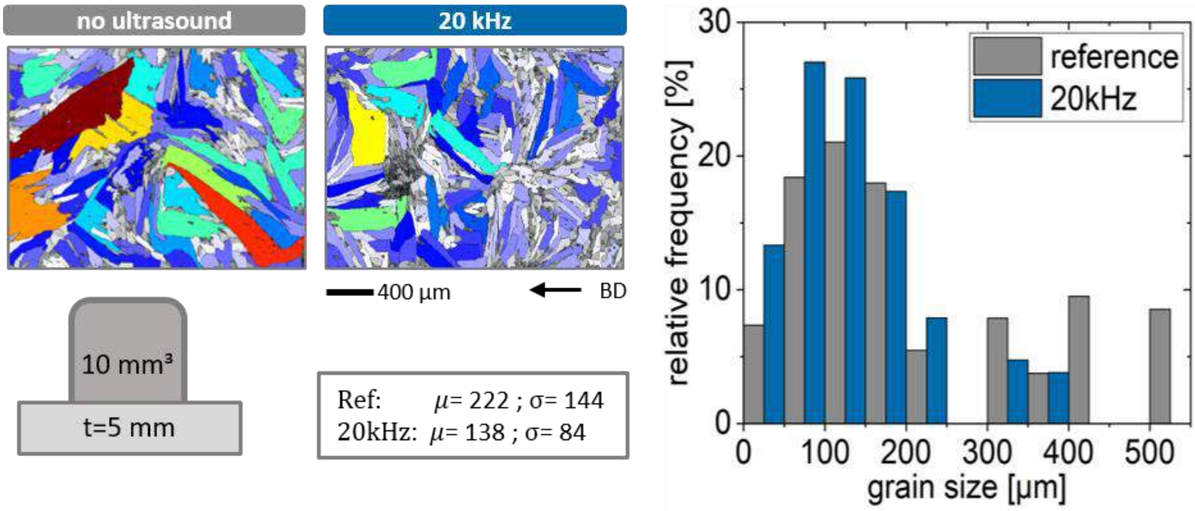
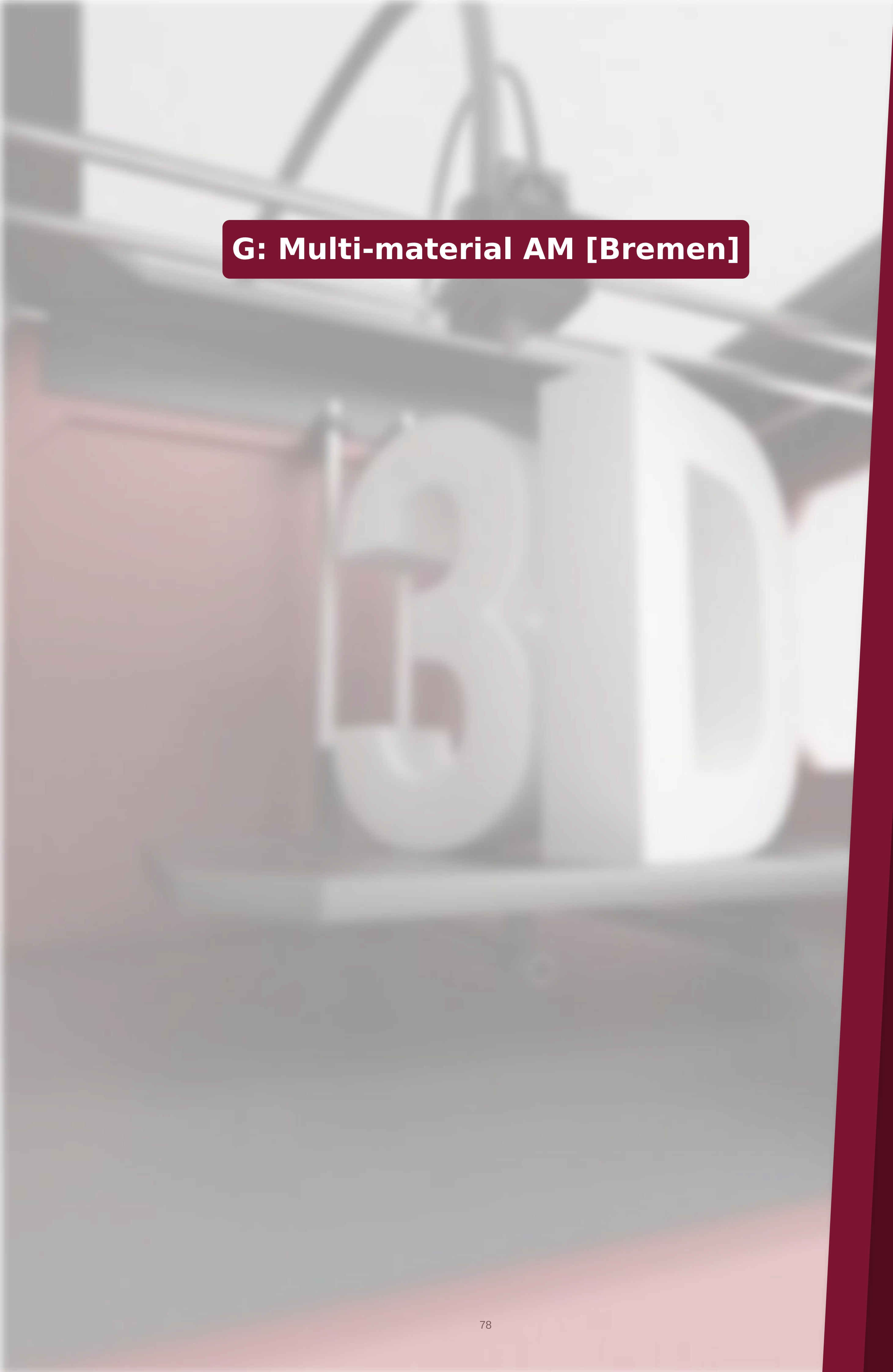


Figure 1: EBSD measurements of the grain size distribution of a cuboid with an edge length of 10 mm, which was produced on a 5 mm thick substrate using DED-LB, were carried out both with and without ultrasonic excitation.

The presented study seeks to expand the understanding of potential process limitations by analyzing the influence of ultrasonic excitation parameters and build envelope sizes on the microstructural evolution of stainless steels fabricated by powder-fed DED-LB using a force-fit excitation source attached to the build platform. The results of the electron backscatter diffraction analyses reveal a pronounced influence of build envelope size and ultrasonic excitation parameters, thus providing new possibilities for the potential use of ultrasonic excitation in future AM applications.

G: Multi-material AM [Bremen]



Voxel-based Data-Compression for Design for Disassembly

D. Laa[1*]

[1] TU Wien
*dominik.laa@tuwien.ac.at

Design for Disassembly (DfD) is a novel paradigm where parts can disassemble autonomously by being exposed to an external trigger. Using this approach, the production of parts that are more environmentally friendly and easier to recycle becomes possible. The DfD process is started with a short heat pulse, this heat pulse triggers a substantial volume expansion of the utilized material, leading to cracking and final separation of defined sub-assemblies. To design such DfD-objects, a software that is capable of handling at least two materials is required. The current predominant vector-based approach is not suitable for modelling structural interactions at the level of individual voxels, which is a requirement for designing parts for DfD. Therefore, the voxel-based approach is chosen for this application. One of the main challenges with this approach is the compression of data, since the uncompressed voxel-based data would require too much memory.

We investigated a combination of different compression methods with the goal of finding a data-structure setup that can hand the required data for DLP-based stereolithography with 2 or more materials. For our machine that means a resolution of up to 1920*1080 pixel. When compressing data, it must still be possible to define material properties for each smallest printable point (voxel).

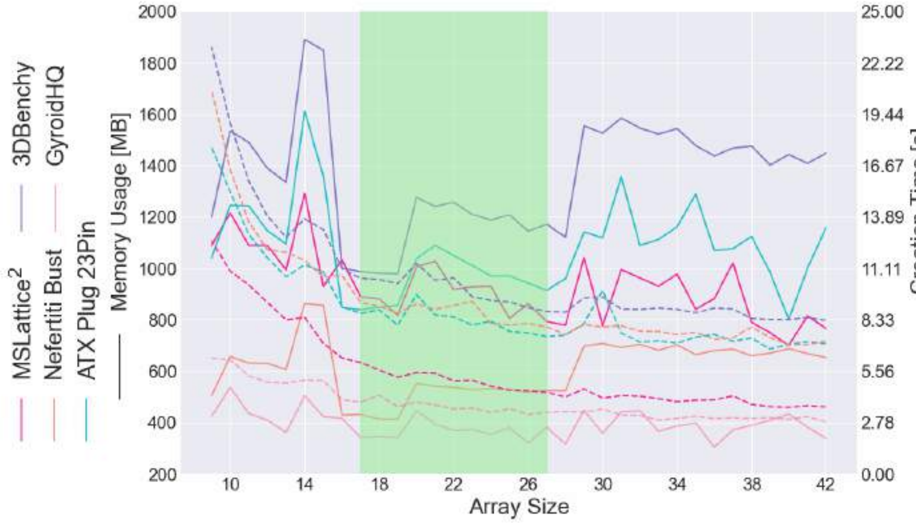
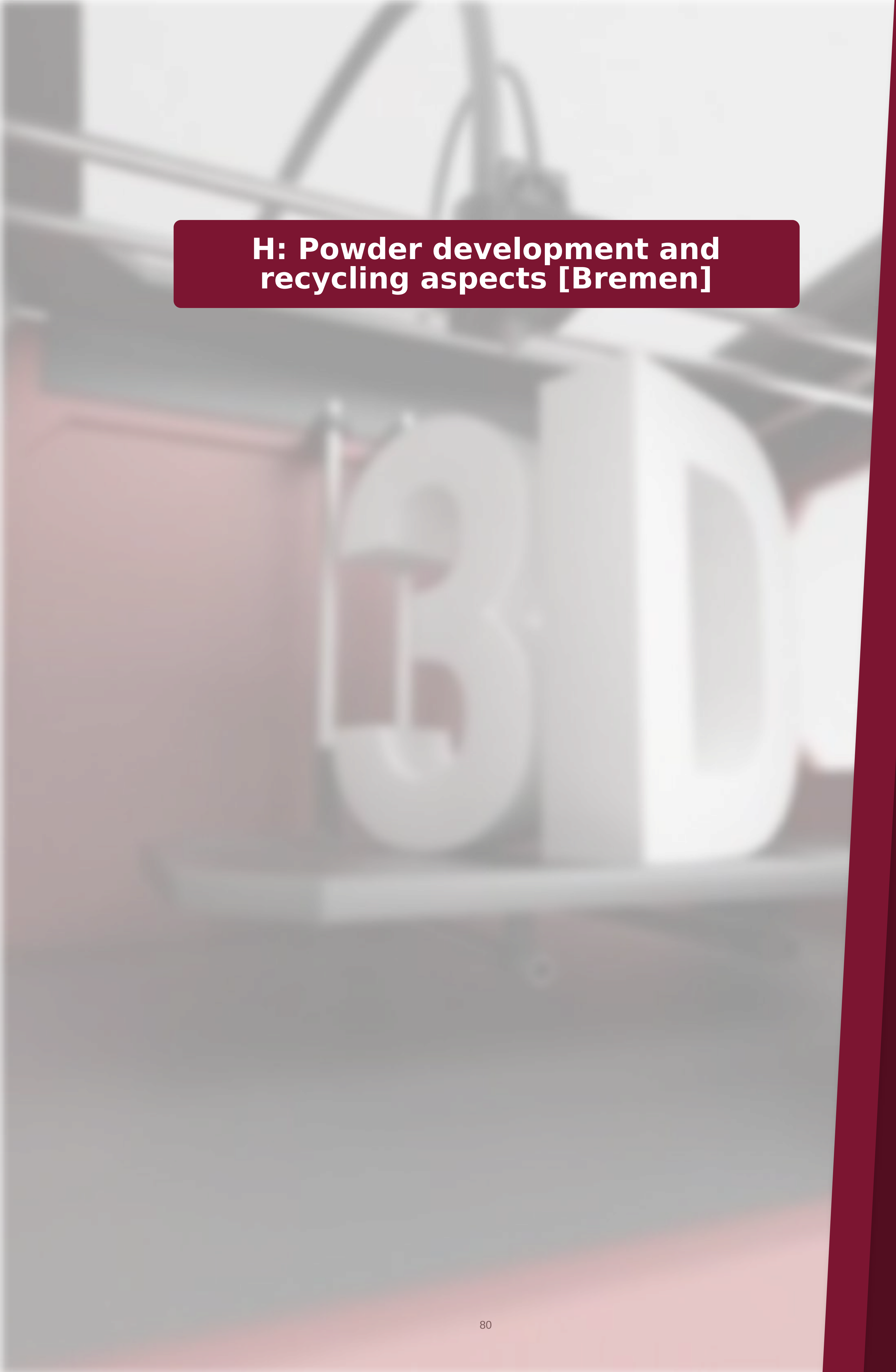


Figure 1. Memory usage and creation time evaluation for different array sizes (a). The green highlighted area shows the array sizes that performed best.

We propose a data structure comprised of c chunks. Each chunk encapsulated o octrees with a maximum depth of d. The leaf node of each octree is implemented as an array of size a. The total capacity of this data structure can be expressed as: $(c \cdot o \cdot 2^d \cdot a)^3$

Our empirical evaluation was run on a 12-core, 24-thread CPU. The number of chunks (c) that achieved optimal performance was in range of 25 to 35. For the number of octrees per chunk (o) the preference value as 1. The maximum depth of each octree (d) was dynamically adjusted based on the array size (a) to ensure sufficient data storage capacity. Figure 1 presents the results of our evaluation with varying array size (a). Based on the observed trends we concluded that the array size should be in the range of 17 to 27 elements for optimal performance.



H: Powder development and recycling aspects [Bremen]

Atomization of K340 Tool Steel by Vacuum Induction Gas Atomization Technique for Using in Directed Energy Deposition Process

M.S. Kenevisi[1*], F.S. Gobber[1], D. Ugues[1], S. Biamino[1]

[1] Department of Applied Science and Technology (DISAT), Politecnico di Torino, Italy
*mohammad.kenevisi@polito.it

Directed energy deposition (DED) is a metal additive manufacturing technique, in which a focused energy source is used to precisely deposit material during the process to repair parts or create complicated metal components [1]. K340 tool steel, known for its excellent wear resistance, toughness, and strength, is widely used as dies and tools that require enhanced durability and performance [2]. Repairing damaged parts by powder-fed DED process gives such benefits as low and controlled heat input, rapid cooling rates, and minimal stress and distortion. As powder of K340 steel is not commercially available, in this study the powders were produced by vacuum induction gas atomization (VIGA) process. The VIGA process involves melting the alloy in a crucible under vacuum conditions and subsequently atomizing it with high-pressure gas. Understanding the atomization process and its impact on the resulting powder properties can improve the processability of the alloy by additive manufacturing processes and lead to fabricated parts with enhanced properties. The produced powder was sieved and characterized by different techniques. The concentration of the alloying elements was studied by energy-dispersive X-ray spectroscopy (EDS) and C, O, and S were analyzed by LECO, and the results were in great agreement with the material specification. The morphology of the powder particles was investigated by electron microscopy. The results showed spherical particles with some satellites attached, mainly to bigger particles. It is also well-known that the cooling rate can affect the microstructure and the possibility of dendritic to cellular growth.

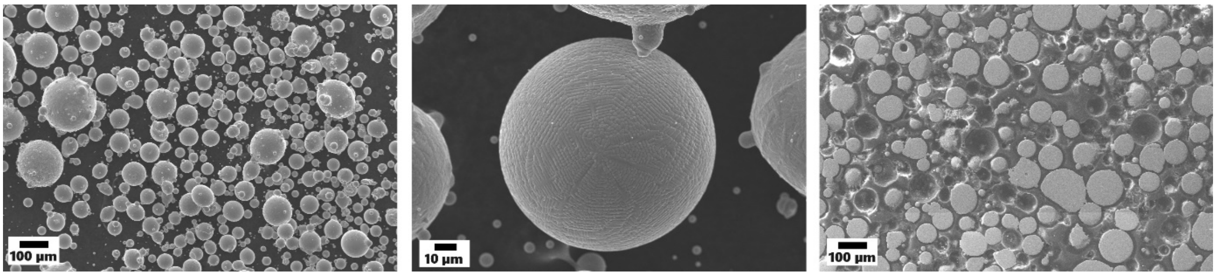


Figure 1. Micrographs of the gas atomized powders at different magnifications and the cross-section area of the particles.

Additionally, the relative density of the particles was high, which was measured by gas pycnometer. The cross-section investigation confirmed that, regarding the internal defects such as gas porosity, high quality powder is produced showing negligible gas pores in the particles, even in those having a diameter of more than 100 µm. These pores are inevitable in gas atomization process [3] and atomizing parameters, such as melt temperature and gas pressure, have great impact on the fraction of internal pores caused by the entrapped gas. Regarding the chemical composition of the powder, it was in good agreement with the starting material, and the oxygen content tends to increase by increasing particle size, which is related to the increase in the surface to mass ratio.

References

[1] A. Vafadar, F. Guzzomi, A. Rassau, and K. Hayward, *Applied Sciences*, **2021**, 11, 1–33.
[2] K. Böhler, "COLD WORK TOOL STEEL.", *[Online] Available: https://www.bohler-edelstahl.com/app/uploads/sites/92/2020/07/productdb/api/k340en_isodur.pdf*, Accessed: Sep **2023**.
[3] M.S. Kenevisi, F. Lin, *Journal of Manufacturing Science and Engineering*, **2023**, 145, 054501-1-7.

Development of a Method for Quality Control and Reprocessing of Metal Powders in Metal Binder Jetting

M. Norda[1]*, J. H. Lübbe[1], Prof. Dr. F. Petzoldt[1], Prof. Dr. R. M. Gläbe[2]

[1] Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Wiener Straße 12, 28359 Bremen, Germany,
[2] HSB Hochschule Bremen - City University of Applied Sciences, Neustadtswall 30, 28199 Bremen, Germany
*michael.norda@ifam.fraunhofer.de

The metal binder jetting (MBJ) process is a powder bed-based Additive Manufacturing (AM) process, which is attracting growing interest. In this process, a liquid binder deposited by a print head bonds the powder particles to create so-called green parts. For a reliable metal binder jetting process, the metal powder must have a high quality. The morphology and particle size distribution have a major influence on the flowability and sinterability of the material. In this work, the aging process is observed particularly regarding the slightly disappearing fine fraction during the process. A practical method is presented to reliably detect the ageing process of the powder. In addition, a method is developed to stop or curb ageing to support constant printing conditions. The experiments are conducted using 17-4PH stainless steel. Several properties of powders and parts are analysed such as particle size distribution, green part density, powder bed density and dimensional tolerances.

Industrial machines process a high amount of powder. Therefore, the powder transportation and refreshment systems have a high level of complexity and consist of many different stations.
In developing a recycling strategy, the first step is to identify the various locations where powder is found after the process. It is then necessary to find out how good the quality of the powder is at each location, whether it can be used for the next print and whether or how it needs to be reprocessed. In the 25Pro powders can occur in the following locations:

- Storage container of the sieving system
- Powder transport system (hopper)
- Powder recoater
- Powder in the powder bed
- Powder in the container of the 25Pro vacuum system
- Powder from broken green parts
- Powder in the container of the depowdering station vacuum system
- Powder in the overflow containers of the 25Pro
- Powder in the overflow container of the sieving system
- Loss of powder during handling

An overview of the different parts and how they interact within the powder cycle is visualized in **Error! Reference source not found.**.

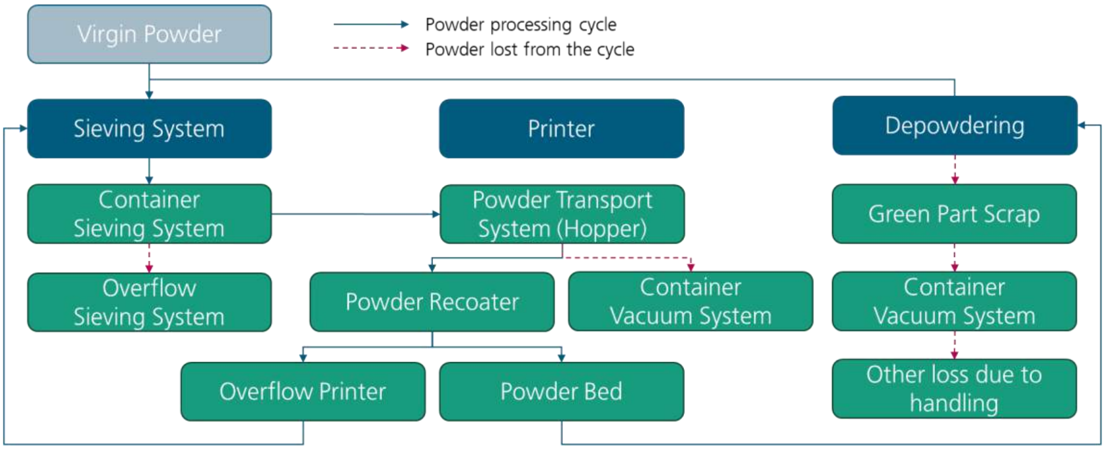


Figure 1. Powder process cycle and the locations where powder is removed.

Powder production of CuCr1Zr: Analysis of process parameters during gas atomization and oxidation behavior

Heinrich von Lintel[1]* (H. von Lintel), Ulrich Krupp[2] (U. Krupp) Katrin Jahns[1] (K. Jahns)

[1]Institute of Materials Design and Structural Integrity, University of Applied Sciences Osnabrück, Osnabrück,
[2]Steel Institute, RWTH Aachen University, Aachen
*heinrich.von-lintel@hs-osnabrueck.de

In the last years, the use of powder bed based additive manufacturing has increased enormously in industrial applications. In particular, the improvement of machine systems has ensured that highly reflective metals, such as copper, can be processed into dense component parts. Hence, the use of copper in additive manufacturing like laser powder bed fusion (LPBF) has risen significantly, which also has increased the request for copper powders. Therefore, production of copper and copper-alloyed powder is of high industrial relevance. In general, metal powders are mostly produced via gas atomization (see Figure 1). The key factor for consistency in a component part is to maintain the powder properties of particle size distribution, morphology, and chemical composition. In particular, the aging behavior of copper powder is a crucial factor. Due to the high surface to volume ratio of the particles, copper powder and its alloys have a high affinity to oxygen.

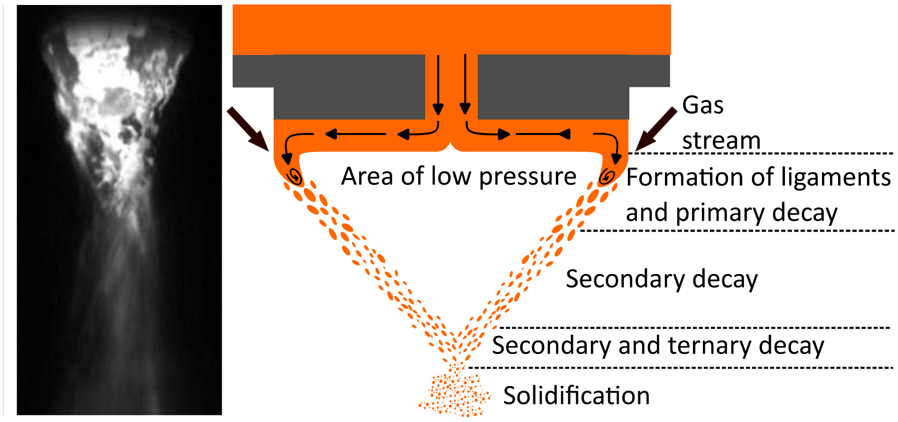


Figure 1: Image of atomization process of CuCr1Zr recorded with a high-speed camera and a schematic drawing of the atomization process

This research studied the atomization process and oxidization behavior of the low-alloyed copper material CuCr1Zr. Powder was produced from the raw material and observed with a high-speed camera during atomization. The focus of the study with respect to the oxidation behavior is based on the comparison of different powder properties before and after a heat treatment. The characterization of the copper powders included the measurement of the particle size distribution as well as the powder density and the flowability. Furthermore, the powders were metallographically prepared and characterized with analytical scanning electron microscopy in combination with EDX, EBSD, and FIB to examine pore formation, anisotropy, and precipitation formation.

Highlight Lectures

OVERPRINTED, UNDERPRINTED, TOO MANY DEFECTS, OR JUST RIGHT?
3D-resolved high-throughput material inspection in additive manufacturing using synchrotron-based µCT.

J. Gerber [1*], E. Bortel [1], C. Seim[1], J.-P. Suuronen [1], B. Hesse [1,#]

[1] Xploraytion GmbH
*gerber@xploraytion.com, # hesse@xploraytion.com

Synchrotron-based X-ray µCT imaging allows the characterization of complex and dense additively manufactured (AM) samples [1]. Due to the extremely high X-ray flux produced by synchrotron sources, synchrotron µCT offers not only high spatial resolution down to the micrometer length-scale but also a high sample throughput, resulting in a unique material quality assessment.

However, synchrotron µCT can only be fully exploited when both the data collection and the 3D data analysis are developed into an AM-specific efficient pipeline.

The successful implementation of the AM technology, relies on maintaining and guaranteeing highest quality of components, and avoiding defects introduced during the 3D printing process. In high temperature applications, e.g. heat exchangers, the performance of the final product is largely determined by the morphology and quality of internal surfaces.

Compared with traditional methods, metal AM gives more freedom of design of the interior surfaces, and can eliminate any additional welding or joining steps from the process. As a downside, producing components as a single AM build also makes inspecting the interior more challenging compared to an assembled component.

In this presentation, we will explore the use of synchrotron-based µCT, focusing on analyzing internal surfaces in terms of defects, surface roughness and integrity, and dimensional accuracy. We will outline our AM-optimized high-throughput data collection coupled with our 3D data analysis strategy.

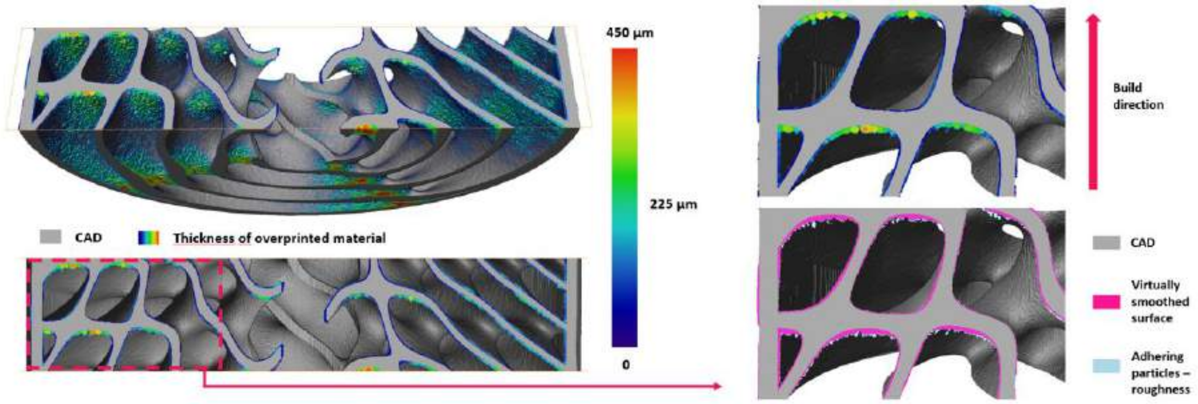


Figure 1. Using synchrotron µCT we find, in the presented showcase, that the additively manufactured piece has a volume that is 20 % higher as compared to the CAD (shown in grey) where the overprinting is more pronounced in overhanging regions. Even though the remnant powder particles contribute to only about 2.6 % volume fraction, they increase the surface of the piece by more than 20 %.

References

[1] R. Otto; Synchrotron µ-CT-based morphological characterization of additively manufactured open porous structures, Additive Manufacturing, 2022

Aluminum - Scandium material concepts for 3D-printing - A review on 20 years from development to exploitation

Frank Palm

Airbus Central Research & Technology (CRT)
frank.palm@airbus.com

3D-printing or more exactly laser powder bed fusion (LPBF) enables very interesting material creation scenarios due to its unique rapid solidification üropensities. Melting layerwise a powder feedstock in a selective localized manner generates net netshape bodies with unique microstructures. In particular the use of Scandium as a major alloying element for Al materials has proven to be extremely efficient when strength and ductility become of major concern. Historically, aerospace Al alloys are always challenged depending on their product applications with respect to strength and toughness because designers and stress specialists have to safeguard their product strength properties to achieve max. reliability. As LPBF refers to a classical welding process with powder as a filler material it was obvious that the well known “under-matching” of Al weld seams compared to high strength Al aerospace bulk would limit material the potential application of 3D-printed parts.

Due to its special metallurgy of Sc in Al and the idea to combine this peculiarity with the powder bed melting process it became possible to directly generate material which can offer the same or even better strength-ductility properties than known from incumbent 2xxx or 7xxx alloys.

The präsentation will give a summary about these developments executed at Airbus Central Research & Technology from its early trials around 2000 until now and what this will further mean for current and further applications. It will show how tailoring of material research based on lab trials still enables breakthrough capabilities in a time where deep & machine learning, big data and artificial intelligence seem to be the sole way forward to create something new.

Challenges of serial production of gas turbine components by powder bed fusion – laser beam/metal (PBF-LB/M)

S. Piegert[1*], C. Haberland[2], D. Rule[2] (First name initials, Last name; J.S. Smith)

[1] Siemens Energy GmbH & Co KG, [2] Sample University
*Sebastian.piegert@siemens-energy.com

In the last decade, PBF-LB/M projects have received large amounts of public funding aimed at the maturation of the technology through research and development. PBF-LB/M is a technology that has been in development from the embryonic stage to the cusp of a fully industrialized technology completely in the information age. One of the disadvantages of introducing a new highly anticipated manufacturing methodology in the modern day is the visibility of the lessons learned and failures in the manufacturing technology development process. The immense number of publications on the technology has made visible the high complexity of influencing factors and the challenges of process control in PBF-LB/M process [1,2]. Publications have made the case that PBF-LB/M, as compared to other conventional manufacturing process, has greater challenges to address and solve in the areas of reproducibility and repeatability.

The Laser Powder Bed Fusion process has many influencing variables which cause potential users to question whether quality assurance including repeatability and reproducibility can be managed and maintained in a large-scale production environment.

This paper contends that despite the number of influencing factors on the process, the resulting product quality is not only controllable with the correct measures but can be more reproducible and repeatable than other commonly used manufacturing process routes. The authors identify the significant influencing factors for their processes and how the deviations highlighted in literature can be one by one either ruled out, controlled or minimized to reducing process deviations to a manageable level. This, however, requires the rigorous adherence to either standards or internal specifications, processes, and standard operating procedures from parameter identification down to serial manufacturing as the cascade in fig. 1 reveals.

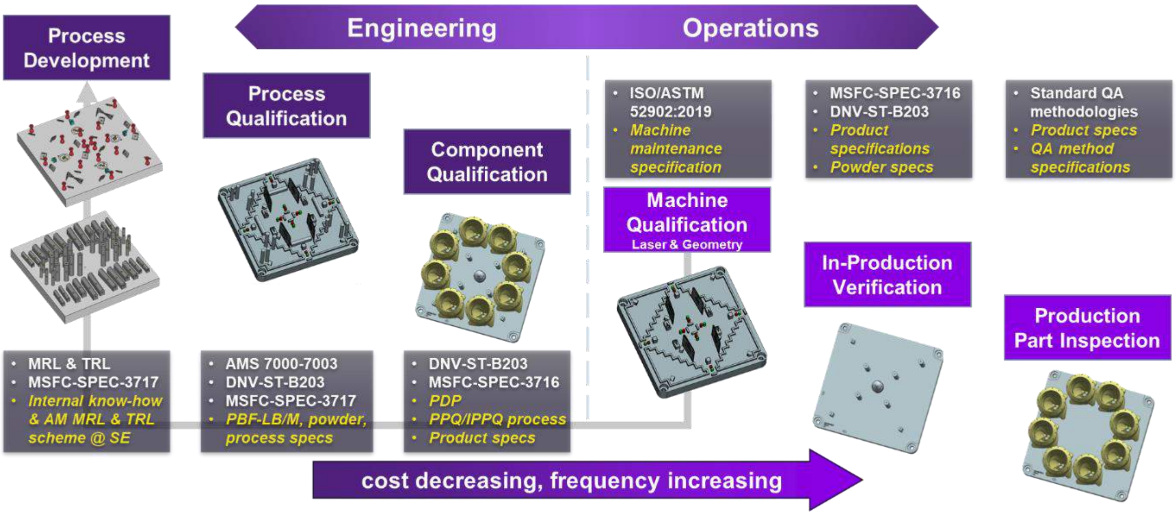


Figure 1: Industrialization Approach for AM Components, Siemens Energy follows the international standards, moreover there is an established process landscape within Siemens Energy to ensure process stability and product quality at every level.

In addition, real production data is displayed analysed and compared from a well-controlled full-scale production to demonstrate the capability of the technology. The authors identify areas of improvement where further alteration of PBF-LB/M process control and repeatability provide an upside potential when compared to the physical limitation that are limiting the levels of control that can be achieved in conventional manufacturing processes.

[1] L. Dowling et al.: A review of critical repeatability and reproducibility issues in powder bed fusion.
[2] G. Tapia & A. Elwany: A review on process monitoring and control in metal-based additive manufacturing. J. Manuf. Sci. Eng. 136 (2014)

Development of a Design Digital Twin for Metal Additive Manufacturing

Jakub Mikula[1], Robert Laskowski[1], Dai Ling[1], Ding Wenjun[1], Bai Kewu[1], Zeng Yingzhi[1], Ramanarayan Hariharaputran[1], Ming Wei[1], Rajeev Ahuwalia[1], Guglielmo Vastola[1*], Zhang Yong-Wei[1]
[1]A*STAR Institute of High Performance Computing (IHPC), 1 Fusionopolis Way, #16-16 Connexis 138632
*vastolag@ihpc.a-star.edu.sg

Despite tremendous efforts in improving metal 3D printers' accuracy and reliability, mainstream insertion of additive manufacturing (AM) in industrial shopfloors is still limited by uncertainty and inconsistency in the AM process. Computer modeling and simulation is the natural answer to address such issues before printing, thus reducing the cost of trial-and-error. However, an exhaustive feature-rich, high-fidelity simulation of AM is extremely challenging, due to the tight coupling between different length scales (from part-scale to powder-scale) and time scales (from build time to scan vector time). By leveraging our in-house capabilities, we have developed an integrated digital platform which combines a thermal simulation at the scale of the part, a discrete element method simulation of powder spreading [1], a ray-tracing simulation of laser-matter interaction, a powder-scale simulation of powder melting and solidification and microstructure evolution [2][3], two phase-field simulations of dendritic and precipitates formation, a crystal plasticity calculation for prediction of mechanical properties, and a part-scale simulation of residual stress and distortion, to provide a multiscale simulation platform for AM. Importantly, we also developed a physics-based classification capability which, given an overall thermal history of the component, identifies the regions that have experiences similarly, or different, thermal histories for microstructure evolution. These capabilities were integrated into a single, end-to-end platform tailored to Nickel alloys, the EOS M290 printer, robot-guided directed energy deposition, with more materials and printers in pipeline to be added. For model validation, test coupons were printed and analysed in terms of porosity, microstructure, and mechanical properties, while distortion was validated with an actual industrial component. Here, we intend to show that a focus on computational speed and a seamless integration among length scales provide the user a holistic view of the manufacturing process and supports informed decisions on material choice, part design, and process parameters.

References

[1] Dai *et al.*, *Powder Technol.*, **2022**, 408, 117790
[2] Wei *et al.*, *Additive Manuf.*, **2022**, 54, 102779
[3] Laskowski *et al.*, *Additive Manuf.*, **2022**, 60, 103266

Development of the Additive Manufacturing market in 2023

M. Munsch

AMPOWER
*munsch@ampower.eu

The worldwide development of Additive Manufacturing has witnessed significant growth in recent years, with the market experiencing remarkable double-digit growth rates. This disruptive technology has revolutionized traditional manufacturing processes, unlocking new possibilities across a wide range of industries. Looking ahead, the growth trajectory of Additive Manufacturing is expected to continue at a similar or even faster pace.

Drawing on insights from the upcoming AMPOWER Report scheduled for release in 2024, this presentation will delve into the market developments of 2023. It will provide valuable insights into the key global developments on a commercial level, shedding light on the progress made in various markets worldwide. Additionally, the presentation will feature forecasts for a five-year horizon, offering projections for the future trajectories of Additive Manufacturing and its key markets. This comprehensive analysis will provide a thorough understanding of the current state and promising future of Additive Manufacturing.

In situ observations of additive manufacturing using synchrotron radiation

H-H. König[1], N. Semjatov[2], P. Bidola[3], P. Hedström[1], C. Körner[2], G. Lindwall[1*]

[1] KTH Royal Institute of Technology, Sweden
[2] Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany
[3]Helmholtz-Zentrum Hereon, Germany
*gretal@kth.se

The final microstructure in additively manufactured (AM) components is determined by a complex interplay between the alloy characteristics, powder properties and printing parameters. To fully map out fundamental mechanisms behind the materials' behaviour during AM processes, observations beyond post-print *ex situ* characterization of printed parts are needed.

This work demonstrates how *in situ* observations using synchrotron X-rays can be used to study AM processes in real time. To generate conditions typical for AM meanwhile allowing for *in situ* X-ray studies, a dedicated AM sample environments is needed. Here, the construction of an electron beam-powder bed fusion (PBF-EB) sample environment is described [1]. Both high-speed X-ray radiography and diffraction are then applied to image the meltpool dynamics and to follow the microstructure evolution during PBF-EB, respectively.

Furthermore, how these *in situ* measurements can be used to validate computational thermodynamics and kinetics models [2], enabling alloy development for AM, is discussed.

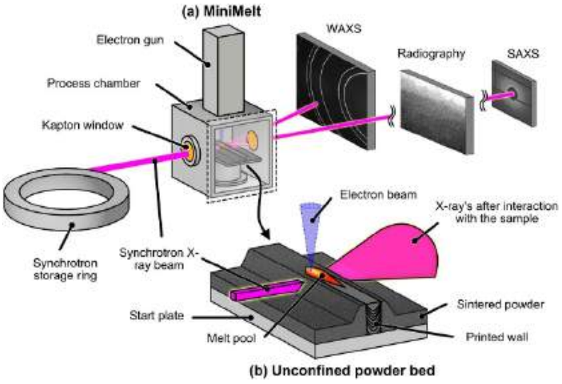


Figure 1. Schematic of the PBF-EB simple environment (MiniMelt) for measurements of Wide-Angle X-ray Scattering (WAXS), radiography, and Small-Angle X-ray Scattering (SAXS) in a synchrotron. (b) Schematic of the unconfined powder bed where the x-ray beam interacts with the simple [1].

References

[1] H-H. König, N. Semjatov et al. *Review of Scientific Instruments*, **2023**, *94*, 125103.
[2] H-H. König et al. *Acta Materialia*, **2023**, 246, 118713.

Laser Powder Bed Fusion of aluminum and titanium spacecraft flight hardware

M. Mulser[1*]

1 OHB System AG
*marco.mulser@ohb.de

Within the last decade, Additive Manufacturing evolved from a concept merely used for Rapid Prototyping into several reliable manufacturing technologies. Today, especially Laser Powder Bed Fusion is a mature technology that enables innovative design solutions with an exceptional freedom of design that provides benefits regarding performance, delivery times and mass reduction.

In the presentation, OHB's recently developed spacecraft flight hardware will be presented with a focus on aluminum and titanium alloys. The design process will be demonstrated exemplarily for a recently developed integrated Twin-Mirror with embedded lattice structures. Key challenges during design, manufacturing, and post-processing are addressed. The presentation features an outlook on requirements and regulations for process verification and AM space hardware qualification following the standards of the European Cooperation for Space Standardization (ECSS).

In a nutshell, the audience will understand the innovative potential of AM and OHB's motivation to use Laser Powder Bed Fusion for spacecraft manufacturing. The presented flight hardware items illustrate the specific advantages of the technology compared to conventional solutions.

Figure 1. Lightweighted twin-mirror made of Scalmalloy by L-PBF for spacecraft spectrometers

Laser Powder Bed Fusion: Fundamentals of Diffraction-Based Residual Stress Determination

J. Schröder*[1], A. Evans[1], A. Kromm[1], M. Hofmann[2], W. Petry[2] G. Bruno[1, 3]

[1] Bundesanstalt für Materialforschung und-prüfung, [2]Heinz Maier-Leibnitz Zentrum, TU München, [3]Universität Potsdam
*Jakob.Schroeder@bam.de

The general term additive manufacturing (AM) encompasses processes that enable the production of parts in a single manufacturing step. Among these, laser powder bed fusion (PBF-LB) is one of the most commonly used to produce metal components. In essence, a laser locally melts powder particles in a powder bed layer-by-layer to incrementally build a part. As a result, this process offers immense manufacturing flexibility and superior geometric design capabilities compared to conventional processes. However, these advantages come at a cost: the localized processing inevitably induces large thermal gradients, resulting in the formation of large thermal stress during manufacturing [1]. In the best case, residual stress remains in the final parts produced as a footprint of this thermal stress. Since residual stress is well known to exacerbate the structural integrity of components [1], their assessment is important in two respects. First, to optimize process parameter to minimize residual stress magnitudes. Second, to study their effect on the structural integrity of components (e.g., validation of numerical models). Therefore, a reliable experimental assessment of residual stress is an important factor for the successful application of PBF-LB. In this context, diffraction-based techniques allow the non-destructive characterization of the residual stress. Figure 1 shows the schematic roadmap for the determination of residual stress by diffraction. In essence, lattice strain is calculated from interplanar distances by application of Braggs law. From the known lattice strain, macroscopic stress can be determined using Hooke’s law. To allow the accurate assessment of the residual stress distribution by such methods, a couple of challenges in regard of the characteristic PBF-LB microstructures need to be overcome [2].

This presentation highlights some of the challenges regarding the accurate assessment of residual stress in PBF-LB on the example of the Nickel-based alloy Inconel 718. The most significant influencing factors are the use of the correct diffraction elastic constants, the choice of the stress-free reference, and the consideration of the crystallographic texture. Further, it is shown that laboratory X-ray diffraction methods characterizing residual stress at the surface are biased by the inherent surface roughness. Overall, the impact of the characteristic microstructure is most significant for the selection of the correct diffraction elastic constants. In view of the localized melting and solidification, no significant gradients of the stress-free reference are observed, even though the cell-like solidification sub-structure is known to be heterogeneous on the micro-scale. [2]

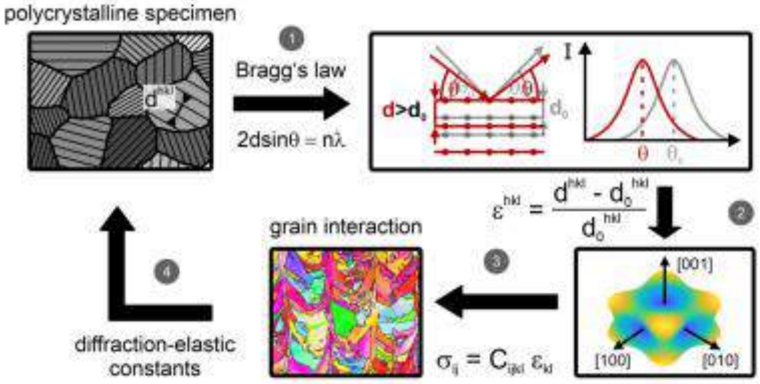
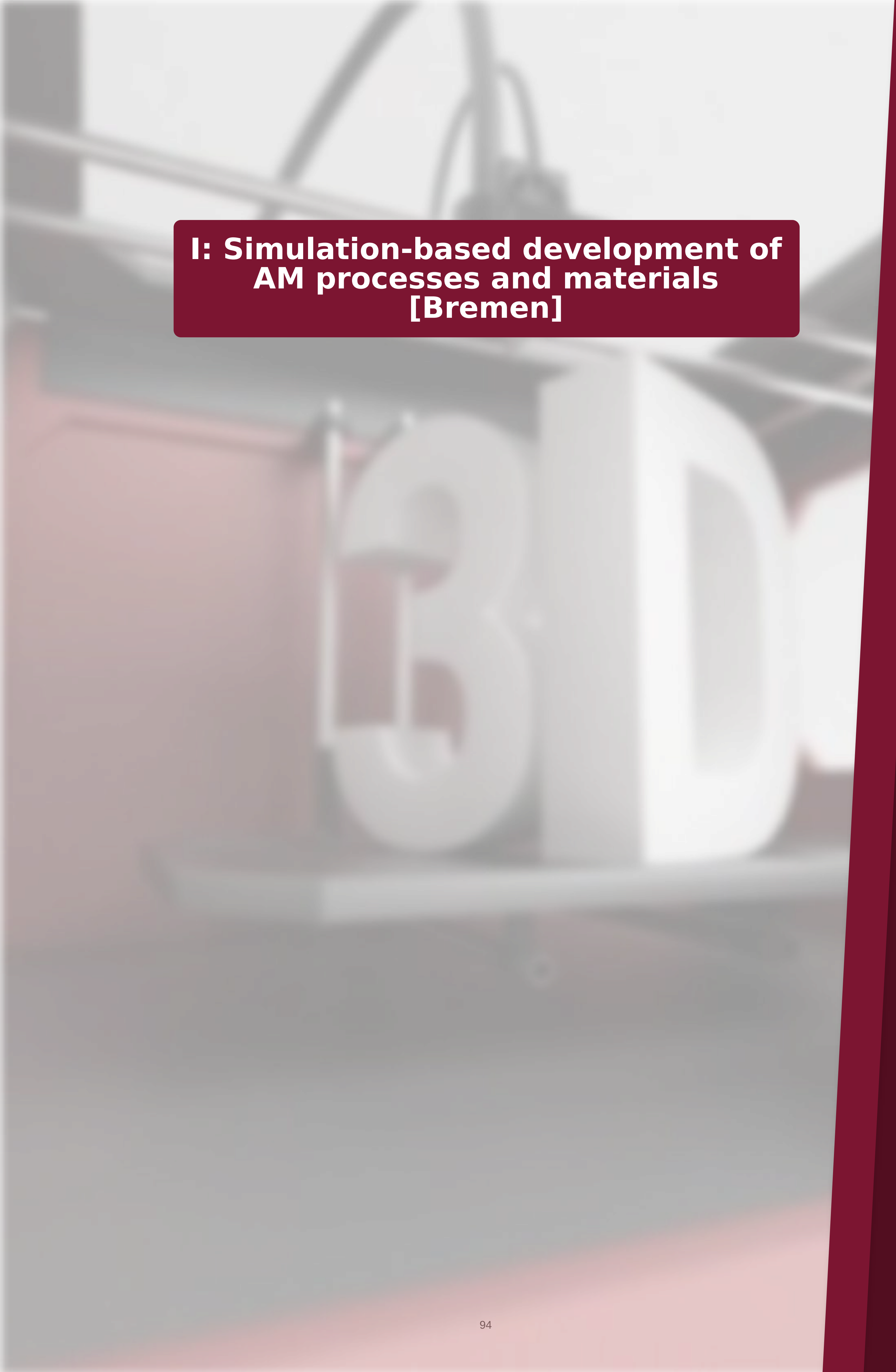


Figure 1. Schematic representation of the challenges in the domain of diffraction-based characterization of residual stress. [2]

References

[1] P. Mercelis, J.-P. Kruth, *Rapid Prototyping Journal,* **2006**, 12, 254-265. Doi: 10.1108/13552540610707013
[2] J. Schröder, Dissertation, Universität Potsdam, **2023**. Doi: 10.25932/publishup-62197

I: Simulation-based development of AM processes and materials [Bremen]



A Coupled CFD-DEM Approach to Modelling Powder Stream in Direct Energy Deposition

Tijan Mede[1*] (T. Mede), Matjaž Godec[2] (M. Godec)

[1] The Institute of Metals and Technology
*tijan.mede@imt.si

Metal-based additive manufacturing (AM) is revolutionizing the production process and introducing unprecedented capabilities, which are quickly becoming indispensable across a wide range of industries [1]. Direct Energy Deposition (DED) in particular exhibits a high potential for space applications due to no imposed limitation on the size of manufactured objects and the ability to operate in micro-gravity conditions [2]. DED however remains hindered by poor deposition quality and reproducibility, which appear to originate in the powder stream condition [3]. Increased accuracy of the blown powder dynamics hence represents a crucial ingredient of next-generation DED models [4]. Powder stream is usually modelled with the use of computational fluid dynamics (CFD) as a two-phase flow problem involving a dispersed second phase [5]. Powder particle collisions and their interaction with the melt-pool cannot be accounted for by these models and are regularly disregarded on account of these particles occupying a small volume fraction in the carrier gas flow [5]. This assumption was put to the test using a Discrete Element Method (DEM) model of the particle stream of a discrete coaxial nozzle. While neglecting the interaction between carrier gas and powder particles, the results showed that non-negligible portions of powder grains are involved in grain collisions with substantial rebound angles, which underlined the need to account for inter-particle interaction in DED stream models. This sparked the development of a fully coupled CFD-DEM model of powder stream in DED, using state-of-the-art approaches for parallelly resolving the fluid and the discrete phase dynamics, accounting for the drag on the powder particles as well as the resulting reactive force on the fluid. The model is thus capable of accounting for the full set of granular dynamics, including grain collisions as an essential influence on powder stream dynamics.

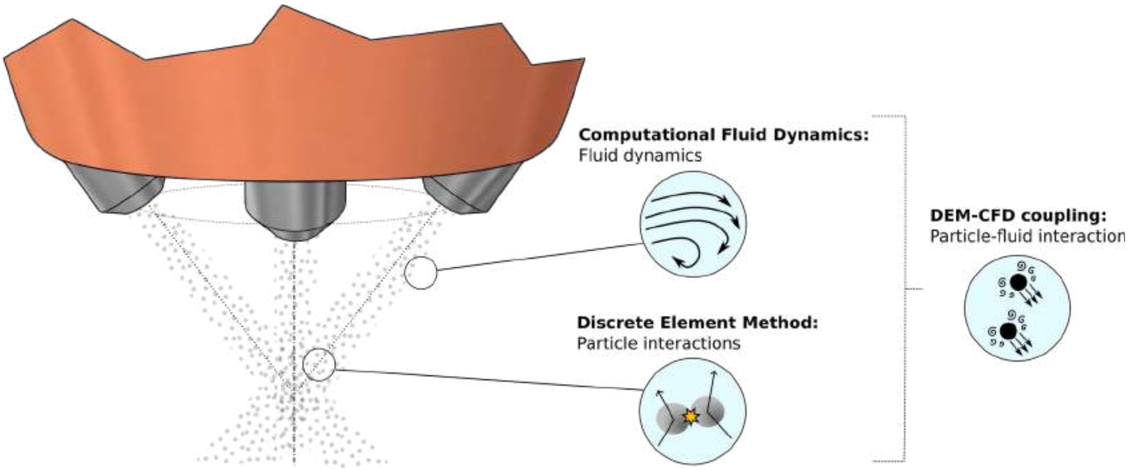


Figure 1. A schematic representation of the numerical approach to modelling powder stream dynamics in DED.

References

[1] P. W. Cooper, “3D Printing: A Potential Game Changer for Aerospace and Defense,” *Gaining Alt.*, vol. 7, 2013.

[2] N. Shamsaei, A. Yadollahi, L. Bian, and S. M. Thompson, “An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control,” *Addit. Manuf.*, vol. 8, pp. 12–35, 2015, doi: 10.1016/j.addma.2015.07.002.

[3] Z. Liu, H. Zhang, S. Peng, H. Kim, D. Du, and W. Cong, “Analytical modeling and experimental validation of powder stream distribution during direct energy deposition,” *Addit. Manuf.*, vol. 30, no. February, p. 100848, 2019, doi: 10.1016/j.addma.2019.100848.

[4] S. M. Thompson, L. Bian, N. Shamsaei, and A. Yadollahi, “An overview of Direct Laser Deposition for additive manufacturing ; Part I : Transport phenomena , modeling and diagnostics,” *Addit. Manuf.*, vol. 8, pp. 36–62, 2015, doi: 10.1016/j.addma.2015.07.001.

[5] H. Tan, C. Zhang, W. Fan, F. Zhang, X. Lin, and J. Chen, “International Journal of Machine Tools and Manufacture Dynamic evolution of powder stream convergence with powder feeding durations in direct energy deposition,” *Int. J. Mach. Tools Manuf.*, vol. 157, no. February, p. 103606, 2020, doi: 10.1016/j.ijmachtools.2020.103606.

Compensation of distortion in sinter-based additive manufacturing using an inverted simulation of the sintering process

F. Tischel[1*], V. Ploshikhin[1]

[1] University of Bremen
*tischel@isemp.de

Sinter-based Additive Manufacturing (SBAM) methods, such as Metal Binder Jetting, bridge the high productivity rate of series production and freedom of design in additive manufacturing [1]. However, SBAM requires a subsequent sintering process to achieve the desired material properties, resulting in distortion due to anisotropic shrinkage and creep distortion [2,3]. Simulative compensation of distortion is one solution to this problem [4].

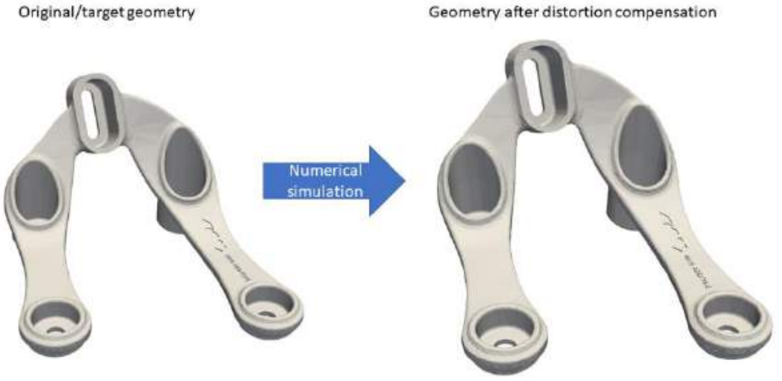


Figure 1. Example simulative compensation of distortion

In this work, the latest research results on the simulative prediction and compensation of distortion in SBAM from the Airbus Endowed Chair for Integrative Simulation and Engineering of Materials and Processes (ISEMP) at the University of Bremen will be presented. In particular, the newly developed method will be discussed in which the compensation of distortion is determined by the inverted simulation of the sintering process. This new numerical method allows to reduce the number of necessary iterations in comparison to conventional ones. The advantages of this method are demonstrated on the components with complex geometries having a high susceptibility for distortion.

References

[1] M. Li et al.; *Journal of Manufacturing Science and Engineering*, **2020**, *142*, 090801.
[2] K. Zhang et al.; *Additive Manufacturing*, **2021**, *47*, 102330.
[3] S. Sadeghi Borujeni et al.; *Materials & Design*, **2022**, *216*, 110490.
[4] S. Sadeghi Borujeni et al.; *Rapid Prototyping Journal*, **2023**, *29.3*, 612-625.

Computational investigation of directional grain growth kinetics by phase-field method

V.M. Kindrachuk[1*], R. Darvishi Kamachali[1]

[1] Federal Institute for Materials Research and Testing (BAM), Unter den Eichen 87, 12205 Berlin, Germany
*vitaliy.kindrachuk@bam.de

The rise of innovative additive manufacturing (AM) methods calls for a reassessment of the significance of the directional grain growth (DGG) phenomenon beneath the melting pool and due to the localized, intrinsic applied heat. Here establishing a computational framework for systematically examining such DGG can greatly assist, since experimental measurements remain quite challenging.

We advanced a combined mean-field modelling and phase-field simulation framework [1, 2] to account for additional driving force during the evolution of a polycrystalline body. The simulations were realized by OpenPhase software package [3]. The obtained results reveal that a steady-state power-law grain growth kinetic can be established during DGG, giving a growth exponent that is generally larger than 0.5 (normal grain growth). This is found to be dictated by the interference between curvature-driven dynamics at grain boundary junctions and directional driving force.

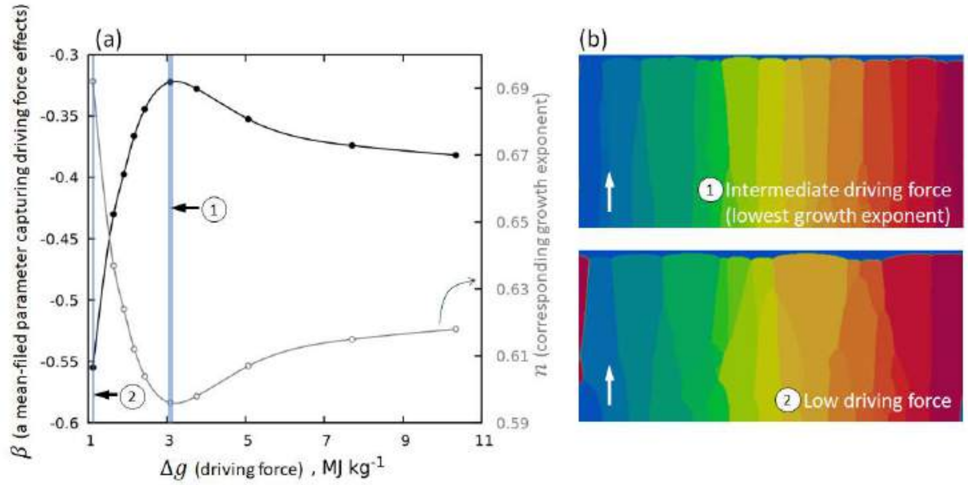


Figure 1. The effect of driving force on the (a) growth exponent and (b) grains microstructure during DGG. The white arrow indicates the direction of the driving force field.

Most interestingly, we found that the slowest growth kinetics is achieved for the intermediate driving forces, whereas the growth exponent approaches asymptotically a constant value when increasing the intensity of the driving force [4]. Figure 1 depicts the growth exponent as a function of driving force and two cross-section views of evolving microstructures under different driving forces.

The simulation findings were analysed in the context of a new mean-field model. We show that an extra model parameter can capture the influence of external driving forces on the grain growth and thus can be used for preassessment of the DGG during AM process [4].

References

[1] R. Darvishi Kamachali, I. Steinbach *Acta Materialia.*, **2012**, *60*, 2719.
[2] R. Darvishi Kamachali et al. *Acta Materialia.*, **2015**, *90*, 252.
[3] M. Tegeler at al. *Comput. Phys. Comm.*, **2017**, *215*, 173.
[4] V.M. Kindrachuk, R. Darvishi Kamachali *Materialia*, **2024**, *33*, 101989.

Consideration of non-uniform temperature histories in inherent strain simulations of residual stress and distortion formation in (metal-)LPBF processes

Marvin Siewert[1*,**] and Vasily Ploshikhin[1]

[1] Airbus endowed chair for Integrative Simulation and Engineering of Materials and Processes, University Bremen
*siewert@isemp.de
*** former member of University of Bremen, meanwhile moved to Airbus Operations GmbH, the contribution and participation entirely belongs to University Bremen / ISEMP*

Residual stress and the resulting deformations, as well as process disturbances, continue to be one of the major problems in Laser Powder Bed Fusion (LPBF) processes of metals. Simulations are meanwhile well established to predict their formation and the induced distortions. They can be used to adapt critical part geometries, the support structure or the manufacturing process even before the parts are manufactured.

In particular methods based on the inherent strain approach enable predictions of even macroscopic parts in tolerable computation times, i.e. in only several hours even for parts with industrial relevant size and complexity. Therefore, the method is widely discussed in the literature, e.g. [1,2,3]. Nevertheless, the predictions are not always reliable. This contribution identifies a critical assumption of classical inherent strain based LPBF simulations and finally proposes an extension of inherent strain methods to adress this issue: The temperature history is assumed to be approximately equal. Depending on factors such as the part geometry or the process environment, it is demonstrated that this is not always the case. Different temperature histories significantly influence the formation of residual stress and distortion. Experimental results confirm this hypothesis.

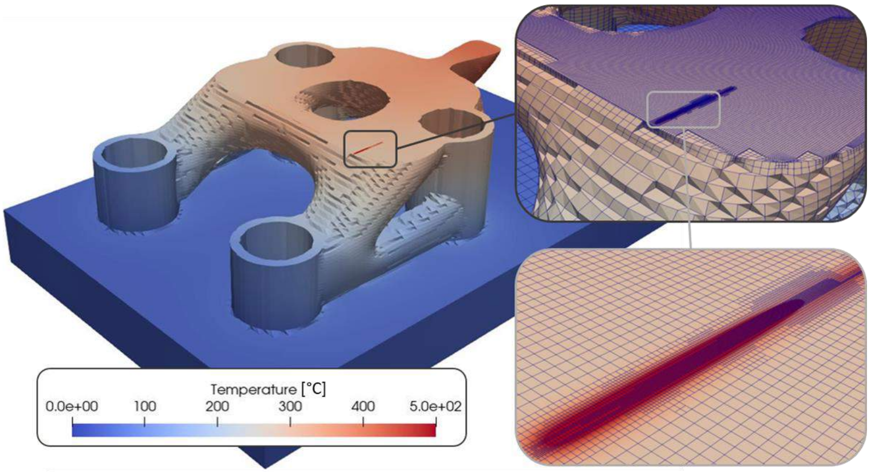


Figure 1 *Coupled multi-scale (meso-macro) simulation to predict tempertures in LPBF*

A multi scale (thermal and thermo-mechanical) simulation framework was developed and utilized to investigate the emergence of non-uniform temperature distributions and histories (*Figure 1*), as well as their impact on the evolving inherent strains. The framework is based on the Finite Elements Method and includes several advanced simulation techniques, e.g. adaptive meshing. The investigation results in an extension of inherent strain methods, by linking it to a reduced order thermal simulation model and choose the applied inherent strain loads with respect to the calculated temperature. This enables predictions even for parts with non-uniform temperature histories and extends its scope of application.

References

[1] N. Keller, V. Ploshikhin; New Method for fast predictions of residual stress and distortion of AM parts; *Solid Freeform Fabrication Symposium*, 2014, 25.

[2] M. Bugatti, Q. Semeraro; Limitations of the inherent strain method in simulating powder bed fusion processes; Additive Manufacturing; 2018; 23; 329-346

[3] X. Liang, Q. Chen, L. Cheng, D. Hayduke, A. C. To; Modified inherent strain method for efficient prediction of residual deformation in direct metal laser sintered components; Computational Mechanics; 2019; 64; 1719-1733

High-throughput multiphysics simulations of metallic powder bed fusion on the mesoscopic level with GPU-enabled software tool KiSSAM: from melt pool dynamics to whole part morphology

A. Zakirov[1], S. Belousov[1*], M. Bogdanova[1], B. Korneev[1], A. Perepelkina[1], B. Potapkin[1]

[1] Hipercone Ltd, Jerusalem, Israel
*belousov@hipercone.com

The quality of parts built with powder bed fusion (PBF) additive manufacturing method crucially depends on solidified material properties and defects (such as porosity), which is determined by the details of the process at the mesoscale level [1]. We have developed a high-throughput simulation package for additive manufacturing (KiSSAM) which accurately captures the diverse physical phenomena occuring during PBF at the mesoscale such as powder layer formation, energy absorption and melt pool dynamics and solidification. At the core of KiSSAM lies the lattice Boltzmann method (LBM) optimized for Graphical Processing Units GPU; a dynamic mesh for the melt pool; an adaptive mesh for the heat solver; a GPU-powered ray tracer and Monte-Carlo scattering solver for beam absorption, and a high-performance discrete element method (DEM) solver for powder bed deposition. High degree of algorithm optimization results in significant gains in simulation speed, allowing us to complete simulations in a few hours and even faster (less than half an hour for single tracks) [2,3].
The high performance of KiSSAM enables multilayer simulations without compromising the accuracy of the description of the PBF process at the mesoscale level, helping gain insights into how evolution of single track morphology affects the morphology of a multilayer part [4]. High-throughput parametric sweeps of single track simulations allowed formulating the criteria for the lack of fusion during Laser PBF with an increased layer thickness, which is expected to provide a scientific basis for the analysis of the maximum layer thickness via simulation to increase the performance of the technology [5].
Other applications of KiSSAM to intensive PBF process simulations, presented in this contribution, include simulation of overhangs and porous multilayer samples. Moreover, implementation of the multicomponent evaporation model allows modeling variation of the alloy composition during multilayer builds.

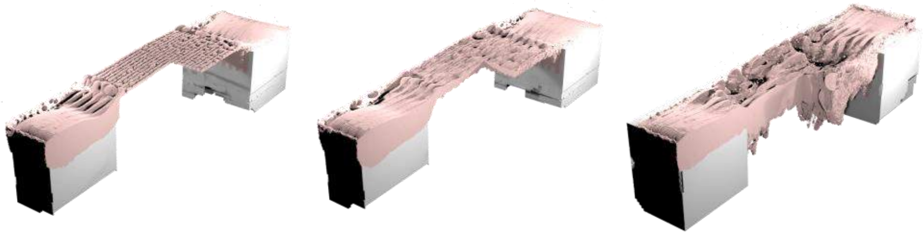


Figure 1. KiSSAM simulation of overhangs with different processing parameters. The processing parameters are from [6].

References

[1] I. Gibson, D. Rosen, B Stucker *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*; Springer: Greer, SC, USA, **2015**; 43–49.
[2] A. Zakirov, S. Belousov, M. Bogdanova, B. Korneev, I. Iskandarova, A. Perepelkina, B. Potapkin *Progress in Additive Manufacturing*, **2024**, 1-18.
[3] A. Zakirov, S Belousov, M Bogdanova, B Korneev, A Stepanov, A Perepelkina, V Levchenko, A Meshkov, B Potapkin *Additive Manufacturing*, **2020**, *35*, 101236.
[3] M. Bogdanova, S. Chernyshikhin, A. Zakirov,L. Fedorenko,M. Lyange,S. Belousov,A. Perepelkina, B. Korneev, B., M. Lyange, I. Pelevin, I. Iskandarova, B. Potapkin, A. Gromov. *Manuf. Mater. Process.*, **2024**, *8(1)*, 7
[5] B. Korneev, A. Zakirov, M. Bogdanova, S. Belousov, A. Perepelkina, I. Iskandarova, B. Potapkin. *Additive Manufacturing*, **2023**, *74*, 103705.
[6] A. Ashby, G. Guss, R.K. Ganeriwala, A.M. Martin, P.J. DePond, D.J. Deane, M.J. Matthews, C.L. Druzgalski, *Additive Manufacturing*, **2022**, *53*, 102669.

Laser melting processes of metals in reduced gravity

P. Müller[1*], H. Götz[1], M. Blank[1], T. Pöschel[1]

[1] Friedrich-Alexander-Universität Erlangen-Nürnberg
*patric.mueller@fau.de

3D printing offers unprecedented capabilities and solutions to challenges inherent in extraterrestrial environments. In particular 3D printing of metallic materials by means of laser melting places high demands on the processing methods [1]. While on Earth, the optimization of the process parameters is well studied and technically mastered in many cases, the behaviour under reduced gravity and weightlessness is largely unknown. By means of Smoothed Particle Hydrodynamics (SPH) [2] simulations we therefore show, how the dynamics of laser-melted metals depend on gravity (Fig. 1). Our simulations make it possible to investigate the phenomena relevant to the manufacturing process cost-effectively under variable gravity and can thus make an important contribution to the development of techniques for additive manufacturing under conditions of weightlessness and reduced gravity.

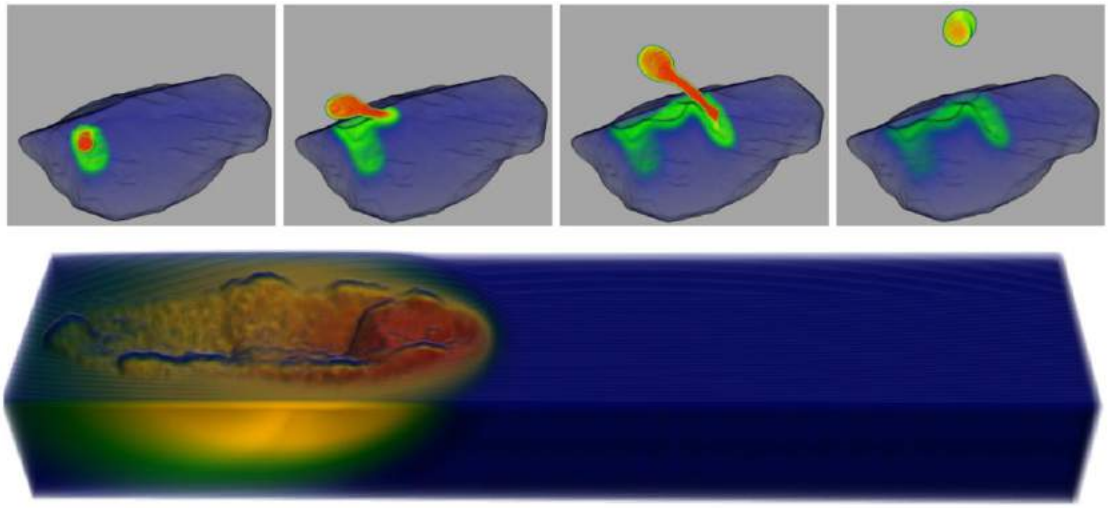


Figure 1. Upper part: Droplet formation caused by droplet formation caused by surface tension during the laser melting process. Lower part: Laser melting process of SS316L.

References
[1] G. Kasperovich et al. *Mater. Des.*, 2016, *105*, 160-170.
[2] J.J. Monaghan *Rep. Prog. Phys.*, 2005, *68.8*, 1703.

Material Characterization in Simulation-based Approaches on automated Post Processing in Powder Bed 3D Printing

M. Luger[1*], N. Rabeneck[1], S. Ritzer, A. Eckl[2], V. Dalbauer[1], S. Kölbl[1]

[1] Deggendorf Institute of Technology – Technology Campus Hutthurm
[2] Deggendorf Institute of Technology – Technology Campus Cham
*marc.luger@th-deg.de

Powder-bed-based 3D printing of polymer components may employ auxiliary agents to enable precise directing of sintering heat flows induced by diffuse thermal sources [1]. These utilized auxiliary agents entail adherent printing powder residuals covering the components' surfaces.
Within an envisaged automated post processing workflow of these printed components aspects correlated to these adherent powder residuals are addressed as well. Resource efficient development of such a workflow suggests purposive numerical simulations to assist the design of process-related devices. For close-to-reality simulations, thorough knowledge of material behavior is prerequisite.

Therefore, besides the description of the adherent powder residuals' elastic material behavior, a failure surface needs to be determined, as the failure behavior of the said powder residuals appears highly relevant within the carried-out finite-element simulations. An experimental approach, based on geotechnical direct shear testing [2], has been developed to enable controlled load subjection to undisturbed cohesive powder residuals for that purpose.

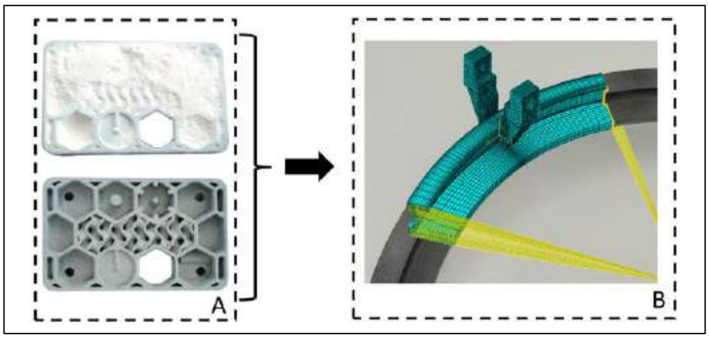


Figure 1. A: A powder bed-based 3d printed component, with adherent powder residuals (top) after cleaning (bottom). B: Both states are investigated by FEA to substantiate the design of further process devices, e.g., in simulations of the mechanical gripper

Simulation campaigns depicting component transportation tasks by means of mechanical gripping systems (Figure 1, B) are suitable to secure safe transportation of components with and without powder residuals (Figure1, A). The effects of variously shaped grippers were investigated regarding required gripping forces and the interactive behavior in the contact area.

Based on the proposed material characterization, future research will focus grit blasting removal of adherent powder residuals from the additively manufactured components including the impact effects of rapid particles onto the plain surface of the individual components. Within this context, anisotropic material properties of the components are considered.

References

[1] C. Cai, W.S. Tey, J. Chen, W. Zhu, X. Liu, T. Liu, L. Zhao, K. Zhou; *Journal of Materials Processing Tech.*, 2021, *288,* 116882.
[2] D. Kolymbas; *Geotechnik – Bodenmechanik, Grundbau und Tunnelbau* 2016, *4. Auflage.*

Multiscale Phase-Field Modelling of Microstructure Evolution under Additive Manufacturing conditions

[1*]P.G.Antala, [2] M.Uddagiri, [3] I.Steinbach

[1,2,3] ICAMS, Ruhr Universität Bochum
*Pankaj.Antala@ruhr-uni-bochum.de

The microstructure of additively manufactured structural alloys can be characterized by epitaxial columnar grains, a phenomenon attributed to directional heat transfer. Differences in length and time scales associated with solute diffusion and rapidly evolving temperature field in conjunction with scaling limitation associated with interface width poses a computational limitation to resolve constitutionally undercooled zone ahead of the growing grain at the scale of melt pool which is a prerequisite to establish relations between grain texture, size distributions and processing parameter viz beam shape, power, speed, etc. A mesoscopic envelop model [1][2] is presented to simulate grain texture evolution under additive manufacturing conditions to overcome these limitations. In the model a continuous surface with a diffuse interface is assumed representing the active branches of the internal grain structure within envelop. The envelop is propagated with a phase field equation. The temperature solution is coupled with quadratic kinetic law which relates constitutional supercooling to solidification velocity and drives the envelop such that without resolving internal grain structure the evolution of grain envelop is predicted thereby allowing concurrent coupling to solution of transient temperature field and evolution of envelop surface. The results indicate that the use of local analytical solutions in numerical calculations is a viable technique for simulating large-scale microstructure evolution under additive manufacturing conditions.

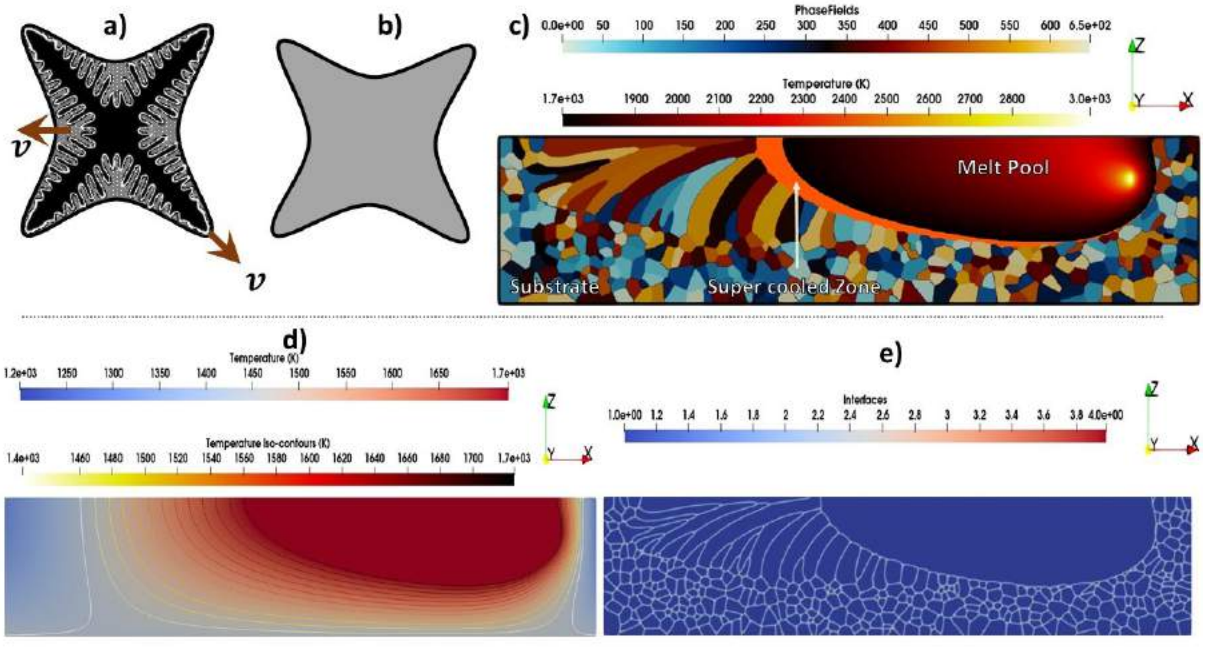


Figure 1. Schematic illustration of a) Envelop around dendrite branches and b) Equivalent envelop surface, c) Figure showing grain texture evolution and identification of different zones. d) Temperature distribution, e) Interfaces depicting grain morphologies along the melt pool path.

References

[1] I. Steinbach et al. *"Three-dimensional modeling of equiaxed dendritic growth on a mesoscopic scale". en. In: Acta Materialia 47.3* (Feb. 1999), pp. 971–982.

[2] I. Steinbach, H.-J. Diepers, and C. Beckermann. *"Transient growth and interaction of equiaxed dendrites". en. In: Journal of Crystal Growth 275.3-4* (Mar. 2005), pp. 624–638.

Numerical and experimental analysis of residual stresses in WAAMed S316L stainless steel parts

A. Sarmast[1*], J. Schubnell[1]

[1] Fraunhofer Institute for Mechanics of Materials, Wöhlerstr. 11, 79108 Freiburg, Germany
*ardeshir.sarmast@iwm.fraunhofer.de

Additive manufacturing (AM) has attracted a lot of attention from science and industry in the past few years due to its advantages, such as the possibility of manufacturing complex geometries and material efficiency. Among AM processes, Wire Arc Additive Manufacturing (WAAM) is widely used form the production of large parts, which is executed by depositing layers of metal on top of each other, until a desired 3d shape is created. Despite its benefits, if it is poorly conducted, AM parts can suffer from microstructural and mechanical properties anisotropy and heterogeneity, and residual stresses. Residual stresses could negatively affect the fatigue life of the components and increase susceptibility to stress corrosion cracking and hydrogen embrittlement. They could be high enough to cause detachment of the deposited material from the substrate during manufacturing or cause undesired distortions, which negatively affect the geometrical precision of the parts. Understanding the formation mechanism and evolution of the residual stresses during the AM process is the key to a successful design and component performance. Experimental methods for analyzing residual stresses, despite providing valuable insight into the magnitude and distribution of residual stresses, are usually restricted to a few points and cannot capture the whole distribution of the residual stresses in the component. Besides, their in-situ implementation imposes more complexity and experimental difficulties. Numerical methods, on the other hand, give a comprehensive view of the residual stress and distortion of the whole part. Although, their reliability depends on the accurate verification and validation of the model [1–3]. Therefore, a combination of both methods could readily give a comprehensive insight into the formation mechanism and evolution of the thermal and residual stresses in AM parts. This work, therefore, aims to investigate the residual stress formation and evolutions in S316L austenitic stainless steel parts manufactured by WAAM. XRD methods were utilized for measurement of the residual stresses and FE-based Abaqus software was used to numerically calculate the thermal and residual stresses in the parts via a thermos-mechanical model. The results show that the residual stresses in the longitudinal and build directions are the highest residual stresses of the component. While the distribution and magnitude of all stress components substantially change by depositing the subsequent layers.

References

[1] T. DebRoy, H.L. Wei, J.S. Zuback, T. Mukherjee, J.W. Elmer, J.O. Milewski, A.M. Beese, A. Wilson-Heid, A. De, W. Zhang, Prog. Mater. Sci., 2018, 92, 112–224.

[2] B.A. Szost, S. Terzi, F. Martina, D. Boisselier, A. Prytuliak, T. Pirling, M. Hofmann, D.J. Jarvis, Mater. Des., 2016, 89, 559–567.

[3] F. Martina, P.A. Colegrove, S.W. Williams, J. Meyer, Metall. Mater. Trans. A Phys. Metall. Mater. Sci., 2015, 46, 6103–6118.

Phase field simulation of microstructure evolution of a super duplex stainless steel (AWS ER2594) part fabricated by additive manufacturing

D. K. M. Isidorio[1*]; J.C. F. Payão[2]; M. N. S. Lira[3]; M. Uddagiri[4]; I. Steinbach[5]

[1,2,3] Universidade Federal do Rio de Janeiro (UFRJ), [1,4,5] Ruhr Universität Bochum (RUB)
daysianne.isidorio@ruhr-uni-bochum.de

Super duplex stainless steels (SDSS) are often used in corrosive environments, such as oil and gas industries, due to their good combination of strength (>450 MPa yield strength and >700 MPa ultimate tensile strength) and corrosion resistance (pitting resistance equivalent number – PREN > 40). Achieving the desired properties of SDSS, as balanced austenite/ferrite phase composition and minimal deleterious phases, is challenging during the arc-based direct energy deposition (arc-based DED) manufacturing process due to its complex thermal cycles [1]. This work aims to gain a comprehensive understanding of microstructure evolution (nucleation, grain growth, phase transformation, elemental segregation, and phase balance) in SDSS arc-based DED parts in the light of phase field simulations. The phase field model is based on thermodynamic-driven partial differential equations, which model is coupled to both mass and heat transport phenomena including release of latent heat of solidification [2,3]. A validation experiment has been carried out by optical microscopy, electron scanning microscopy, differential scanning calorimetry, and X-ray diffraction, showing that the simulation results are consistent with the experimental results. Simulation reveals insights into local equilibrium conditions about heterogeneous nucleation, cellular solidification mode, oriented grain growth, phase fraction during solidification, and elemental partitioning; therefore, enhancing the understanding of solidification and phase transformation of the SDSS during arc-based DED process.

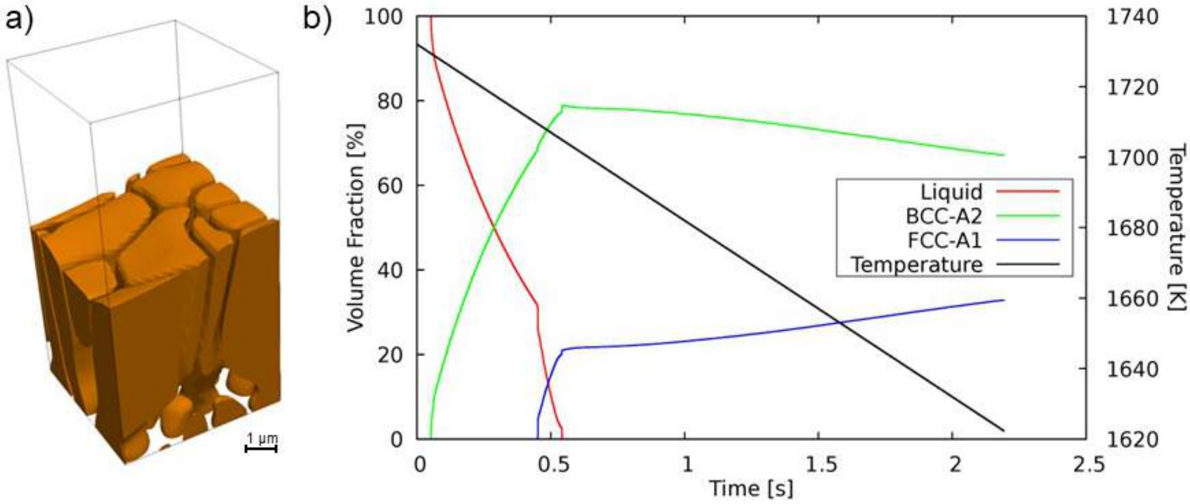


Figure 1. Phase field simulations for SDSS part as AM deposited: a) cellular growth of delta ferrite during solidification, and b) volume fraction of phases during solidification.

References

[1] Zhang, X.; Wang, K.; Zhou, Q. et al. *Microstructure and mechanical properties of TOP-TIG-wire and arc additive manufactured super duplex stainless steel (ER2594),* **2019**, 762, 11.

[2] Steinbach, I. *Phase-field models in materials science,* **2009**, Modell Simul Mater Sci Eng, 17,31.

[3] Uddagiri, M.; Shchyglo, O.; Steinbach, I. *et al.* *Solidification of the Ni-based superalloy CMSX-4 simulated with full complexity in 3-dimensions,* **2023**, 12.

Simulation-based Detection of Defect Formation in Laser Metal Deposition

J. Käsbauer[1*], A. Prihodovsky[1]

[1] Technische Hochschule Deggendorf
*johannes.kaesbauer@th-deg.de

Powder-based Laser Metal Deposition offers opportunities for the build-up of complex structures with various materials, but improper process parameters can cause defects like lack of fusion and pores. Maintaining suitable melt pool characteristics is crucial, often requiring parameter adjustments due to local temperature and geometry variations.

Several developments have been made to ease the parameter selection. The numerical process simulation allows for the prediction of the melt pool evolution and can be used for the virtual optimisation of process parameters before the start of the actual deposition process. The results of the numerical simulation can be validated using in-situ monitoring systems, which are suitable for continuous examination of the melt pool size and offer a high potential to detect inappropriate melt pool characteristics [1]. To assess the build-up process, the information gathered from monitoring systems and process simulation need to be linked with the formation of internal defects.

In this study, the complex time evolution of the melt pool characteristics, yielded by process monitoring and numerical simulation, is investigated regarding the detection of the internal defect formation. For this purpose, multi-layer sample parts of the material Ferro55 [2] are manufactured and metallographically analysed. The variation of the melt pool properties in different layers is caused by the evolution of the accumulated sample temperature and the layer-wise adjustment of the laser power. The melt pool is monitored using the coaxial camera system described in [3]. In some regions a steep decrease of the laser power leads to too excessive reduction of the melt pool size and to formation of lack of fusion defects.

The numerical analysis of the building process using a thermal FEM simulation predicts the transient temperature distributions and the progression of the melt pool size. The melt pool sizes in simulation and measurement show a very similar evolution (Figure 1). Through the comparison with the metallographic and computed tomography investigations of the sample part the critical size of the melt pool can be evaluated. The segment at which lack of fusion defects are visible coincides with the location at which the melt pool size is below a specific critical threshold value. To avoid defects, new process parameters can be designed via simulation.

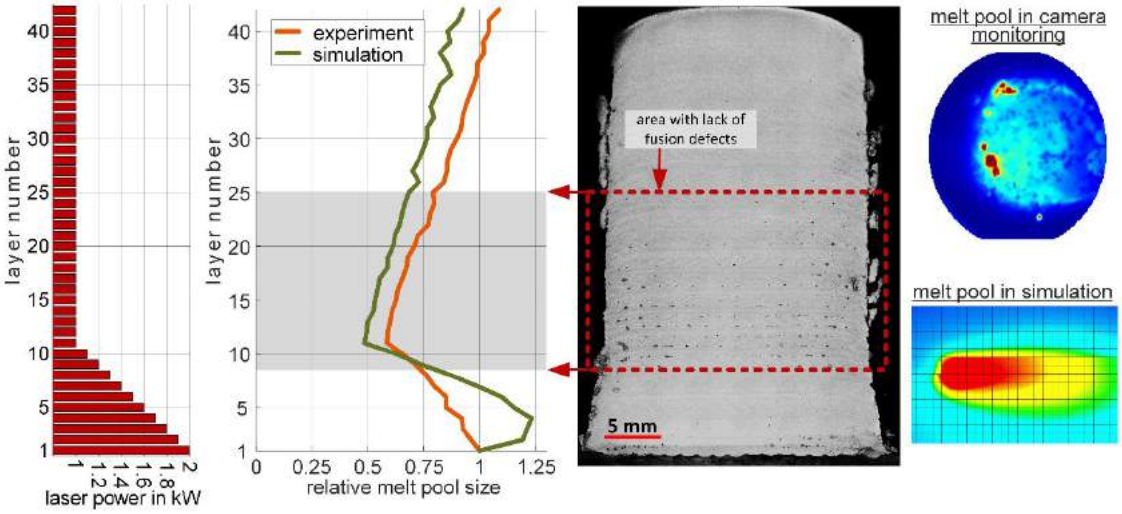


Figure 1. Comparison of melt pool sizes in simulation and experiment with defect distribution in sample part.

References

[1] J. Käsbauer, K. Schröcker, D. Scheider, M. Reisacher, A. Prihodovsky; Lasers in Manufacturing Conference, 2023.

[2] voestalpine Böhler Welding Group GmbH; Datasheet Ferro 55.

[3] C. Kledwig, H. Perfahl, M. Reisacher, F. Brückner, J. Bliedtner, C. Leyens; Materials, 2019, 12, 308.

Simulation-driven predeformation for buckling prevention in thin-walled parts produced by wire arc additive manufacturing

C. Behrens[1*], S. Neubert[2], V. Ploshikhin[1]

[1] Universität Bremen, [2] Gefertec GmbH
*behrens@isemp.com

Wire arc additive manufacturing (WAAM) is a promising direct energy deposition (DED) process that enables high deposition rates and produces large components of moderate complexity [1] with comparable or better material properties than conventionally manufactured parts [2]. However, the residual stresses generated during the process can cause thin and slender parts to buckle under compressive loads, a well-known issue in DED [3] and other additive manufacturing processes [4,5]. In this study, an oscillation in the displacement was observed in a thin-walled cylindrical specimen (see Figure 1a), which was assumed to be buckling due to the similarity to buckling of higher eigenvalues for hierarchical beam structures [6].

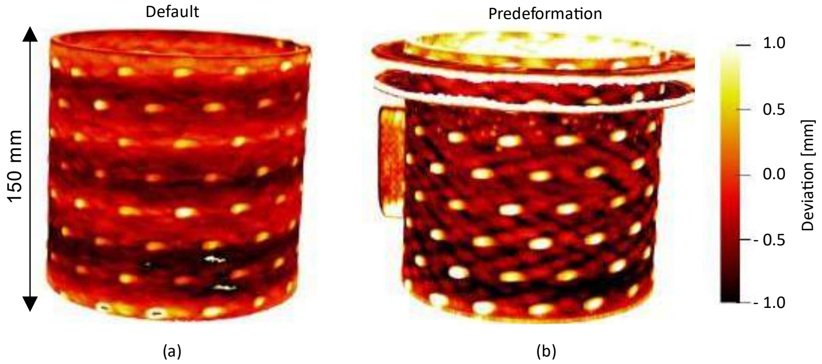


Figure 1. Comparison of the deviations from a WAAM specimen to the desired geometry for (a) a cylindrical specimen and (b) a predeformed complex cylindrical specimen.

This study utilized an inherent strain simulation, specifically adapted to the Wire Arc Additive Manufacturing (WAAM) process [7], to create a predeformed structure (Figure 2b) that compensates for displacements induced by additional structures on a cylinder. The simulation-based predeformation successfully eliminated buckling, confirmed by the absence of buckling in the printed predeformed specimen. The results of the study demonstrate a high potential of the inherent strain simulation to be a very effective numerical method to improve the stability of the build-up process by wire-arc additive manufacturing of thin-walled components.

References

[1] D. Ding, Z. Pan, D. Cuiuri, H. Li, Wire-feed additive manufacturing of metal components: technologies, developments and future interests, The International Journal of Advanced Manufacturing Technology 81 (2015) 465–481. https://doi.org/10.1007/s00170-015-7077-3.

[2] K. Treutler, V. Wesling, The Current State of Research of Wire Arc Additive Manufacturing (WAAM): A Review, Applied Sciences 18 (2021) 8619. https://doi.org/10.3390/app11188619.

[3] D. Weisz-Patrault, P. Margerit, A. Constantinescu, Residual stresses in thin walled-structures manufactured by directed energy deposition: In-situ measurements, fast thermo-mechanical simulation and buckling, Additive Manufacturing 56 (2022) 102903. https://doi.org/10.1016/j.addma.2022.102903.

[4] P. Anant Pidge, H. Kumar, Additive manufacturing: A review on 3 D printing of metals and study of residual stress, buckling load capacity of strut members, Materials Today: Proceedings 21 (2020) 1689–1694. https://doi.org/10.1016/j.matpr.2019.12.012.

[5] G. Vastola, W.J. Sin, C.-N. Sun, N. Sridhar, Design guidelines for suppressing distortion and buckling in metallic thin-wall structures built by powder-bed fusion additive manufacturing, Materials & Design 215 (2022) 110489. https://doi.org/10.1016/j.matdes.2022.110489.

[6] M.G. Tarantino, K. Danas, Programmable higher-order Euler buckling modes in hierarchical beams, International Journal of Solids and Structures 167 (2019) 170–183. https://doi.org/10.1016/j.ijsolstr.2019.03.009.

[7] C. Behrens, S. Neubert, M. Siewert, M.S. Mohebbi, V. Ploshikhin, Integration of annealing into the inherent strain simulation of wire arc additive manufacturing, Additive Manufacturing Letters 4 (2023) 100115. https://doi.org/10.1016/j.addlet.2022.100115.

The lightweight potential of anisotropic plate lattice structures

M. Maier[1*], C. Stangl[1], H. Saage[1], O. Huber[1]
[1] University of Applied Sciences Landshut
*Martin.Maier@haw-landshut.de

Additive manufacturing processes enable the production of complex structures beyond the reach of conventional methods. A widely employed and extensively investigated additive manufacturing technique for metals is the Laser Powder Bed Fusion (LPBF) process. One class of structures that can be additively manufactured in this way are cellular lattice structures. In [1] it is demonstrated that isotropic plate lattice structures can achieve the upper limit [2] of the achievable weight-specific elastic material properties of an isotropic cellular material.

The subject of the research outlined herein is the investigation of anisotropic plate lattice structures with high weight-specific stiffness and strength to be manufactured within the LPBF process. Three lattice unit cells are designed, with the first one intended for tension/compression loading, the second one for shear loading and the third one for a combined loading scenario. The elastic homogenized material properties are determined using FEM with unit cell models and periodic boundary conditions (PBC) [3]. Subsequently, an investigation of the stability behavior of the lattice structures is conducted using various modeling approaches with different representative volume elements. A detailed examination of the occurring stress concentrations is carried out by using different concepts. Figure 1 shows the three steps, stiffness analysis, stability analysis and strength analysis, which were carried out to fully characterize the elastic material behavior of the lattice structures. In addition, first samples produced using the LPBF process are shown.

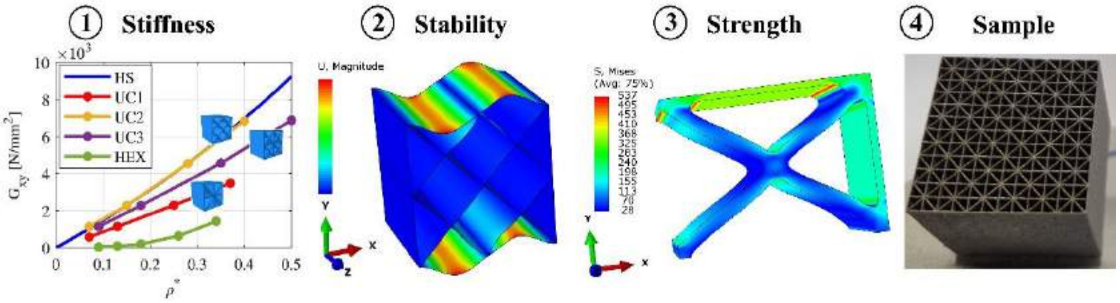


Figure 1. Stiffness analysis (1), stability analysis (2) and strength analysis (3), for the material characterization and a manufactured sample using the LPBF process (4)

To evaluate the lightweight potential of the developed lattice structures, their effective elastic material properties are compared to those of a honeycomb structure. The work demonstrates that using anisotropic structural behavior enables the development of plate lattice structures characterized by a comparatively simple and for the LPBF process manufacturing-friendly cell architecture, high weight-specific stiffness, and consequently, significant lightweight potential. The stability analysis reveals that in all lattice structures, plastic deformation initiates before linear buckling occurs. It is shown that by selecting appropriate representative volume elements, reduced models with PBC can be employed for buckling analysis instead of more complex multi cell models. Furthermore, the weight-specific strength of the plate lattice structures is evaluated and it is shown that stress concentrations can be significantly reduced through the deliberate implementation of radii. Simultaneously, the radii lead to an increase in weight-specific stiffness. It will be shown, that plate lattice structures with a wall thickness of 0.2 mm can be manufactured using the LPBF process with AlSi10Mg powder. The subject of further research will be the experimental investigation of the lattice plate structure.

References

[1] T. Tancogne-Dejan, M. Diamantpopoulou, M.B. Gorji, C. Bonatti, D. Mohr, *Advanced materials*, **2018**, *30.*
[2] Z. Hashin, S. Shtrikman, *Journal of the Mechanics and Physics of Solids*, **1963**, *11,* 127-140.
[3] S. Li, E. Sitnikova, *Comprehensive Composite Materials II*, **2018**, 451-489.

J01: Process monitoring and process quality assurance I [Berlin]

Session Chairs

Gunther Mohr
Bundesanstalt für Materialforsc...

Advanced 3D Printing – Smart Fusion, Beam-Shaping and New Materials

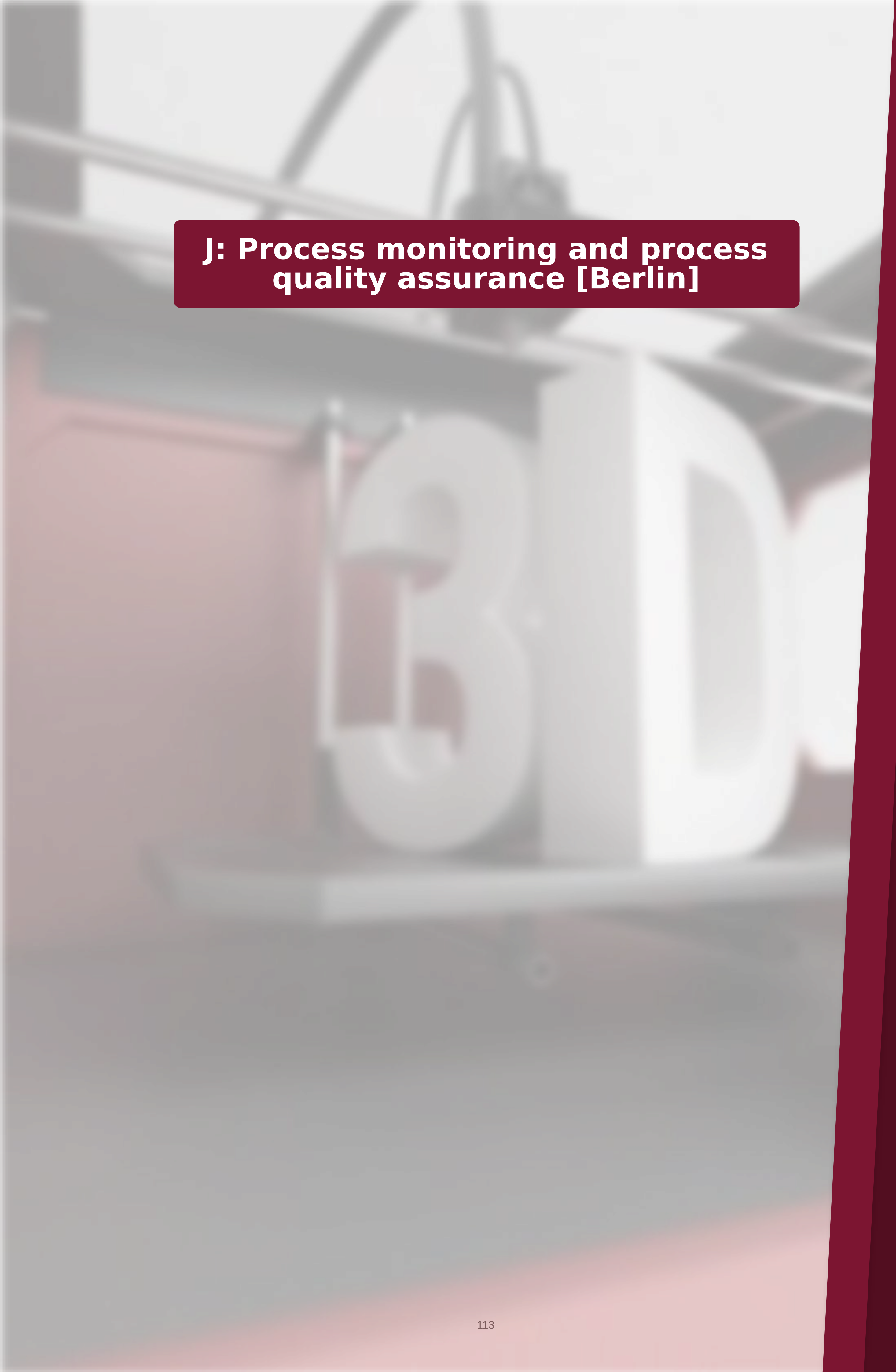
T. Schlingmann[1*], M. J. Galba[2]

[1] EOS GmbH Electro Optical Systems
* tina.schlingmann@eos.info

In order to establish industrial Additive Manufacturing (AM) in series production, a reliable, reproducible and, above all, economical process is required. High post-processing costs, long printing times and inefficient material consumption do not meet the requirements.

But how does “advanced 3D Printing” work? In this presentation, you will learn more about the working principle of a new process control solution that includes a unique intelligent real-time thermal management system that reduces or eliminates support structures while working 2 to 5 times faster than other additive manufacturing technologies.

EOS Smart Fusion is the latest development for the advancement and promotion of metal AM. This technology automatically adjusts the laser power of EOS metal AM systems in real time to solve potential manufacturing problems quickly and efficiently. The technology measures the laser energy absorbed by the powder bed and adjusts it using advanced algorithms. As a positive side effect, support structures that would be mandatory in other metal AM applications can be avoided. This not only eliminates slower build times, but also lowers your cost per part by reducing post-processing and material usage. It also adds significant value in terms of sustainability. With Smart Fusion software, precise Beam Shaping and a wide range of New Materials, more industries can make a positive business case for metal AM applications. This is particularly beneficial for industries with highly technical components such as energy, space tech, mobility, and aerospace.



J: Process monitoring and process quality assurance [Berlin]

A raw data approach for porosity prediction in PBF-LB/M based on thermographic image sequences

S. Oster[*1], N. Scheuschner[1], T. Becker[1], P. P. Breese[1], S. J. Altenburg[1]

[1] Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany
*simon.oster@bam.de

Metal-based additive manufacturing processes are increasingly used in industry to produce complex-shaped components. In this regard, the laser-based Powder Bed Fusion process (PBF-LB/M) is one of the key technologies due to its capability to produce components in high spatial accuracy. The formation of porosity during manufacturing poses a serious risk to the safety of the printed parts. For quality assessment, in-situ monitoring technologies such as thermography can be used to capture the thermal history during production. It was shown that discontinuities within the thermal history can be correlated with the probability of porosity or defect formation [1]. In this context, Machine Learning (ML) algorithms have achieved promising results for the task of porosity prediction based on thermographic in-situ monitoring data [2]. One important technique is the use of thermogram features for porosity prediction that are extracted from the raw data (e.g., features related to the melt pool geometry or spatter generation). However, the reduction from large thermogram data to discrete features holds the risk of losing potentially important thermal information and, thereby, introducing bias in the model.

Therefore, we present a raw data-based deep learning approach that uses thermographic image sequences (Fig. 1a) for the prediction of local porosity. The model takes advantage of the self-attention mechanism [4] that considers not only the thermogram information but also its positional context within the sequence. The model is used to predict porosity in the form of a many-to-one regression. It is trained and tested on a dataset retrieved from the manufacturing of HAYNES282 cuboid specimens (Fig. 1b). The model results are compared against state-of-the-art thermogram feature-based ML models and artificial neural networks. The raw data model outperforms its feature-based counterparts in terms of prediction scores and, therefore, seems to make better use of the information available in the thermogram data.

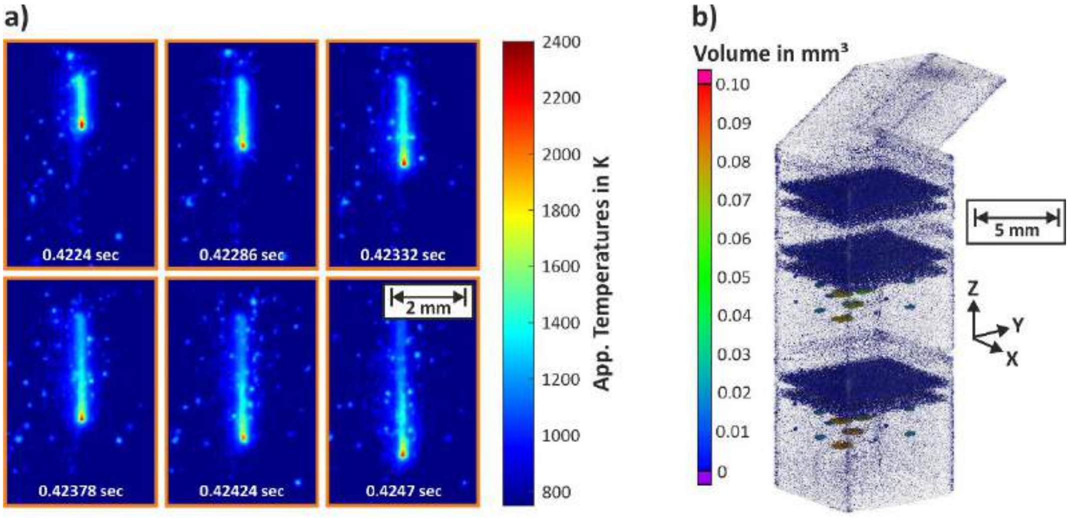


Figure 1. a) Raw thermogram image sequences. b) Porosity distribution in HAYNES282 specimen.

References
[1] C. Lough *Additive Manufacturing*, 2020, *35*.
[2] S. Oster *Journal of Intelligent Manufacturing*, 2023.
[3] A. Vaswani *Proc. of 31st Conference on Neural Information Processing Systems (NIPS 2017)*, 2017.

Comparative Analysis FFF vs. cold rolled 316L Samples

D. Schob[1*], J. Tabin[2], J. Kawałko[3], R. Roszak[4,5], G. Ziółkowski[6], M. Ziegenhorn[5], K. Hilgenberg[1]

[1] Bundesanstalt für Materialforschung und -prüfung, FB 9.6 Additive Fertigung metallischer Komponenten, 12205 Berlin, Germany
[2] Institute of Fundamental Technological Research, Polish Academy of Sciences, 02-106 Warsaw, Poland
[3] Academic Centre for Materials and Nanotechnology, AGH University of Science and Technology, 30-059 Krakow, Poland
[4] Institute of Applied Mechanics, Poznan University of Technology, Poznan, Poland
[5] Brandenburg University of Technology Cottbus-Senftenberg, 01968 Senftenberg, Germany
[6] Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland
*Daniela.schob@bam.de

This study provides insights into the properties of 316L stainless steel produced by additive manufacturing using fused filament fabrication (FFF). One key finding is particularly noteworthy: in significant contrast to cold-rolled 316L, FFF316L develops a pronounced martensite phase after fabrication. The comprehensive comparative analysis shows that FFF316L not only retains the ferrite volume content, but that this is also significantly influenced by the build-up direction, Fig. 1.

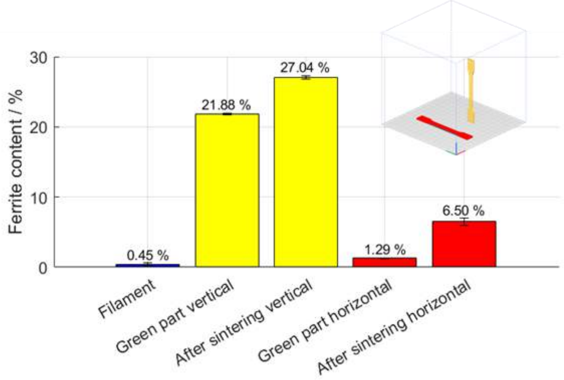


Fig. 1 Ferrite volume content

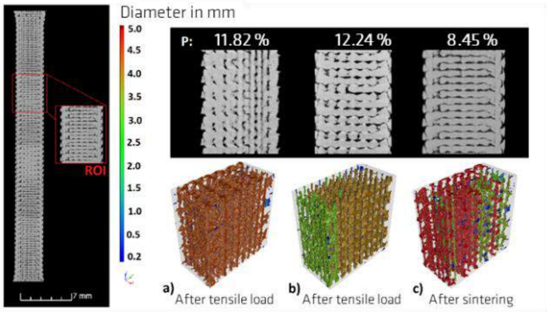


Fig. 2 Void volume content

Despite the sintering process, which typically involves densification of the material, a pore volume fraction of 8.45 % remains, which influences the mechanical properties, Fig. 2. Although FFF316L has lower elastic modulus and tensile strength values compared to cold-rolled 316L, its ductility is still competitive, Fig. 3. The study further reveals that deformation-induced martensite forms at the intersections of the deformation twins and ferrite islands form at the grain boundaries during the compression and sintering phases, Fig. 4.

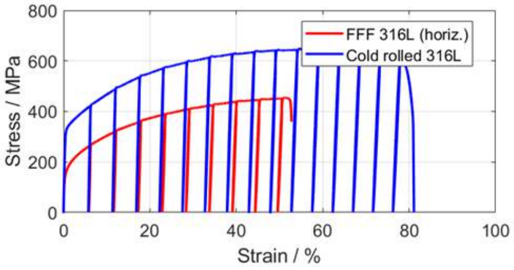


Fig. 3 Material behaviour

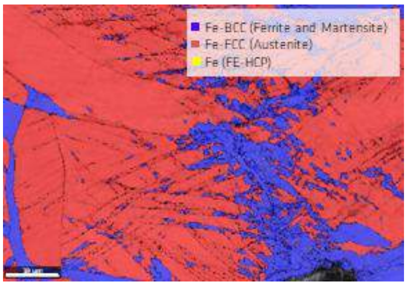


Fig. 4 Microstructure and chemical composition

These findings highlight the challenges associated with FFF316L in specific application fields and signal the need to continue to carefully evaluate and improve the development of manufacturing technologies.

Conception of an automated and intelligent post-processing station for powder-based 3D printing

N. Rabeneck[1*], E.-M. Menges[1], C.Y. Aubeeluck[2], M. Schall[2], S. Kölbl[1], M. Hien[2], W. Aumer[3], M. Hartmann[4]

[1] Deggendorf Institute of Technology – Technology Campus Hutthurm
[2] Deggendorf Institute of Technology – Technology Campus Cham
[3] Deggendorf Institute of Technology – Faculty of Applied Natural Sciences and Industrial Engineering
[4] Deggendorf Institute of Technology – Faculty of Mechanical Engineering and Mechatronics
*nils.rabeneck@th-deg.de

In powder-based 3D printing, various post-processing steps are required from additive manufacturing to the finished component. These include, for example, the removal of residual powder from the components, the allocation and sorting of the components and an optical quality check. These steps are currently mainly carried out manually as the manufactured parts often require individual cleaning and post-treatment [1]. The current process sequence is therefore complex and time-consuming.

Thus, a universal, automated post-processing station is envisaged that includes a fully automated transport and sorting process, automated powder removal and an integrated quality assurance system.
The concept provides a step-by-step cleaning process, a transport by robotic devices using an intelligent gripping system and quality assurance via image recognition based on artificial intelligence. This enables an efficient, space- and cost-saving design.

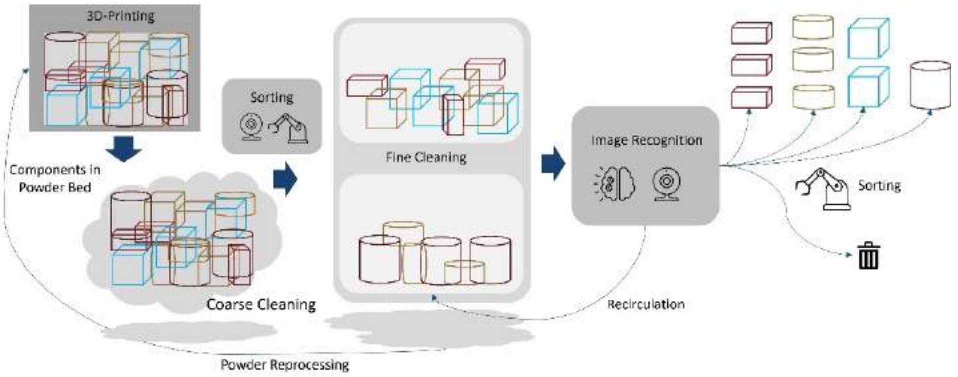


Figure 1. Illustration of the post-processing concept from manufacturing to final sorting.

The development of the post-processing station is supported by simulations regarding functionality of subsystems as well as the overall workflow. This includes physics-based simulations of cleaning and transport processes and a virtual commissioning.

As seen in Figure 1, the concept provides a recirculation of the removed powder. Future research will investigate recycling strategies for used powder of poor quality as it is the case in binder jet 3D printing, where powder is contaminated by adhesive agents [2].

References

[1] J.R.C. Dizon, C.C.L. Gache, H.M.S. Cascolan, L.T. Cancino, R.C. Advincula; *Technologies*, **2021**, *9*, 61.
[2] S. Mirzababaei, B.K. Paul, S. Pasebani; *JOM*, **2020**, *72*, 3070-3079.

Elemental Composition Analysis via in-situ Optical Emission Spectroscopy during Laser Powder Bed Fusion

P. Gabriel[1], A. R. Ziefuß[1], R. Streubel[1], F. Eibl[2], S. Barcikowski[1*]

[1] Technical Chemistry I and Center for Nanointegration Duisburg-Essen (CENIDE), University Duisburg-Essen, Universitätsstraße 7, 45141 Essen, Germany, [2] Aconity GmbH, Kaiserstraße 98, 52134 Herzogenrath, Germany
*stephan.barcikowski@uni-due.de

Laser powder bed fusion of metals (PBF-LB/M) is an established AM technique that enables efficient net-shape fabrication with enhanced resource utilization compared to traditional methods.[1] Despite the recognized advantages of in-situ quality tracing and control instrumentation over post-processing measures, the current landscape of PBF-LB machine upgrades primarily features cameras or pyrometers, which fail to provide insights into the chemical composition.[2,3] Acknowledging this gap, our exploration into voxel-wise tracking of chemical composition during PBF-LB/M emerges as a pivotal endeavour. Our approach seeks to establish meaningful correlations between compositional alterations and resultant material properties, thereby enhancing manufactured components' overarching quality control capability.

Delving into elemental composition analysis through in-situ optical emission spectroscopy (OES) during the PBF-LB/M process, our study draws inspiration from the successful application of OES in laser welding for in-situ metal vapor plume analysis [4,5]. Focusing on initial investigations, we explore the elemental analysis of metallic samples, exemplified by an Nd-Fe-B-based alloy [6]. For direct comparison, the established technique of ex-situ inductively coupled plasma OES (ICP-OES) has been applied, revealing a commendable correlation. Notably, our findings underscore the potential of local emissivity within Fe and Nd lines as reliable indicators for determining plasma temperature and elemental concentration. Overall, our study provides valuable insights into the in-situ OES analysis of PBF-LB/M and expands the quality tracing by information on the local composition of the produced parts.

References

[1] S.R. Narasimharaju, W. Zeng, T.L. See, Z. Zhu, P. Scott, X. Jiang et al, J. Manuf. Process., 2022, 75, pp. 375
[2] Deutsche Akademie der Naturforscher Leopoldina e.V., Nationale Akademie der Wissenschaften, Schriftenreihe zur wissenschaftsbasierten Politikberatung, 2020
[3] A. Molotnikov, A. Kingsbury and M. Brandt, J. Fundamentals of LPBF of Metals, 2021, 23, pp. 621
[4] L. Zhou, M. Zhang, X. Jin, H. Zhang and C. Mao, Int. J. Adv. Manuf. Technol., 2017, 88, pp. 1373
[5] B. Ribic, P. Burgardt and T. DebRov, J. Appl. Phys. (2011), 109, pp. 083301
[6] A.R. Ziefuß, R. Streubel, P. Gabriel, F. Eibl, S. Barcikowski, ChemRxiv., 2023

Multi-scale Characterization of Functionally Gradient Bimetallic Ni-Cu CSAM Alloys

J. Yorston[1], M. Riccio[1], H. Francois-Saint-Cyr[1], P. Sudera[1*], H. Hoell[2], M. Ellingsen[2], J. Rinck[3], K. Batte[3]

[1] Thermo Fisher Scientific, [2] VRC Metals, [3]Waygate Technologies
*prerna.sudera@thermofisher.com

Weight reduction and improvement in efficiency of rocket engine components, are highly desirable in aerospace to reduce payload, lower launch costs, increase specific impulse, and enable their reuse in successive launches.

We focused in this study on functionally gradient Ni-Cu alloys, which offer both high-temperature strength and high heat flux properties to combustion liners, jackets and nozzles. The microstructures of those bimetallic alloys prepared by nitrogen-based cold spray additive manufacturing (CSAM), have been evaluated using 3D X-ray microscopy, large-scale automated scanning electron microscopy, and energy dispersive spectroscopy. Information such as grain size, shape, distribution, porosity, and chemical maps will help guide researchers in their understanding of the mechanical properties of that material.

Operando X-ray tomoscopy of laser powder bed fusion

Paul H. Kamm[1,2], Tillmann R. Neu[1,2], Christian M. Schlepütz[3] and Francisco García-Moreno[1,2]

[1]Institute of Applied Materials, Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany
[2]Institute of Materials Science and Technology, Technische Universität Berlin, Berlin, Germany
[3]Swiss Light Source, Paul Scherrer Institute, Villigen, Switzerland

Recently, tomoscopy (also known as time-resolved tomography) has been used to observe dynamic processes in various materials and systems. It can now capture up to 1000 tomograms per second (tps) for an extended duration of minutes. Focused laser beams can be used for local melting of material for cutting, cladding, or welding parts. This technique can also be used to sinter powder particles for additive manufacturing of components.

Despite its potential, laser-based powder bed fusion (LPBF) parts often contain many pores, limiting their application potential. X-ray tomoscopy can help in analyzing pore formation in detail and improving production parameters. Image superposition which is typical for radiography is no longer an issue, and it allows edge effects of thin samples to be avoided. In a proof-of-concept operando tomoscopic experiment, loose aluminum powder was processed under realistic production conditions with a fiber laser and a fast positioning system for beam guidance by superimposing the movement of the laser on that of the rotating powder bed, the last being necessary for tomography. That way the interaction area could be advanced while simultaneously recording tomograms with a temporal resolution of 100 tps.

The temporal evolution of the aluminum powder particles during the formation of the first molten layer in this simplified LPBF sintering was recorded along two complete circles of 2 mm diameter with a relative laser feed rate of 1 m/min in 0.72 s and the results were analyzed. The experiment showed the formation of balling (caused by low laser energies), denudation zones and porosity. The first circle showed individual melt lumps forming at the position of the laser spot. The lumps had an equivalent diameter of 0.2-0.5 mm and retained their original shape throughout the process until they solidified. X-ray tomoscopy was used to quantify the evolution of the total volume of molten powder and the porosity formed within the particles in the first circle. The total volume of the molten powder increased almost linearly with time, while the majority of pores did not form until the first lumps began to solidify, as residual gases cannot diffuse out fast enough to avoid being trapped. After passing the laser again and melting the lumps again, the porosity was reduced about tenfold.

These findings provide insight into improving production parameters and developing dedicated alloys for additive manufacturing. Overall, this study demonstrates the potential of in-situ operando tomoscopy to advance our understanding of laser interaction and ultimately improve the quality of additively manufactured parts.

Figure 1. LPBF of AlSi10Mg powders observed with X-ray tomoscopy operando, time-resolved and in 3D during formation.

Quality assurance of additively manufactured components

Dr.-Ing Thorsten Leist

HTV Conservation GmbH
leist@htv-conservation.com

The possibilities of additive manufacturing have grown more and more in recent years and now cover almost the entire material spectrum of series production. Almost all shapes can be produced that would either not be possible at all using conventional methods or only at enormous cost. With the increasing spread of 3D printing technology, it is also finding its way into new markets reaching from automotive to aerospace applications. Quality assurance measures are becoming increasingly important and must be taken into account accordingly. Especially, the medical sector, but also the automotive, aerospace and defence industry is known to have strong quality assuring processes. This includes contious monitoring and improvement of the quality relevant parameters. For 3D-Printing processes, high costs per part, makes it sometimes difficult to inplement standard quality testing methods, such as metallographic cuts or tensile testing. In the event of damage, a precise analysis is often the right way to improve product reliability or to gain a better understanding of the failure mechanism in order to prevent the cause of damage in the future. HTV Conservation GmbH highlights various opportunities for the quality assurance of 3D-printed components. It will be shown how the processes in 3D printing can be monitored and how product quality can be documented and traced comprehensively. Various strategies and analytical methods will be presented, and their potential and practical utility will be discussed.

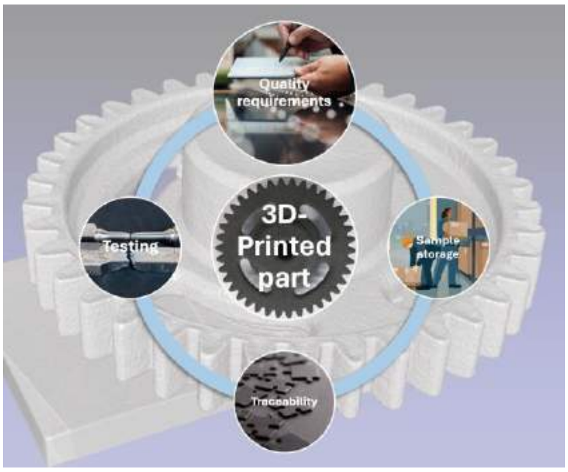


Figure 1. Schematic on the considerations to be made during the quality assurance process

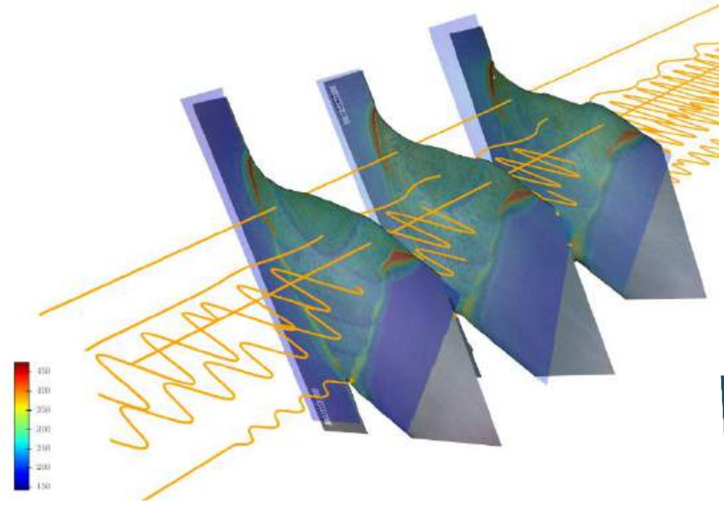
Towards arc welding reference data: Open Science laboratories at BAM

Ç. Fabry[1*], A. Pittner[1], M. Rethmeier[1]

[1] Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin
*cagtay.fabry@bam.de

As industries move for ever faster development and adoption cycles of emerging new technologies in the field of welding, the meticulous and longer-winded approach of the scientific research process can feel harder to integrate. To help bridge this gap and increase the speed, quality, and adoption rate of publicly funded research, the Bundesanstalt für Materialforschung und -prüfung (BAM) continues to work towards enabling scientists with direct access to necessary software tools and - in the future – highest quality welding research reference data to further foster collaborations [1].

On the experimental side, the arc welding group at BAM division 9.3 “welding technologies” is continuing to expand and upgrade its capacities of robotic welding systems with integrated state of the art sensor technologies and software solutions. This allows all experiments to be recorded and measured in micro-millimeter accuracy and at sub-millisecond precision, including welding process data, complete spatial geometry and temperature measurements, process video recordings and more. The custom software-based solutions and interfaces allow scaling of the welding systems from large thick plate offshore applications to small additive repair weldments in wind turbine blades to multi-hour continuous weldments in additive manufacturing applications. In addition to the data gathered during the welding process itself, the relevant testing results and materials properties produced at BAM or externally can be integrated seamlessly. This allows detailed traceability of all results back to the actual welding process.
Regardless of the scope and application, complete datasets can be made accessible for research or industry partners in the highest resolution based on the open source WelDX (welding data exchange) file format.



welding data exchange
open science initiative

Figure 1. Welding experiment representation including dynamic process data, cross-section imaging and hardness measurements from a single weldx file.

The talk will give an overview of the experimental facilities and workflows as well as current software developments with a focus on research data quality assurance, traceability, and accessibility.
Based on the integration into latest research trends and activities of the “welding technologies” division, the path to publishing reference datasets for arc welding process for various applications and materials is outlined and discussed.

References

[1] Ç. Fabry, A. Pittner, V. Hirthammer et al. *Weld World*, **2021**, *65*, 1661–1669.

Why ISO compliant laser measurement is key in laser powder bed fusion processes (LPBF)

Nicolas Meunier* (Meunier, N.), Kevin Kirkham (Kirkham, K.), Jed Simmons,(Simmons, J.)

*nicolas.meunier@mksinst.com

When it comes to laser powder bed fusion, the constancy of the laser parameters is of great importance. Both, the manufacturers of the laser systems and the users thereof should be aware of the quality of the focused beam. As measuring a (high power) laser beam in the limited space of a production chamber is a challenge, new measurement technology had to be developed. Today, different technologies are available to measure the focused beam quickly and cost-effectively within the process. Especially for regulated industries it is key to measure the laser beam parameters in compliance with ISO standards.

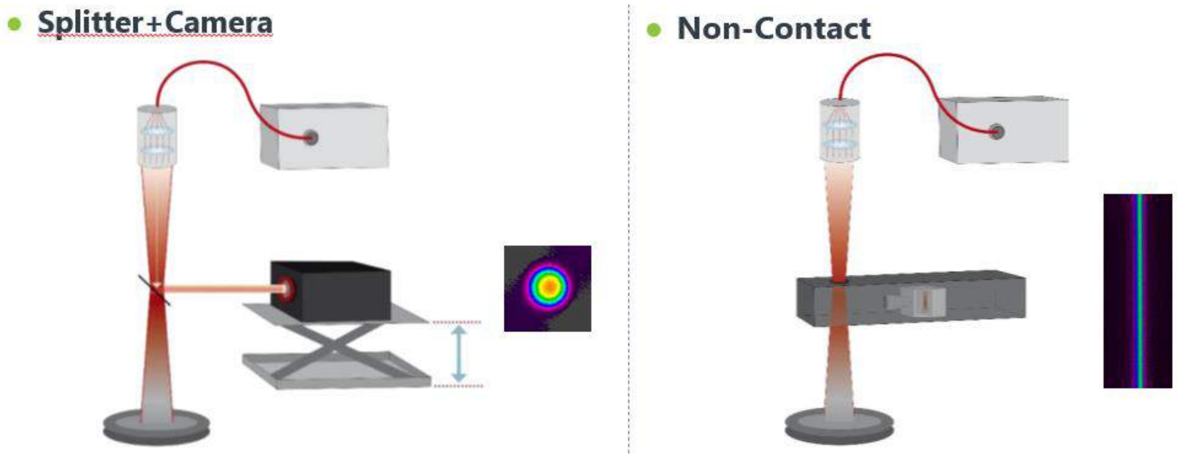
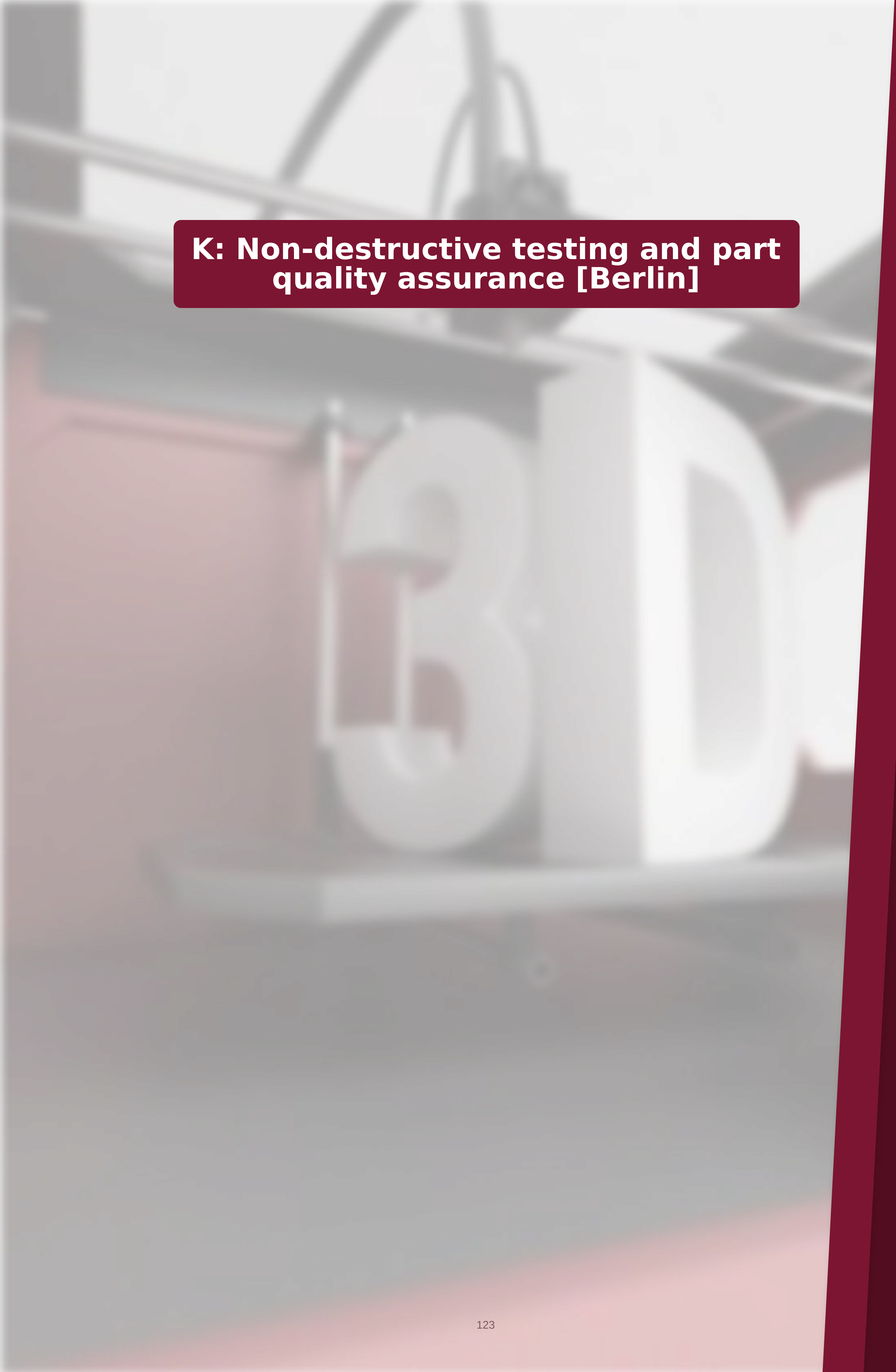


Figure 1. Two different approach to Laser Beam Profiling: Beam splitter and Rayleigh-Scattering

The paper introduces the relevant measurement parameters for LPBF processes and depicts challenges in gaining those. It compares different measurement technologies and introduces suitable devices that can be used in regulated industries as they are based on international standards. Innovative technology for measuring beams with different wavelengths and high-power densities are introduced.
LPBF offers an enormous potential for mass production of critical parts in many industries; to really take advantage of the benefits it is crucial to ensure high quality standards. The presentation aims to sensitize users of LPBF machines to regularly check the laser beam and introduces new solutions to measure high power laser beams in constraint building chambers and regulated industries.

References

[1] j: Simmons, K. Kirkham, 2019, White Paper, Last Online Check 20.2.24 .



K: Non-destructive testing and part quality assurance [Berlin]

A unique authenticator for additively manufactured parts derived from their microstructure

K. Gupta[1], K. Poka[1], A. Ulbricht[1], G. Mohr[1], A. Waske[1*]

[1] Bundesanstalt für Materialforschung und -prüfung, Berlin
*anja.waske@bam.de

Components produced using additive manufacturing can be marked for unique identification and secure authentication [1,2]. Serial numbers and machine-readable codes can be used to identify the component, and link digital product-related data (i.e., a digital product passport) to the actual components. The most prevailing solution consists of local process manipulation, such as printing a quick response (QR) code [3] or a set of blind holes on the surface of the internal cavity of hollow components. However, local manipulation of components may alter the properties, and external tagging features can be altered or even removed by post-processing treatments. This work therefore aims to provide a new methodology for identification, authentication, and traceability of additively manufactured (AM) components using microstructural features that are unique to each part. X-ray computed tomography (XCT) was employed to image the microstructural features of AlSi10Mg parts. Based on size and geometry, the most prominent features were selected to create a unique digital authenticator. We implemented a framework in Python using open-access modules that can successfully create a digital object authenticator using the segmented microstructure information from XCT. The authenticator is stored as a QR code, along with the 3D information of the selected features.

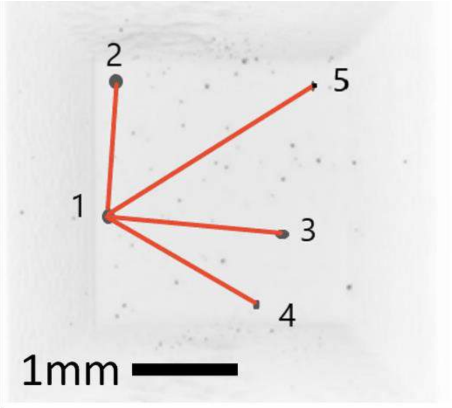


Figure 1. Rendering of a 3D-printed Al-based part with spherical micropores. The most prominent pores with respect to their size and shape are selected for building a unique identifier of the manufactured part.

References

[1] D. Eisenbarth, *Additive Manufacturing,* **2020,** *35*, 101298
[2] U. Jahnke, *„Systematik zum präventiven Schutz vor Produktpiraterie durch AM“*. Dissertation, Universität Paderborn, 2019.
[3] D., Lehmhus, et. al., *Procedia Technol*, **2016**, *26*, Issue 1, 284-301

Fast and non-destructive mechanical characterization of additively manufactured materials with surface acoustic wave spectroscopy - Opportunities and perspectives for use in science and industry

M. Zawischa[1,2*], S. Makowski[1], J. Moritz[2], F. Günther[2]

[1] Fraunhofer-Institut für Werkstoff- und Strahltechnik, Dresden, Germany, [2] Technische Universität Dresden, Dresden, Germany
*martin.zawischa@iws.fraunhofer.de

Laser-induced surface acoustic wave spectroscopy (LiSAWS) allows quick and non-destructive access to elastic properties of coatings, surfaces and surface-near bulk materials. Furthermore, the mechanical weakening due to cracks, pores and delamination can be evaluated, as they influence the propagation of surface waves as well. Therefore, the method is established as a quick and powerful tool for surface characterization and established today in research and development, quality control and as a precise and scientific reference method [1,2].
After successful application of the method to semiconductor materials and thin coatings from PVD, ALD, and other deposition techniques in the thickness range of few micrometers [1], recent works showed that using different sensors the depth of information can be extended to at least 500 µm. That allows measurement of thicker coatings and surface properties of freestanding build up structures made by laser cladding, powder bed processes, thermal spraying, and others.

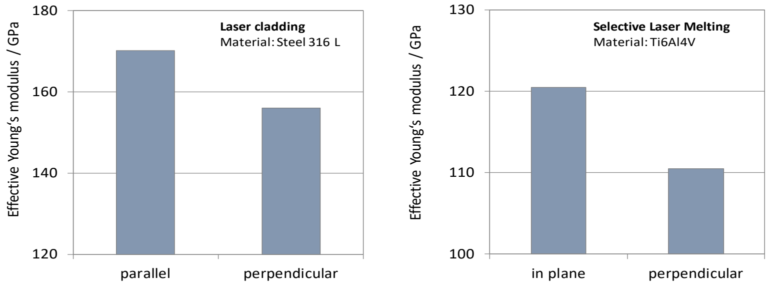


Figure 1: Effective Young's modulus for additively manufactured components depending on generation direction for steel 316L (left) and Titanium alloy Ti6Al4V (right)

In this work, precise measurement of the effective Young's modulus was used to determine the influence of process parameters such as temperature distribution and build-up direction, as well as material properties such as residual porosity on various examples (laser cladding WC-Co/316L, electron beam melted TiAl alloy, thermally sprayed Al_2O_3 insulation coating). Furthermore, it is shown whether the effective modulus is related to the tensile strength and the number of cycles in fatigue tests of a β-Ti-42Nb alloy prepared by laser powder bed fusion at different build-up directions and residual porosities.
With regard to the practical implementation of the measurement, the advantages compared to other methods for measuring the Young's modulus of additively manufactured components, like indentation or tensile test, are emphasized. Furthermore, technical possibilities and limitations with regard to the in-situ use for layer-by-layer characterization in powder bed processes are discussed.

References

[1] D. Schneider, in Handbook of Advanced Nondestructive Evaluation (Eds: N. Ida, N. Meyendorf), Springer International Publishing, Cham, 2019, pp. 171–234.
[2] A. Zarei, S. Pilla Laser ultrasonics for nondestructive testing of composite materials and structures: A review. Ultrasonics (2024), 136, 107163

How to experimentally determine residual stress in AM structures

T. Fritsch[1], J. Schröder[1], T. Mishurova[1], A. Ulbricht[1], I. Serrano Muñoz[1], A. Evans[1], L. Farahbod-Sternahl[2], M. Hofmann[3], G. Bruno[1]*

[1] Bundesanstalt für Materialforschung und -prüfung, Unter den Eichen 87, 12205 Berlin, Germany, [2] Siemens AG, Gas and Power, Huttenstrasse 12, 10553 Berlin, Germany, [3] Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, 85478 Garching, Germany
*Giovanni.bruno@bam.de

The experimental determination of residual stress becomes more complicated with increasing complexity of the structures investigated. Unlike the conventional and most of the additive manufacturing (AM) fabrication techniques, laser powder bed fusion (PBF-LB) allows the production of complex structures without any additional manufacturing step. However, due to the extremely localized melting and solidification, internal stress-induced deformation and cracks are often observed. In the best case, significant residual stress is retained in the final structures as a footprint of the internal stress during manufacturing.

Here we report solutions to the most prevalent challenges when dealing with the diffraction-based determination of residual stress in AM structures, in particular the choice of the correct diffraction elastic constants. We show that for Nickel-based alloys, the diffraction elastic constants of AM material significantly deviate from their conventional counterparts [1]. Furthermore, measurement strategies to overcome the hurdles appearing when applying diffraction-based techniques to complex-shaped lattice structures are presented: a) proper sample alignment within the beam, b) the proper determination of the residual stress field in a representative part of the structure (i.e., with an engineering meaning). Beyond the principal stress magnitude, the principal direcions of residual stress are discussed for different geometries and scan strategies, as they are relevent for failure criteria [2, 3].

We show that the RS in the lattice struts can be considered to be uniaxial and to follow the orientation of the strut, while the RS in the lattice knots is more hydrostatic. Additionally, we show that strain measurements in at least seven independent directions are necessary for the correct estimation of the principal stress directions. The measurement directions should be chosen according to the sample geometry and to an informed choice on the possible strain field (i.e., reflecting the scan strategy) [3].
We finally show that if the most prominent direction is not measured, the error in the calculated stress magnitude increases in such a manner that no reliable assessment of RS state can be made. [2]

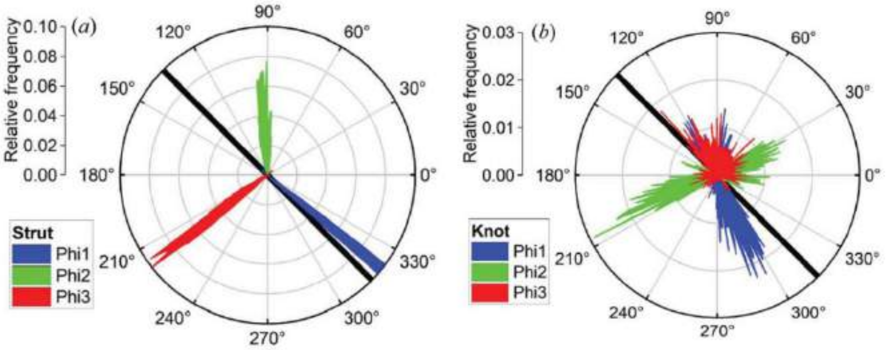


Figure 1. Principal direction of the residual stress tensor in a strut (a) and in a knot (b) of a lattice structure. The statistical significance of the determination is given by the relative frequency of occurrence. [2]

References

[1] J. Schröder, T. Mishurova, T. Fritsch, I. Serrano-Munoz, A. Evans, M. Sprengel, M. Klaus, C. Genzel, J. Schneider, G. Bruno. Mater. Sci. Eng. A, **2021**, 805, 140555.

[2] T.Fritsch, M.Sprengel, A.Evans, L.Farahbod-Sternahl, R.Saliwan-Neumann, M.Hofmann, G.Bruno. J. Appl. Cryst. **2021**, 54, 228–236.

[3] J. Schröder, A. Evans, V. Luzin, G. Abreu Faria, S. Degener, E. Polatidis, J. Capek, A. Kromm, G. Dovzhenko, G.Bruno. J. Appl. Cryst. **2023**, 56, 1076-1090.

In situ Crack detection during Laser Directed Energy Deposition using frequency resolved Acoustic Emission Testing

J.F. Mätje[1*], J. Hendl [2,1], M. Riede[1], E. Lopez[1], F. Brückner [1,3], C. Leyens [2,1]

[1] Fraunhofer Institute for Material and Beam Technology IWS, [2] TUD Dresden University of Technology
[3]Luleå University of Technology

*jacob-florian.maetje@iws.fraunhofer.de

One of the main barriers to utilizing additive manufacturing in an industrial environment is a robust and reliable quality control. To ensure the reliability, repeatability, and cost-effectiveness of additively manufactured parts, in situ non-destructive testing (NDT) is a very useful tool [1]. The in situ NDT tools used today are mainly based on optical or infrared imaging. Hence, the data gained by using these NDT tools is primarily related to surface information [2]. For the quality of mechanically stressed parts, avoiding internal defects is of great importance due to their great impact on the (fatigue)-strength properties [3]. Promising results for in situ NDT can be obtained by using Acoustic Emission Testing (AET). AET is an inspection method that analyses acoustic emissions that occur from solids when a material undergoes changes in its internal structure, such as crack formation and propagation. Defects are discerned through the examination of variations in the amplitude of acoustic waves emitted during defect formation in contrast to the base acoustic signature of the monitored structure. This method is already being used for detecting and tracking defects in pressure vessels and other structures like wind turbines or bridges. Concluding, this method has great potential for additive manufacturing regarding in situ quality control. However, due to the inherently passive signal detection, adapting the approach for Laser Directed Energy Deposition (DED-LB/M) presents significant challenges that need to be addressed. These include signal interference from the noisy process environment, variations in acoustic behaviour between different process setups, and the constantly changing geometry due to material buildup [4].

This work aims to demonstrate that by carrying out frequency-resolved AET and obtaining an intensity distribution, these challenges can be overcome and distinguished acoustic patterns of defects and random interference can be analysed.

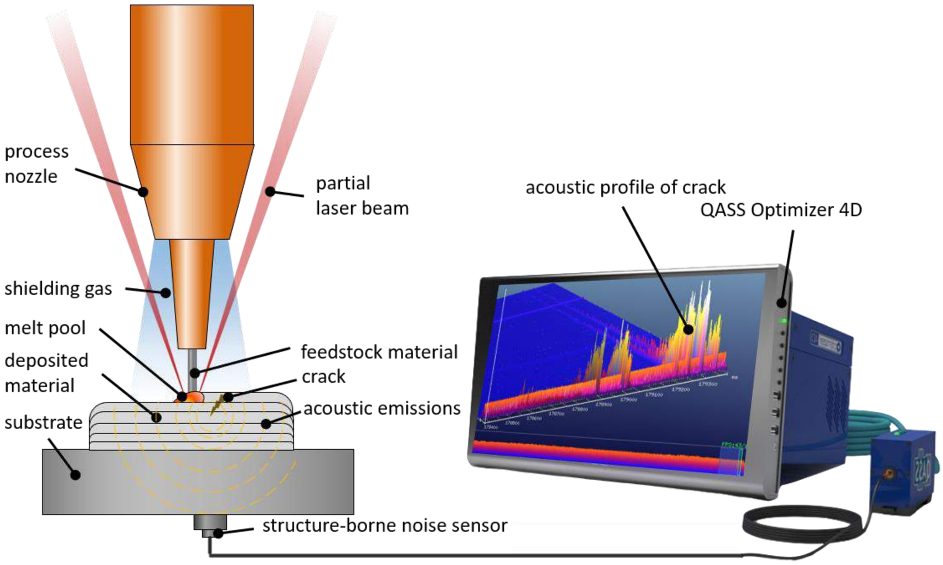


Figure 1. Schematic representation of in situ passive acoustic spectral analysis during DED-LB/M

In order to use frequency-resolved AET as a quality control tool, it is necessary to gain an understanding of the acoustic emission profiles that occur during deposition and to set up thresholds for automated defect detection. Two types of samples are fabricated and monitored using frequency resolved AET: Reference samples that are processed to result in near defect-free bulk material and samples where process parameters and conditions are chosen to facilitate cracking during deposition or cooling, such as processing Ti-6Al-4V without sufficient shielding gas. The time and frequency-resolved intensity distribution recorded during deposition is analysed, and possible cracking events are identified. Samples are further investigated using µ-focus computer tomography to confirm the presence of defects in the samples and to ensure the quality of the reference samples. A correlation between defect size, acoustic profile, and crack location can be made to evaluate the suitability of in situ frequency-resolved AET for quality control.

References

[1] S. Tofail, E.P. Koumoulos et al.; *Materials Today*, 2018, *Volume 21*, Pages 22-37.
[2] D.Y. Kononenko, V.V. Nikonova et al.; *Additive Manufacturing Letters*, 2023, *Volume 5*
[3] A. Yadollahi, N. Shamsaei; *Int. J. Fatigue*, 2017, *Volume 21*, S. 18
[4] L.W. Koester, H. Taheri et al.; *AIP Conf. Proc.*, 2019, *Volume 38*

In-situ subsurface defect detection in PBF-LB/M with active thermography

C. Sauer*,[1], D. Höfflin[1,2], Andreas Schiffler[1,2]

[1] University of Applied Science Würzburg-Schweinfurt; [2] Technology Transfer Center Main-Spessart
*christian.sauer@thws.de

This work introduces an advanced active thermography method that utilizes the distinctive abilities of Synchronized Path Infrared Thermography (SPIT) [1, 2], to provide a novel process monitoring approach in Laser Powder Bed Fusion of Metals (PBF-LB/M). This technique leverages a dual-scanner system, integrating non-destructive thermal excitation via the processing laser, and enhanced defect detection using a high-speed MWIR thermography system. The SPIT system strategically utilises the manufacturing laser to heat the specimen surfaces, thereby enabling the simultaneous capture of thermal behaviour of the surface through a secondary, infrared-optimised optical path. This setup is adept at identifying subsurface defects, which is crucial for assessing the integrity of components produced via additive manufacturing and that traditional surface inspection methods might miss.

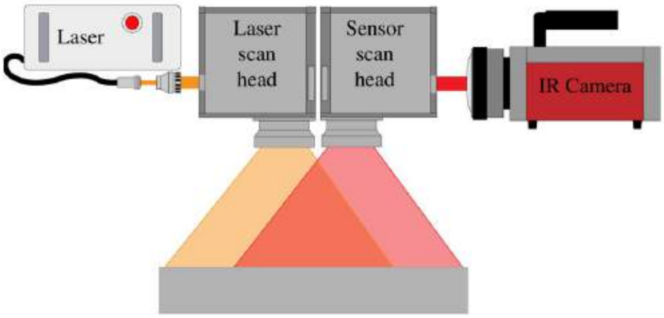


Figure 1. The schematics of the SPIT setup, with two galvanometer scanners situated above the working area. One dedicated scanner controls the laser, while the other is employed for the field of view of the infrared thermography system.

In this technology, the resulting temperature fluctuations caused by locally differing thermal material properties are measured. These differences can be caused by a variety of manufacturing imperfections and result in a decreased heat dissipation, which can be reflected in measurably higher temperatures on the surface of the part.

The presented measurement and evaluation methods demonstrate the efficacy of detecting artificially introduced defects in additively manufactured samples of 1.4540 stainless steel. The examined defects exhibit a diameter range of 0.35 mm to 1 mm, with the capacity to identify them to a depth of 200 µm below the surface of the specimens. The results show the capabilities of the SPIT setup in non-destructive testing and its ability to deliver accurate and reliable detection of defects.

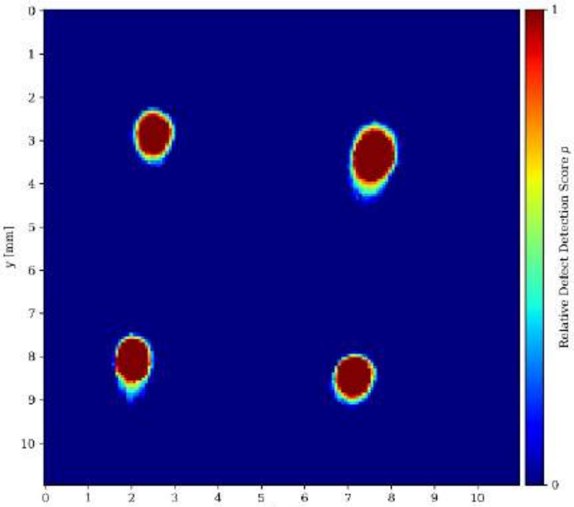
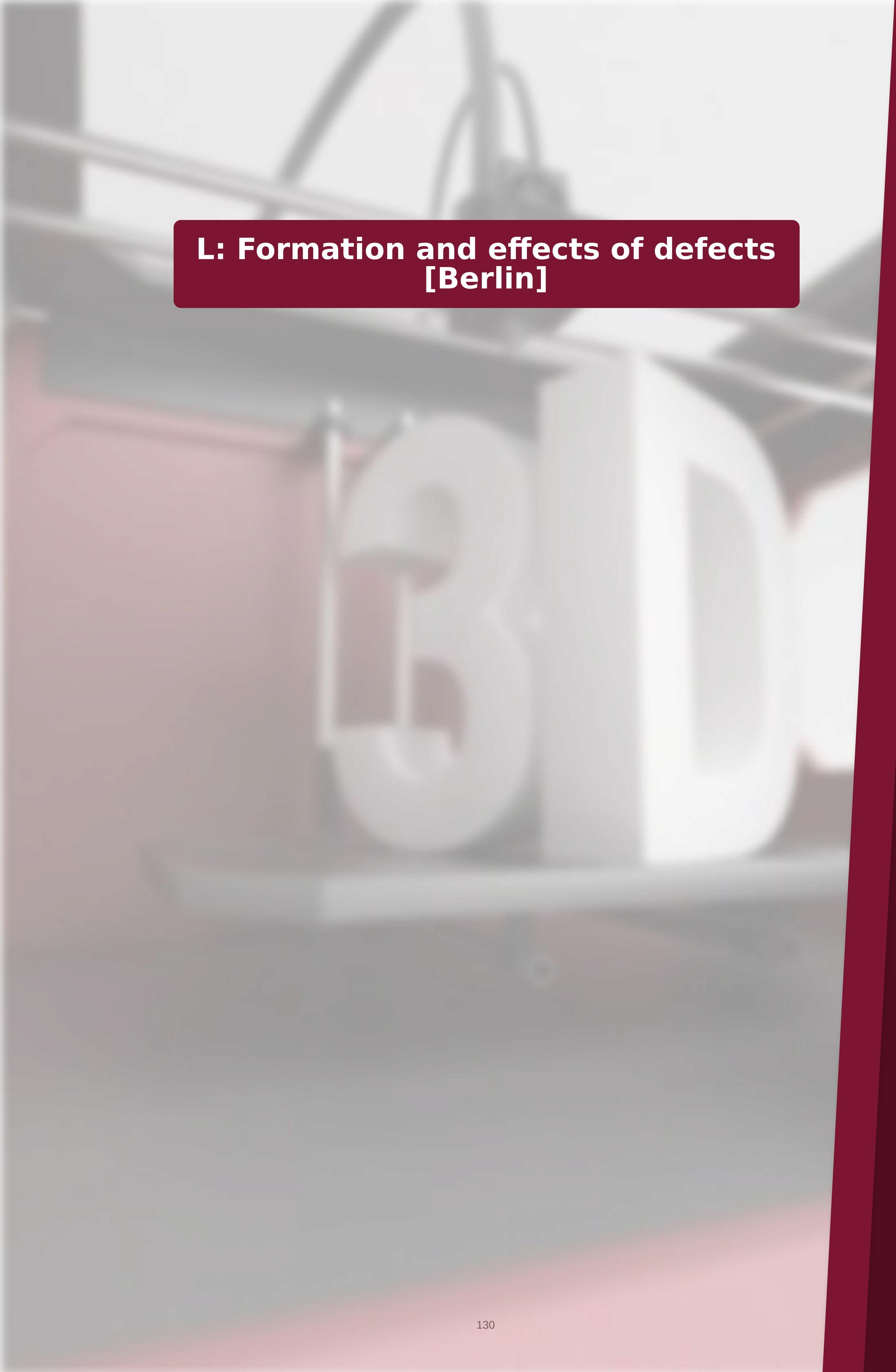


Figure 2. Active Thermography detection result of four defects with ⌀ = 1 mm, located 120 µm below the surface

[1] D. Höfflin, C. Sauer, A. Schiffler, und J. Hartmann, „Process Monitoring Using Synchronized Path Infrared Thermography in PBF-LB/M“, *Sensors*, Bd. 22, Nr. 16, Art. Nr. 16, Jan. 2022, doi: 10.3390/s22165943.

[2] D. Höfflin, C. Sauer, A. Schiffler, J. Manara, und J. Hartmann, „Pixelwise high-temperature calibration for in-situ temperature measuring in powder bed fusion of metal with laser beam“, *Heliyon*, S. e28989, Apr. 2024, doi: 10.1016/j.heliyon.2024.e28989.



L: Formation and effects of defects [Berlin]

Fatigue life and effect of defect for various engineering alloys made with laser powder bed fusion

E. Amsterdam[1*], W.W. Wits[1], M.L. Montero-Sistiaga[1], M. de Smit[1]

[1] Royal Netherlands Aerospace Centre (NLR), The Netherlands
*emiel.amsterdam@nlr.nl

Round specimens of AlSi10Mg, Ti-6Al-4V and Inconel 718 are printed with laser-powder bed fusion (L-PBF) and machined & polished to obtain the bulk material fatigue lives and exclude influences from surface roughness or porosity between the hatch and the contour lines. The fatigue lives give information on material properties and the maximum of the defect distribution inside specimens. Tensile and fatigue specimens are printed with different settings, because the mechanical properties and defect distribution can vary with build parameters, location & orientation and post processing. The long axis of the specimens are printed in three orientations with respect to the build direction. A selection of the Inconel 718 specimens received a hot isostatic pressing (HIP) treatment prior to the conventional heat treatment to obtain information on the effect of the HIP treatment on the defect distribution of the material. The results for Inconel 718 are compared with results from fatigue tests on Inconel 718 plate material that received a similar heat treatment. The results show significant higher fatigue lives for the printed material in all three orientations compared to the fatigue tests on Inconel 718 plate material and results from literature, despite the presence of typical defects such as porosity. Fractography and microstructural analysis indicate that the higher fatigue lives likely originate from the subcellular microstructure. For the Inconel 718 specimens that received a HIP treatment the grain structure changed, but the subcellular microstructure is partly retained, which results in fatigue lives between conventionally heat treated L-PBF material and plate material. The specimens of Ti-6Al-4V show lower fatigue lives compared to those of plate material in literature due to the presence of typical L-PBF defects such as porosity. Fractography on Ti-6Al-4V and AlSi10Mg specimens allowed to establish a fracture mechanics informed relationship between the size of surface defects, the applied stress and fatigue life. Hence, this general relationship can be used to determine the effect of defects on the fatigue life (see Figure 1).

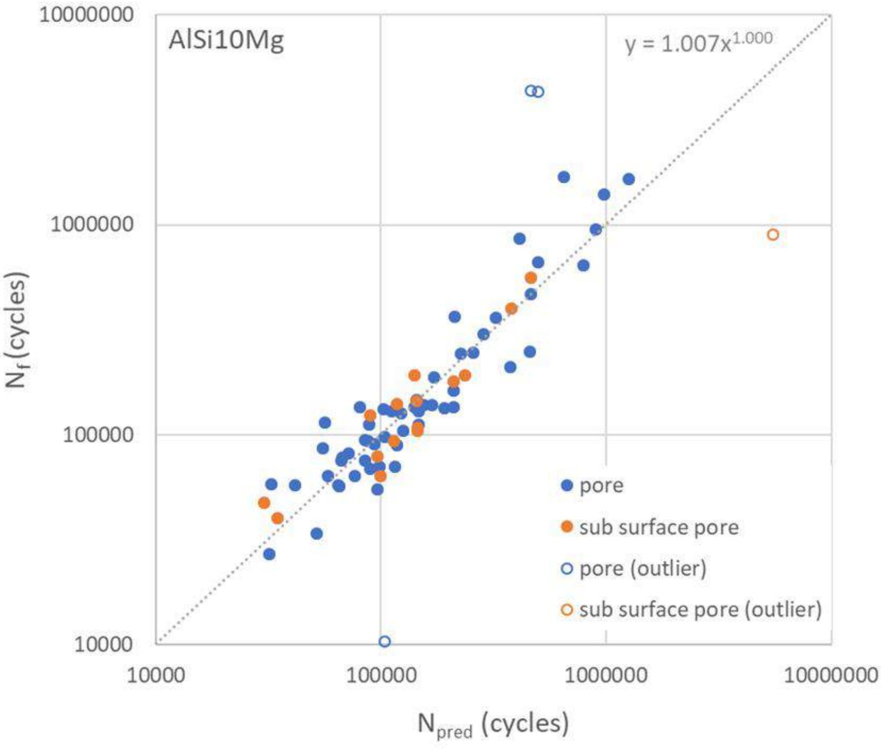
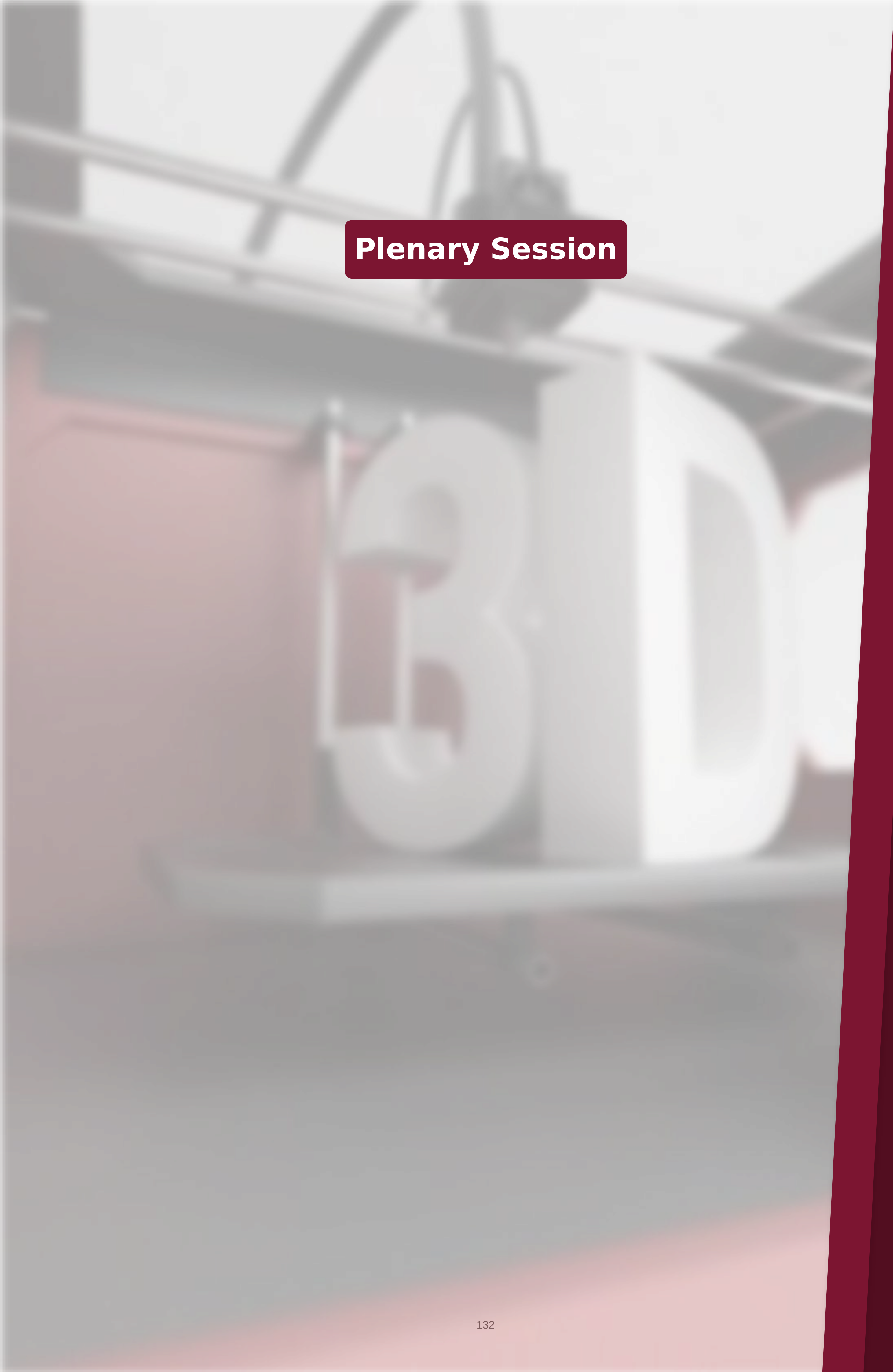


Figure 1. fatigue life as a function of the predicted number of cycles to failure for all AlSi10Mg samples.

Plenary Session



Additive Manufacturing in automotive industry

F. v. Lacroix[1*], A. Ruetjes[2], D. Fuchs[1],S. Sadeghi[1]
[1] Volkswagen AG,
*frank.lacroix@volkswagen.de

The industrial Additive Manufacturing (AM) market, including both metal and polymer systems, materials, and part manufacturing services, was assessed to be worth EUR 9.53 billion in the year 2022. As per projections, the AM market is expected to witness a robust compound annual growth rate (CAGR) of 17.7% from 2022 to 2027. With this anticipated growth, the overall market value is predicted to reach more than EUR 21 billion in sales by the end of 2027. Notably, the medical industry is the primary customer with a turnover of EUR 380 million in 2022. The automotive sector is also expected to remain a key player in the market [1]

The automotive industry is experiencing a rapid shift towards electric and smart mobility, necessitating faster development processes, increased efficiency, and enhanced performance. However, alongside technical considerations, there are significant challenges posed by environmental concerns and lengthy supply chains. In response, AM emerges as a promising solution, leveraging its inherent advantages, such as tool-free manufacturing, accelerated lead times, streamlined digital inventory management, optimization of performance-to-weight ratios, and the ability to enable mass customization [2, 3, 4, 5].

Laser Powder Bed Fusion (LPBF) is widely employed as the primary metal AM method in the automotive industry. Its strengths lie in the production of geometrically flexible and near-net shape components, successfully catering to various automotive use-cases, particularly high-performance applications in premium cars and custom tool manufacturing for further production technologies [6, 7]. However, despite its benefits, the widespread adoption of LPBF is constrained by its high costs [8]. As a promising alternative, Metal Binder Jetting (MBJ) has recently gained significant attention in the sector due to its faster build rates and potential for small to medium mass production manufacturing [9].

Despite the continuous advancements in metal AM processes, the automotive industry has not fully embraced it as a robust and cost-effective manufacturing technology. The sector's emphasis on high standardization, repeatability, and safety has hindered the widespread adoption of metal AM. To establish metal AM in the automotive sector, several critical actions need to be taken to address challenges related to part quality, process reproducibility and costs, as well as environmental impacts. The paper discusses the current obstacles and essential areas for improvement in MBJ and LPBF. Key focus areas include material costs, machine reliability and reproducibility, process automation and digitalization, optimizing build volumes and speed, as well as employing innovative think-additive methodologies. Successfully addressing these challenges is imperative to enhance the technological readiness level of metal AM and unlock its potential in the automotive industry [3, 4, 8, 9].

References

[1] AMPOWER GmbH, "AMPOWER REPORT 2023 Additive Manufacturing Market Report," 2023.

[2] A. Charles, A. Hofer, A. Elkaseer and S. G. Scholz, "Additive Manufacturing in the Automotive Industry and the Potential for Driving the Green and Electric Transition," in *Sustainable Design and Manufacturing*, Springer Singapore, 2022.

[3] S. Basak , M. Baumers, M. Holweg , R. Hague and C. Tuck , "Reducing production losses in additive manufacturing using overall equipment effectiveness.," *Additive Manufacturing,* vol. 56, p. 102904, 2022.

[4] A. Menekse, A. V. Ertemel and H. C. Akdag, "Additive manufacturing process selection for automotive industry using Pythagorean fuzzy CRITIC EDA," *Plos one,* vol. 18(3), 2023.

[5] Markforged, "How 3D Printing Drives Change in the Automotive Industry," [Online]. Available: https://markforged.com/de/resources/blog/how-3d-printing-drives-change-in-the-automotive-industry. [Accessed 12 July 2023].

[6] AMFG, "10 Exciting Examples of 3D Printing in the Automotive Industry in 2021," 28 May 2019. [Online]. Available: https://amfg.ai/2019/05/28/7-exciting-examples-of-3d-printing-in-the-automotive-industry/. [Accessed 12 July 2023].

[7] S. Hendrixson, "Real Examples of 3D Printing in the Automotive Industry," 18 May 2021. [Online]. Available: https://www.ptonline.com/articles/real-examples-of-3d-printing-in-the-automotive-industry. [Accessed 12 07 2023].

[8] J. C. Vasco, "Chapter 16 - Additive manufacturing for the automotive industry," in *In Handbooks in Advanced Manufacturing*, Elsevier, 2021, pp. 505-530.

[9] M. Freeman, "Overcoming Cost Barriers of Metal-Binder-Jet Additive-Manufacturing for Automotive Product Applications," 2022.

Industrializing Additive Manufacturing: Advancing Production through Technology Integration

Christian Fleißner-Rieger*
*Materialise GmbH, Konrad-Zuse-Straße 7, 28357 Bremen, Germany

Additive Manufacturing (AM) has evolved from a prototyping technology to a disruptive force in the manufacturing industry. Although the metal AM market has expanded continuously over several years, the focus of the customer has shifted. While manufacturers and customers recognize the benefits, lack of experience continuously hinders an extensive utilization and seamless integration of the 3D printing technology into their existing processes.

While the metal 3D printing process itself is manageable, challenges arise in design-for-additive manufacturing, standardization, and the sustainable integration of post-processing techniques, such as machining and surface finishing. In light of these challenges, this presentation aims to emphasize the crucial steps for a successful implementation of the metal additive manufacturing technology. Moreover, it also provides an overview of strategies to catalyze the transfer process, leading to a smoother adaptation of AM.

Illustrating the practical application of these principles, Figure 1 showcases a practical example—a depiction of 3D-printed injection rings. These innovative components resulted from a collaboration between CMB.TECH and Materialise manufacturing in 2023. The engineers at CMB.TECH swiftly leveraged the advantages of AM, capitalizing on design freedom to create a unique product. The outcome will be a fleet of trucks operating with a dual-fuel (hydrogen and diesel) system, where the injection rings played a vital role in mixing hydrogen with air for the combustion process. This reduces the need for oil-based fuel and step-by-step contributes to an even more ambitious goal of CMB, a CO2 reduction of Diesel engines by 80% in 2050 [1].

Figure 1. CMB.TECHS hydrogen injection rings made of AlSi10Mg by Materialise showcase the industry's successful implementation of metal 3D printing.

References

[1] Materialise NV, (**2023**), How 3D Printing's Design Freedom Empowers Sustainable Dual-Fuel Hydrogen Technology, accessed on January 16th, 2024, www.materialise.com/en/inspiration/articles/cmbtech-converting-diesel-engines.

Short biography of the author: *Christian Fleißner-Rieger received his doctoral degree at the Montanuniversität Leoben, Austria, and is currently responsible for material and process development activities at Materialise. In his work, he deals with novel applications and software products used in metal 3D printing.*

Metal AM serial production in Aerospace industry

T. Bielefeld[1*]

[1] PREMIUM AEROTEC (a busines unit of AIRBUS GmbH)
*thomas.bielefeld@premium-aerotec.com

Since more than a decade tremendous work and money had been invested to develop and qualify AM of metals for Aerospace application. Powderbed fusion became the most commonly applied process when talking metal AM serial production of Aerospace parts. Meanwhile also first DED parts have been qualified for Aerospace and serial production by wire arc additive manufacturing is ramping up. Up to now Aerospace industry focuses on only few materials like Inconel® and Ti6Al4V, but there are many other materials used, at least in niche applications.

Figure 1. Titanium bracket manufactured by powderbed fusion.

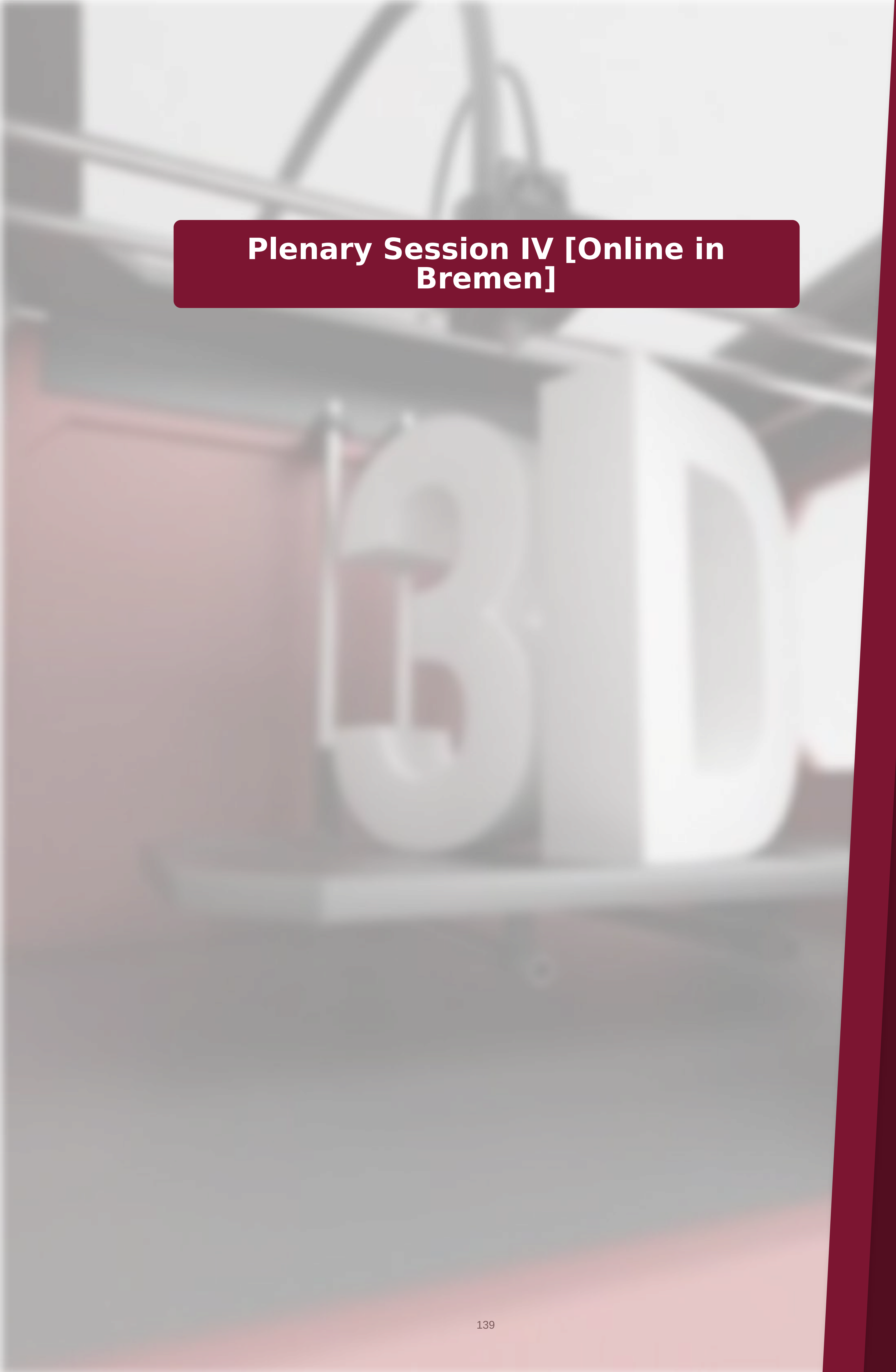
The paper illustrates the industrialisation of metal AM from an exotic process for demonstrators and unique parts towards an established and trusted serial production process for Aerospace parts. Metal AM is capable to deliver homogeneous material properties at highest quality and reproducibility. Moreover, the cost situation had been improvement by factors, the design freedom remains unchallenged and the sustainability of AM Aerospace parts over the complete life cycle exceeds traditional production by far.

Quality, Cost and Capability of 3D Printing

X.Wu[1, 2, 3*]; A. Huang[2]; T. Jarvis[2]; W.H. Kan[2]; Z. Chen[1,3]; H. Zhang[2]; S. Wu[1,3]
1. AmPro Innovations Pty Ltd, Melbourne, Australia
2. Monash University, Melbourne, Australia
3. Soochow University, Suzhou, China

*x.wu@amprogroup.com.au

Following the effort over the last decade, 3D printing has been studied broadly and used in aerospace, biomedical and civil sectors. In industrial applications, issues such as defects, consistency, powder recycling, cost and size capability become extremely important. This talk will discuss the formation of porosity, influence and elimination of porosity, mechanical properties, efficiency and cost of 3D printing for a large quantity of components in particular Ti alloys. In terms of size capability, a machine with the size of 1200x600x1500mm, equipped with 12 lasers, has been developed and it has found the printing speed using such machine has been increased dramatically. In addition cracking of Ni superalloys, such as Inco 738, CM247LC, has been a major problem and a new 3D printer has been developed to successfully resolve this problem. The latest results in those áreas will be reported.



Plenary Session IV [Online in Bremen]

High-performance non-destructive techniques for quality assurance of complex-geometry additively manufactured parts

A-F. Obaton[1*]

[1] French National Metrology Institute (NMI), Laboratoire national de métrologie et d'essais (LNE), Paris, France
*anne-francoise.obaton@lne.fr

As additive manufacturing (AM) is more and more used in industry, the quality control of AM parts is becoming increasingly important. Commonly used non-destructive testing (NDT) techniques for parts conventionally manufactured may no longer be adapted for AM parts. Indeed, AM parts can have much more complex geometries, such as lattices, can contained internal features, and their surfaces can be very rough. Several NDT techniques have been investigated for AM parts [1-8]. Among them, the two most suitable for complex geometries are X-ray computed tomography (XCT) [1, 5] and Resonant Ultrasound Spectroscopy (RUS) [1, 5, 8]. They are both volumetric NDT techniques. XCT provides a three dimensional (3D) image of the volume of the parts enabling to detect and localise defects, and to perform dimensional measurements. RUS, including swept-sine and impulse excitation (Fig. 1) methods [8], provides the frequency spectrum of the vibrational modes of a part, mechanically excited, that needs to be compared to the spectra of other parts from the same family to detect change in geometry or density or elasticity of the part, or to detect if the part is defective. XCT and RUS are actually complementary techniques. RUS is a global and comparative technique requiring a set of parts from the same family, but it is fast, cheap, easy to use, and enables testing large and dense parts. XCT is an expensive technique, requiring skills, and is not suitable for large and dense parts, but it provides a 3D image of the whole volume.

The talk will address these two techniques and will show relevant results obtained on AM parts. It will also present the results of studies to evaluate the reliability of these techniques.

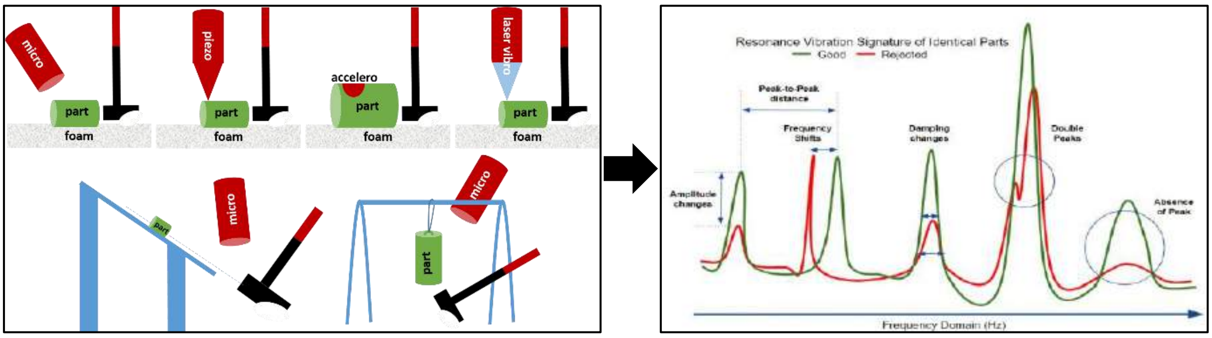


Figure 1. Schematic of the Impulse Excitation Methods (IEM).

References

[1] E, Todorov; R, Spencer; S, Gleeson; M, Jamshidinia; and M, Kelly Shawn; "America Makes: National Additive Manufacturing Innovation Institute (NAMII) Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures," *Interim Report*, 2014.

[2] "Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts after Build," *E3166-20, ASTM International, West Conshohocken, PA,* 2015.

[3] A-F, Obaton; M-Q, Lê; V, Prezza; D, Marlot; P, Delvart; A, Huskic; S, Senck; E, Mahé and C, Cayron; "Investigation of new volumetric non-destructive techniques to characterise additive manufacturing parts", *Weld World, Vol. 62, Issue 5, pp. 1049-1057,* 2018, https://doi.org/10.1007/s40194-018-0593-7.

[4] A.-F, Obaton; "Overview of the EMPIR Project: Metrology for Additively Manufactured Medical Implants", *Euspen*, 2019, https://www.euspen.eu/knowledge-base/AM19106.pdf.

[5] A-F, Obaton; B, Butsch; S, McDonough; E, Carcreff; N, Laroche; Y, Gaillard; J, Tarr; P, Bouvet; R, Cruz; A, Donmez; "Evaluation of Nondestructive Volumetric Testing Methods for Additively Manufactured Parts". *Structural Integrity of Additive Manufactured Parts, West Conshohocken, PA, pp 51–91*, 2020.

[6] J, Wilbig; F, Borges de Oliveira; A-F, Obaton; M, Schwentenwein; K, Rübner; J, Günster; "Defect Detection in Additively Manufactured Lattices", *Open Ceramics 100020*, 2020.

[7] "Additive manufacturing of metals - Non-destructive testing and evaluation - Defect detection in parts", *ISO/ASTM TR 52905*, 2023.

[8] A.-F, Obaton; "Resonant Ultrasound Spectroscopy Testing Methods in Additive Manufacturing", *Additive Manufacturing Design and Applications, Vol 24A, ASM Handbook,* 2023, ISBN: 978-1-62708-437-6.

Author index

IMPRINT – IMPRESSUM

4TH Symposium on Materials and Additive Manufacturing - ADDITIVE 2024 – Book of Abstracts

Editor: Prof. Dr. Vasily Ploshikhin, University of Bremen

Symposium Organization:
Deutsche Gesellschaft für Materialkunde e.V. (DGM)
Kamillenweg 16-18
53757 Sankt Augustin
Germany

T +49 (0) 69 75306 750
F +49 (0) 69 75306 733
E-Mail: dgm@dgm.de
Web: www.dgm.de

ISBN 978-3-88355-440-2

DGM
The network for
materials science
and **engineering**