Newsletter #1

ENABLING LASER POWDER BED FUSION

FOR HIGH PRECISION MASS PRODUCTION OF MULTI-MATERIAL COMPONENTS ON DISSIMILAR SUBSTRATE MATERIALS

01. Key Idea & Demonstrator

While laser powder bed fusion (LPBF) inherently allows the production of complex geometries it isn't yet introduced to mass markets due to prohibitive cycle times and uncompetitive product precision and quality.

A hybrid production where complex components using LPBF's flexibility are built on top of conventionally manufactured substrates at near-net-shape geometry can speed up the production process dramatically and may open up the road towards mass production as is shown with a demonstrator from power electronics application:

As a demonstrator the additive manufacturing of cooling elements directly printed onto ceramic based power electronics substrates is chosen. The objective here is to assemble the cooling elements much closer to the component (cf. Fig. 1, right), significantly increasing cooling performance, compared to current solutions which rely on soldering of separate coolers onto the electronic substrates and thus exhibit a much longer thermal path (cf. Fig. 1, left). Furthermore, current cooling elements are very limited in terms of their geometric design while with additively manufactured cooling elements, there is almost unlimited design freedom resulting in a further potential to increase the cooling performance. The increase in cooling performance allows for new electronic designs resulting in a smaller case volume (increased energy density), a weight reduction of the electronic product, and a higher performance of the semiconductor chips inside the electronic element.

A further advantage of directly printing the cooling elements is that no additional assembly work is required, and material is saved due to the replacement of soldering.

The EU-funded project GlobalAM was launched on 01.01.2024 and aims to advance and combine existing state-of-the-art approaches, namely beam shaping, beam splitting, in-situ geometry correction, and process monitoring + control in an advanced machine concept that allows fixation of multiple substrates and laser beam positioning to produce components on a large scale.

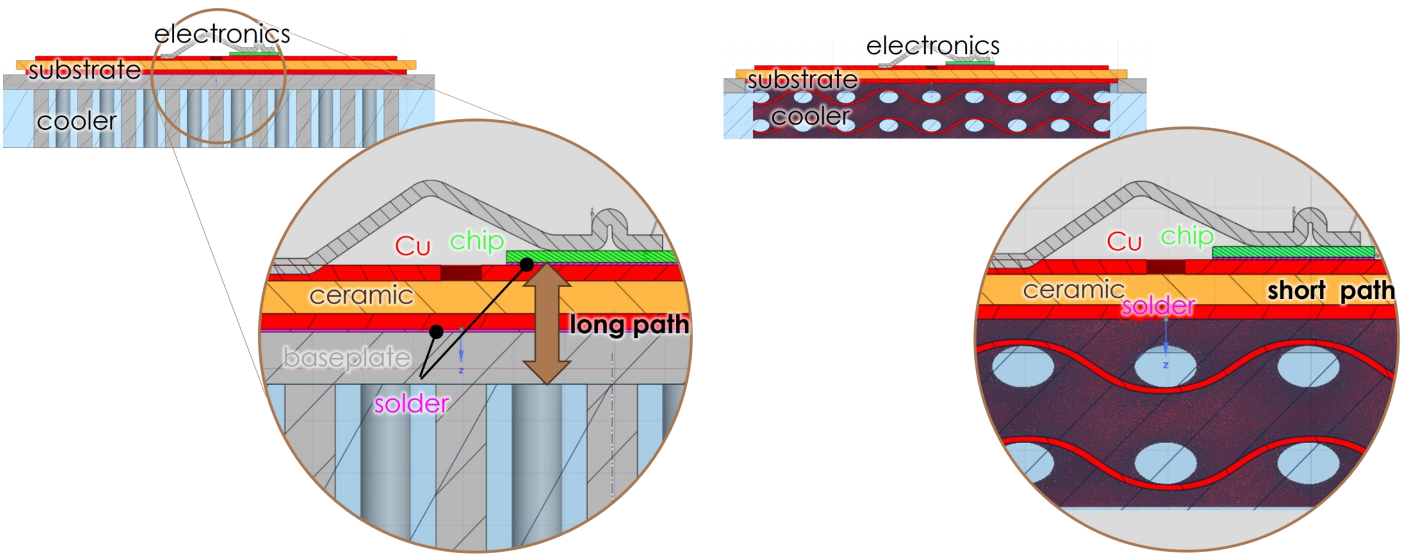

Fig. 1: *Long cooling path, limited cooling performance, limited geometrical freedom, extended assembly (left). Short cooling path, high cooling performance, geometrical complexity for free, integrated production process (right).*

02. Consortium

AMAZEMET is a spin-off company of the Warsaw University of Technology. The company focuses on metal 3D printing, particularly in the areas of new materials, R&D, and industrialisation. The solutions offered allow the production of metallic powders from any alloy, suitable for various applications (e.g. 3D printing). The company also develops post-processing solutions, such as compact high-vacuum laboratory furnaces.

AMAZEMET maintains a strong connection with academic researchers by participating in collaborative research activities focused on developing new materials for additive manufacturing and partnering with universities and companies around the world in various projects.

Tasks in GlobalAM:

- Manufacturing of powders with tailored chemical composition
- Optimisation of the atomisation process for selected materials

The Bosch Group is a leading global supplier of technology and services. Its operations are divided into four business sectors: Mobility, Industrial Technology, Consumer Goods, and Energy and Building Technology.

The Bosch Group comprises Robert Bosch GmbH and its roughly 470 subsidiaries and regional companies in over 60 countries. Including sales and service partners, Bosch's global manufacturing, engineering, and sales network covers nearly every country in the world. The basis for the company's future growth is its innovative strength. At 136 locations across the globe, Bosch employs some 90,000 associates in research and development, including the Bosch Research team as well as nearly 48,000 software engineers.

Tasks in GlobalAM:

- Contribution to the project boundary conditions for a production on an industrial scale
- Integration of modelling, monitoring, material development and machining concepts into industrial process development activities with a special focus on near-net-shape production and residual stress management
- Responsible for the production of a demonstrator which combines the project developments and which is assessed in terms of its functional properties

DTU is an internationally recognised technical university with the objective of utilising the technical and the natural sciences for the benefit of society. We have a strong focus on combining fundamental science and application in an industrial and business-oriented approach with focus on sustainability, digitalisation, and high-class engineering education.

Tasks in GlobalAM:

- Multiphysics simulations of metal additive manufacturing processes with non-standard beam shaping
- High-fidelity computational fluid dynamics simulations
- Thermo-mechanical simulations at solid state
- Part-scale and AI-based reduced order models

Prima Additive develops industrial systems for metal additive manufacturing with two different technologies based on the use of lasers: Powder Bed Fusion and Direct Energy Deposition. In addition to the machines, Prima Additive provides consultancy and support to its customers, accompanying them throughout the process of adopting the technology in their production context: from design optimisation to the choice of materials, to the study of the business case up to the choice of most suitable machine.

Tasks in GlobalAM:

- Elaboration of process parameters and laser configuration to work different metal materials with high quality
- LPBF machine redesign and adaption in order to accommodate the new sensors and print particular features on the existing part

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Politecnico di Milano is among the leading scientific and technological universities in Europe, and it is the largest technical university in Italy. According to QS Ranking 2024, Politecnico ranks 23rd worldwide position in Engineering and Technology, and 9th in the field of Mechanical, Aeronautical & Manufacturing Engineering. Established in 1863, Polimi trains engineers, architects, and industrial designers. Education is at bachelor, master's, and PhD level.

Currently more than 1,300 professors and researchers work at the university and 42,000 students study in 7 different campuses. Polimi is organised in 12 departments including all main areas of engineering, architecture and industrial design. Polimi belongs to IDEA League (http://idealeague.org/) and Alliance4Tech (http://www.alliance4tech.eu/) EU networks, which will be a key element to enhance the exposure of ESRs to international and multi-cultural networks and to improve the impact on their careers. The department of Mechanical Engineering has more than 100 faculty members, about 200 PhD and post-PhD and 40 members of the technical and administrative staff. Since 1951, the Department of Mechanical Engineering (DMEC) of Politecnico di Milano represents one of the top scientific institutions in the field and it has been recently recognised (January 2018) among the 180 "Excellent Departments" in Italy.

A network consisting of over 250 companies acts as a strategic partner for the development of research.

The main research lines include materials, methods and tools for product design, manufacturing and production systems, machine and vehicle design, measurements, dynamics, and vibration.

Competitive research projects, as well as those related to product innovation and services, are developed, accounting for approximately EUR 7 million per year, of which 70% come from the private industrial sector and 30% from public funding (National Ministries and European Community). The department of Mechanical Engineering makes state-of-the-art laboratories and large spaces available to its teachers, researchers and students to carry out cutting-edge research. They include the AddMe.Lab, the laboratory of additive manufacturing (AM), a unique centre for experimentation, the creation of new process solutions, the design of new materials and the development of new methods of design for additive manufacturing.

Tasks in GlobalAM:

- Robust in-situ defect detection
- Layerwise adaptive control for thermal stress mitigation/avoidance
- Hybrid / metamodelling to augment process monitoring and control
- Fine laser positioning to accurately build up on substrates

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SAFINA

Safina is a manufacturer of copper alloy and precious metal products with a long tradition. A broad portfolio of products for the glass industry, electronics, laboratory equipment and the rapidly growing additive manufacturing industry. Our materials are used by the world's leading manufacturers of additive technologies such as Laser Powder Bed Fusion, Direct Energy Deposition or Binder Jetting. Alloys for the production of atomised powder are prepared in the company's metallurgical plant and the gas atomised material is tailored to specific requirements.

Tasks in GlobalAM:

- Development and production of gas atomised copper
- Verification of the manufacturability of the selected alloy or metal on an industrial scale
- Understanding the life cycle of atomised copper (material degradation)
- Recycling & modifying selected gas atomised materials

UNIKASSEL VERSITÄT | MASCHINENBAU

The department of Metallic Materials of the Institute of Materials Engineering at the University of Kassel focuses on process-microstructure-property-damage relationships in conventionally and additively processed metallic materials. Generally, the research interests can be departed into four main groups. Besides Additive Manufacturing (AM) and Shape Memory Alloys (SMA), the activities in the department focus on residual stresses as well as fatigue and damage.

In case of AM, powder bed processes (PBF-LB/M and PBF-EB/M) as well as laser metal deposition / direct metal deposition (LMD/DED/DMD) are used to realise microstructurally and functionally graded components. Research activities include the realisation and in-depth characterisation of filigree lattice structures. In-situ characterisation techniques are widely employed to assess microstructure-property relationships on the local scale. A special emphasis is on the development of novel alloys for AM. Based on a profound knowledge of the open challenges in AM, i.e. porosity, anisotropy, residual stress, chemical heterogeneity, surface roughness, limited damage tolerance, etc., new alloy designs are proposed and assessed to overcome such issues. So far, the focus was on metallic alloys for structural applications, e.g. Ti-6Al-4V, aluminium alloys, stainless steels, and Ni-based superalloys, however, within the last few years also numerous

SMAs processed by AM were investigated. The department of Metallic Materials has access to numerous advanced characterisation methods.

Lab-based experiments including mechanical tests (under quasi-static and cyclic loading), optical microscopy, high-resolution electron microscopy, transmission electron microscopy, computed tomography (CT), X-ray diffraction (texture, phase fractions and residual stress) as well as mechanical residual stress measurements by means of the hole drilling method are further supported by in-situ experiments based on Neutron- and Synchrotron-diffraction. Not only the use of well-established approaches is considered, but also new and efficient approaches, e.g. for screening of material properties are elaborated and assessed.

Tasks in GlobalAM:

- Methodology and test description for residual stress measurements
- Characterisation of all current XRD methods for high resolution residual stress measurement with respect to validity and stability
- Assessment and refinement of selected experimental methods
- Mutual validation of the residual stress measurements by results from simulation
- Residual stress measurements in components with complex geometries
- Evaluation of the process conditions on the residual stress development

EurA AG has been established in Ellwangen (Baden-Württemberg, Germany) in 1999. The company currently employs more than 200 persons on 15 locations. As an innovation service provider, EurA advises more than 2600 companies all over Europe, covering all industrial sectors. From the beginning, one emphasis lay on the manufacturing sector as one of the most innovative, challenging, and interesting sectors. EurA accompanies its customers along every stage of the innovation process, providing services ideally tailored to the individual needs of the respective partner.

The portfolio ranges from the development of a general company or innovation strategy based on a thorough business plan, over the determination of the financial aspects, the initiation and mediation of promising partnerships, the implementation of innovative products, technologies and services, up to the development of appropriate commercialisation strategies and the market introduction of those innovations.

Tasks in GlobalAM:

- Project administration (assistance of the coordinator Robert Bosch)
- Implementation of a life cycle assessment for the significantly improved AM processes
- Development of an appropriate exploitation and replication strategy for the project

03. Project Progress

Project Structure

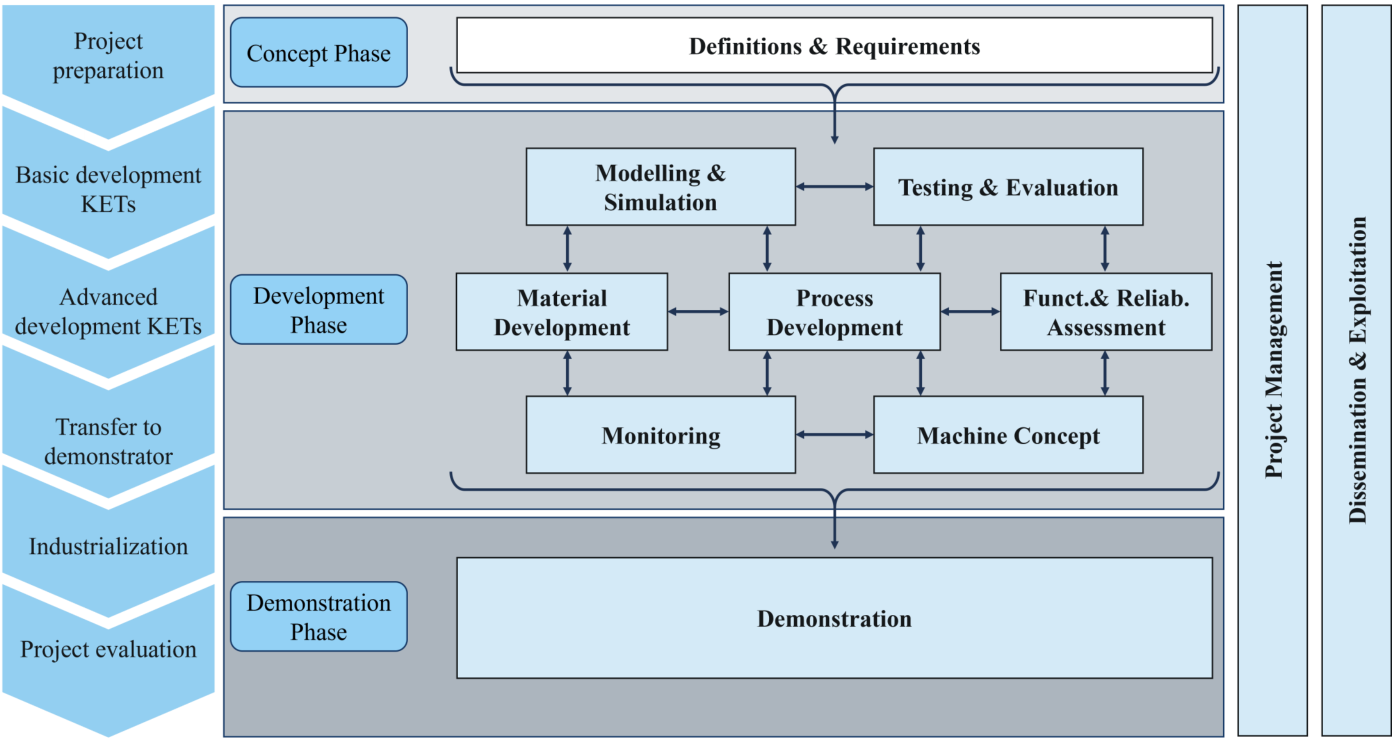

Fig. 2: *Project structure of GlobalAM: KET indicates the 9 key enabling technologies developed in the project, namely: substrate positioning, substrate fixation, beam splitting, beam shaping, high resolution residual stress analysis, multi-material powders, multi-scale & hybrid modelling, process & defect monitoring, in-line defect compensation.*

In order to achieve the objectives, GlobalAM is structured 6 development steps which are shown on the left-hand side of Fig. 2. These development steps consist of a requirements capturing part focusing on the specific challenges of multi-material hybrid LPBF, a basic design and development phase in which the basic methods and approaches for the Key Enabling Technologies (KETs) are specified, an applied development phase which delivers the actual tools and technologies (i.e. the KETs), a transfer part which applies the developments to the demonstrator, an industrialisation part to improve results in terms of economics, efficiency, reliability, and a key evaluation phase that will compare achievements to project goals and address environmental aspects. The technical work packages are parallelised by work packages which address impact generation activities necessary for an efficient dissemination and exploitation of project results.

In the following the results of the two public deliverables at the end of the basic development step, namely *Melt pool and part scale modelling (D2.1)* and *Refinement residual stress analysis (D2.4)*, are presented.

D2.1 - Melt Pool and Part Scale Modelling

Goals

In laser powder bed fusion large temperature gradients lead to considerable (residual) stress which in turn can cause damage and needs to be controlled if applied to an industrial environment. Therefore, a quantitative description of the physical phenomena by high fidelity models is necessary for a thorough process understanding. Due to the complexity of the phenomena involved, different models are developed to describe different aspects such obtaining a complete picture while keeping computational effort to practical limits. A melt pool model (MPM) is developed to describe the thermo-fluidic behavior characteristic for the molten state of powder as a function of process parameters and physical properties. A deposition scale model (DSM) is used to describe the thermo-mechanic behavior, namely the development of mechanical stress as a function of the melt pool dimensions.

In deliverable D2.1 the validation of MPM against experimental data is described. Also, the advancements in deposition scale modelling are summarised. Experimental data was obtained by Robert Bosch and taken from literature, model development and validation were accomplished by DTU.

The challenge in validating the named models is that physical quantities such as temperatures and residual stress are hard if impossible to determine in sufficient resolution and accuracy. Therefore, properties which can be derived from the state variables must be used for validation. In WP2 the focus was on validating the thermal behavior by comparing the melt pool dimensions obtained from simulation against the melt pool dimension obtained from metallographic cross-sections.

Status

In WP2 a MPM was set-up which describes the thermo-fluidic behaviour of a melt pool as developed during laser powder bed fusion of metals. The model describes physical phenomena related to laser absorption, fluid dynamics (e.g. Marangoni flow, recoil pressure, …), heat transfer (conduction, convection, radiation) and phase transition (melting/solidification, evaporation/condensation). Required inputs include local absorptivity, process parameters such as scan speed and laser power and the physical properties of the solid/liquid/gas phase materials. The model allows to calculate the transient temperature field from which the melt pool dimensions and the surface morphology can be derived.

Also, in WP2, a DSM was set-up, which describes the coupled thermo-mechanical behaviour. It considers the melt pool as a moving heat source causing changes in temperature and through thermal expansion induces mechanical stress. Required inputs are the melt pool dimensions, process parameters such as scan speed and laser power and the physical properties of the material. The model allows to calculate the transient temperature and stress field and can be applied to larger domains due to its reduced level of complexity.

Once the models were set-up they were validated against single track experiments. For this, Robert Bosch provided different test samples: from pretrials single track experiments on a solid copper plate were available which later were completed with single track experiments on the project substrate.

Additional validation data was obtained from literature sources. Validated models could then be used for first variations in process conditions, e.g. applied to different materials and beam shapes.

Results & Next Steps

In setting up the melt pool model, it became apparent that melt pool dimensions are extremely sensitive to the temperature predictions if copper is used instead of conventional materials such as e.g. AISI 316L. This is due to an approximately 20 times higher thermal conductivity of copper compared to AISI 316L. Due to this extreme conductivity small deviations in temperature suffice to extremely change predicted melt pool dimensions, cf. Fig. 3, left. It also turned out, that literature data for radiation absorptivity ranges from as low as 3% to values up to 50% which can be attributed to the fact, that absorption depends on the state of the surface, namely its temperature and surface morphology, resulting in what is termed conduction and keyhole welding. Applying the right local absorptivity, the melt pool dimensions measured by Bauch et al.[1] could be successfully obtained from model calculations within an accuracy of 15%.

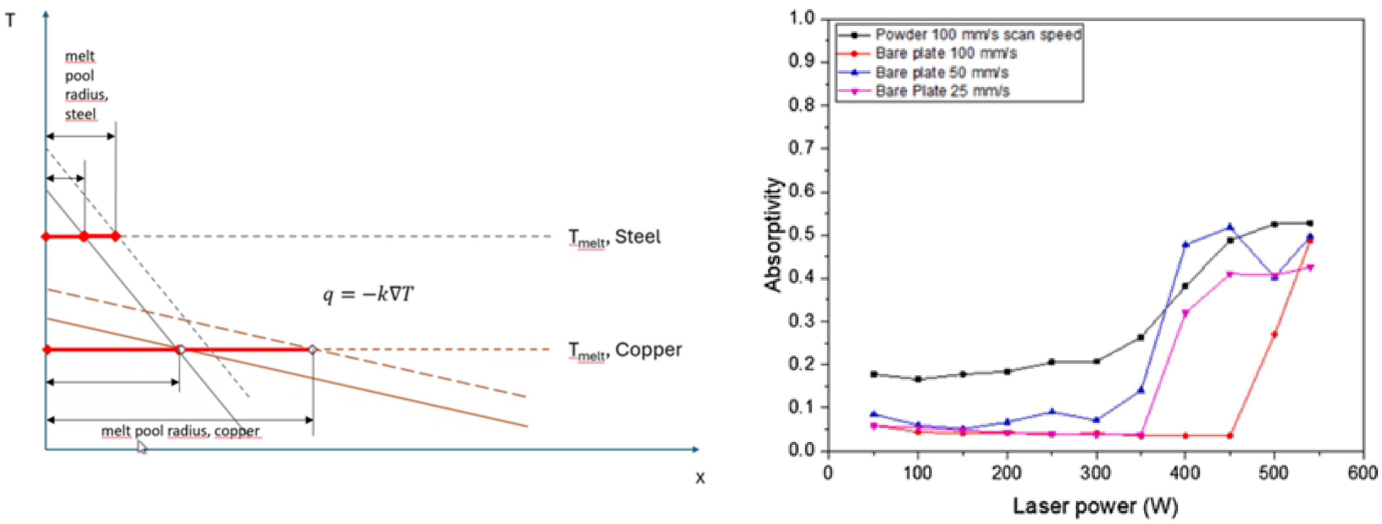

Fig. 3: *Schematic to illustrate the high sensitivity of melt pool dimension x as a function of temperature T for steel and copper (left). For the same change in temperature (dashed vs. solid lines) the change in melt pool dimension for copper is considerable larger due to its much higher thermal conductivity k. Effective absorptivity as a function of laser power as taken from Bauch et al.[1] (right). The effective absorptivity suddenly increases from effective absorptivity of ≈ 20% (for powder) to values up to ≈ 50% as the melt pool changes from conduction mode to keyhole welding.*

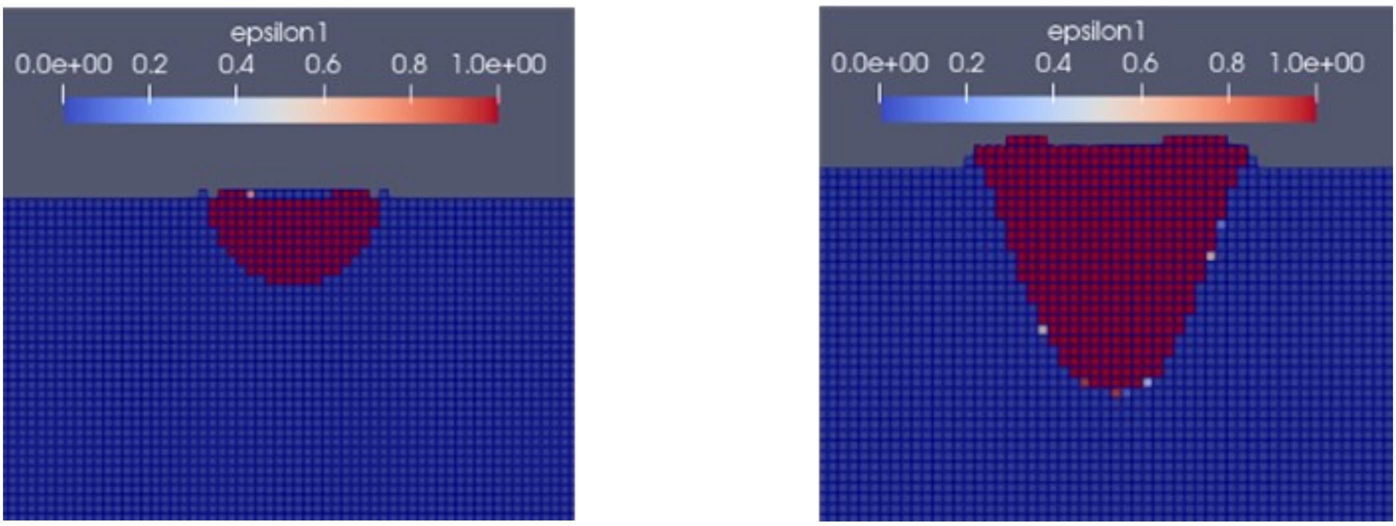

Fig. 4: *Melt pool dimension as determined from MPM for different process conditions. Left: 400 W laser power, 0.5 m/s scan speed, 62 µm spot size and a local absorptivity of 0.2 leads to an effective absorptivity of ≈ 0.2 corresponding to a conduction mode behaviour with a shallow melt pool. Right: Increasing power to 500 W, 0.5 m/s scan speed, 62 µm spot size and 0.2 as local absorptivity leads to an effective absorptivity of ≈ 0.5 corresponding to a behaviour similar to keyhole welding with a deep melt pool.*

Bauch et al. 2023, [DOI: 10.2351/7.0001118]

Examples are shown in Fig. 4. Deviations in predicting the melt pool dimensions from the preliminary experiments of Robert Bosch on a copper plate must be attributed to the oxidised surface of the experimental specimen which presumably changed the absorptivity and – due to the above mentioned very high sensitivity of melt pool dimension on temperature – also the effective melt pool dimensions. Therefore, further validations with melt pool dimensions obtained from single track experiments on non-oxidised project substrates are currently processed.

Also, the thermal portion of the DSM was successfully validated against single track experiments. This was done not only for copper and a standard Gaussian beam profile but also for Ti64 alloy and a ring spot beam profile. From the temperature fields obtained, the stress field could be determined as shown in Fig. 5. together with their corresponding residual stress depth profiles in the middle of the hatch line. Clearly, Ti64 exhibits a much higher maximum residual stress compared to copper, which is attributed to the low tensile strength of the latter. Also, the two materials differ in terms of the depth at which the maximum residual stress is observed. In case of copper the maximum residual stress occurs at 50 µm while for Ti65 it falls between 150-200 µm which corresponds in both cases to the melt pool depth. Besides, the effect of changing beam profile from Gaussian to ring spot can be studied and shows reduced melt pool depth which is also expressed in a reduced depth at which the maximum residual stress is obtained. Next steps aim to validate the mechanical portion of the DSM by results from residual stress measurements and to speed up the simulation by applying a flash heating approach.

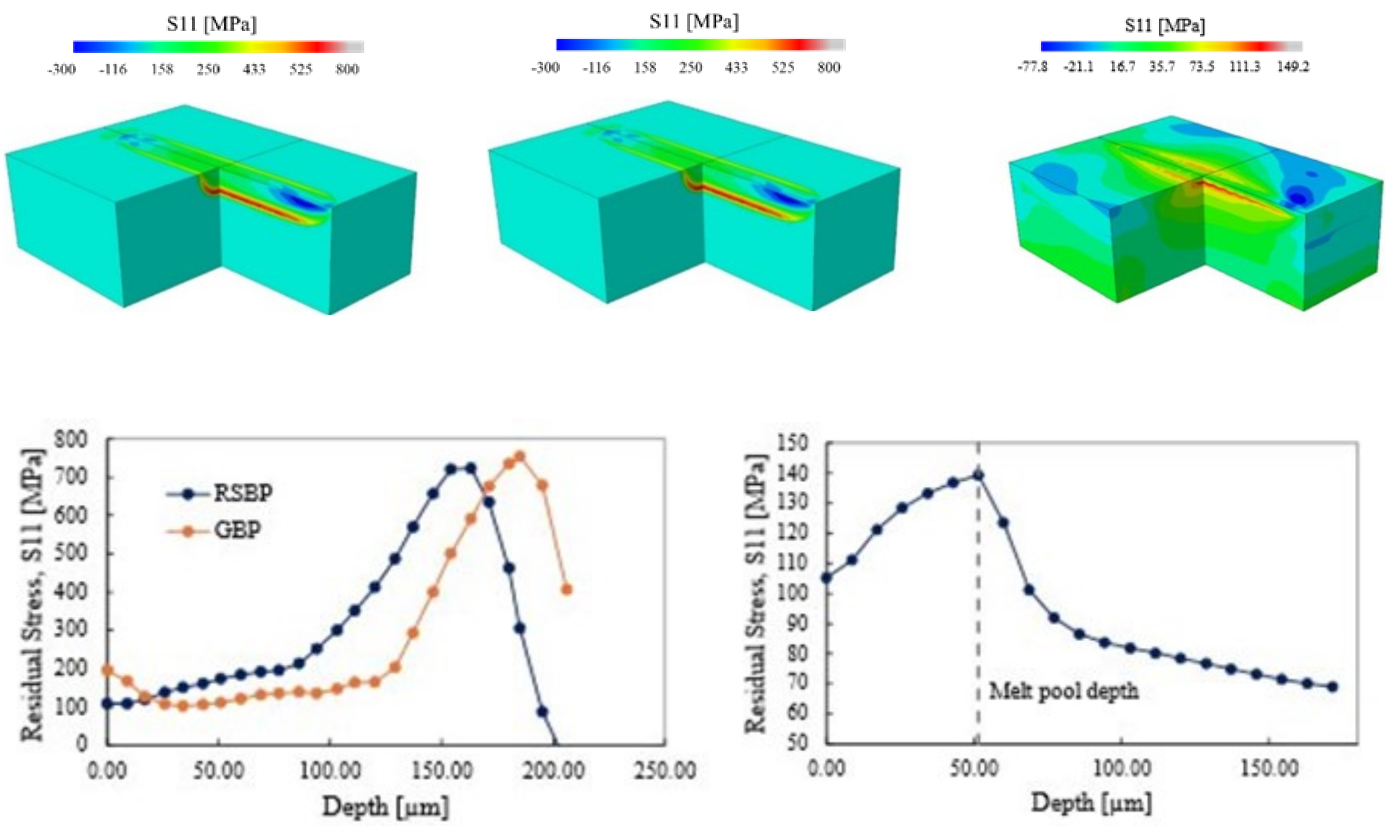

Fig. 5: *Mechanical stress as determined from the deposition scale model for Ti64, Gauss beam profile (left), Ti64, ring spot beam profile (middle) and pure Cu, Gauss beam profile (right). The top row depicts the stress field, the diagrams in the bottom row the residual stress profile in the centre of the stress field as a function of distance to the surface ("depth").*

D2.4 - Refinement Residual Stress Analysis

Goal

An important aspect for a robust production of the demonstrator is a deep understanding of how process conditions, material properties and residual stress interact, because stress causes warpage and contributes to the generation of cracks. Therefore, measurement techniques to reliably determine the stress state of a component at a resolution as high as possible are required.

Deliverable D2.4 seeks to develop techniques which are applicable to the specifics of LPBF built components. Since residual stress is present not only in the metallic built component but also in the ceramic layer of the substrate (as becomes obvious from the warpage observed for virgin substrates) another objective of this deliverable is to develop a method which allows to characterise the stress state of the ceramic layer in virgin substrates. XRD based residual stress measurement is an established measurement technique.

However, LPBF built components show in many cases textured and coarse-grained microstructures which requires an adaption of the standard methods to obtain reliable results. A peculiarity in measuring the stress depth profile of the substrate ceramic layer is the fact that ceramic material cannot be thinned out without changing its residual stress. Therefore, either energy dispersive XRD techniques must be applied or angle dispersive XRD measurements of different radiation sources must be combined.

Samples manufactured with Gaussian beam profile (GBP) and with so-called top hat beam profile (THBP) as well as virgin substrate samples with two different geometries were provided by Robert Bosch. Subsequent characterisation of microstructure, texture and stress as well as sample preparation was done at University Kassel.

Status

For characterisation, sample cubes with edge lengths of 3 × 3 × 1.8 mm³ were produced from copper powder via LPBF under optimal process conditions for two different beam profiles (GBP and THBP). Subsequently, the microstructure and texture of the sample were characterised using electron backscatter diffraction (EBSD) and X-ray diffraction (XRD) to determine grain orientation and grain morphology. Furthermore, residual stress was measured as a function of the x-/y-direction (gas flow/recoater direction) using XRD measurements with a monocapillary of 0.3 mm in diameter. On the x-/y-surface of a single cube, 3 × 3 measurement points were recorded.

Due to poor statistical reliability, additional measurements were carried out using a polycapillary with a diameter of 0.5 mm at a measurement point in the center of the cubes.

Additionally, residual stress measurements were performed on the ceramic substrate. For stress-depth profiles, the copper layers were removed from both sides of the substrate by chemical etching. Subsequently, depth profiles could be determined using XRD by combining different lattice planes and two different types of radiation. Furthermore, initial energy-dispersive measurements were tested and carried out on the same samples to reduce measurement effort in the future.

Result & Next Steps

EBSD measurements showed a pronounced texture in samples manufactured with GBP, especially along the gas flow and recoater direction. In contrast, the sample produced with THBP exhibited low texture. Moreover, the GBP-produced sample had a significantly finer grain structure compared to the THBP-produced sample. These findings are in good agreement with additional XRD measurements. While the GBP sample exhibited a symmetrical pole figure, typical for the presence of texture, the THBP sample showed less pronounced symmetries. The presence of individual high-intensity spots suggests a coarse-grained structure. Additionally, the ring-shaped intensity distribution in the XRD measurements of the pole figures suggests the formation of a fiber-like grain morphology along the build direction, cf. Fig. 6.

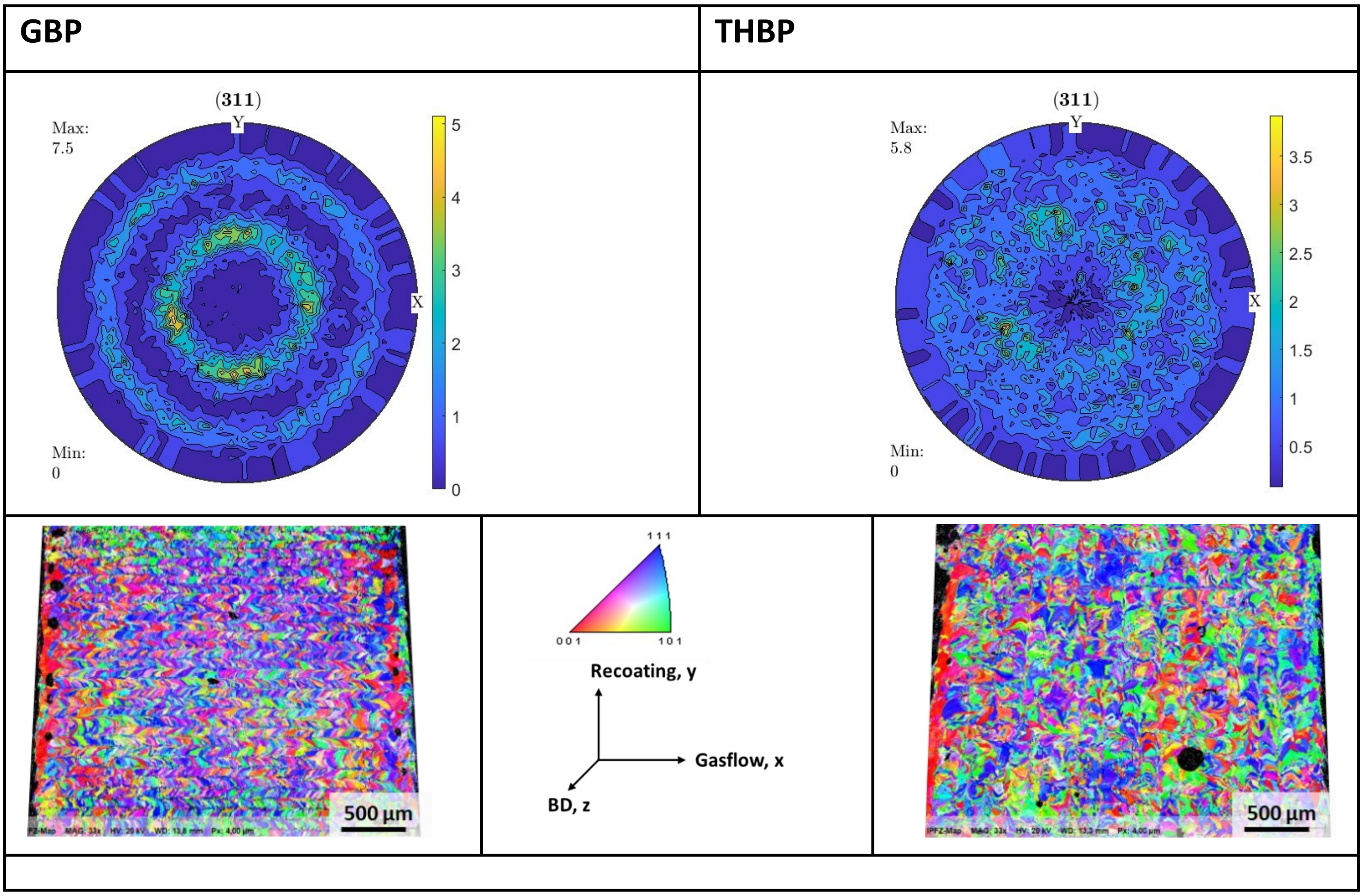

Fig. 6: *Pole figures (top) and EBSD inverse polefigure maps plotted with respect to building direction (bottom) for GBP (left) and THBP (right). For the GBP specimen, a fibre like intensity distribution is observed, for the THBP specimen, a more homogeneous intensity distribution is observed.*

Strain measurements using a 0.3 mm monocapillary yielded poor statistical reliability but indicated a clear trend of higher stresses on the gas-flow-facing side of the fabricated cube. This is likely due to higher cooling gradients resulting from improved heat transfer from the solid to the gaseous phase. Due to the poor statistical reliability caused by weak measured intensities, the monocapillary was replaced with a 0.5 mm polycapillary. The results obtained in this way showed low compressive stresses of ≈ -30 MPa in both the gas flow and recoater direction in the center of the cube, with similar values for both the GBP and THBP samples.

Residual stress measurements on the substrates revealed negligible stresses in the copper layer, whereas measurements in the ceramic layer indicated a complex three-dimensional stress state with different stress profiles in the x- and y-directions, cf. Fig. 7.

The determined shear stresses and the likely presence of a triaxial stress state are consistent with the results of geometric measurements, which indicate that some substrates are not only bent but also twisted. However, the variations between individual substrates are significant, suggesting a large variation in the initial state of the substrates. To improve measurement statistics and identify general trends, further samples need to be characterised.

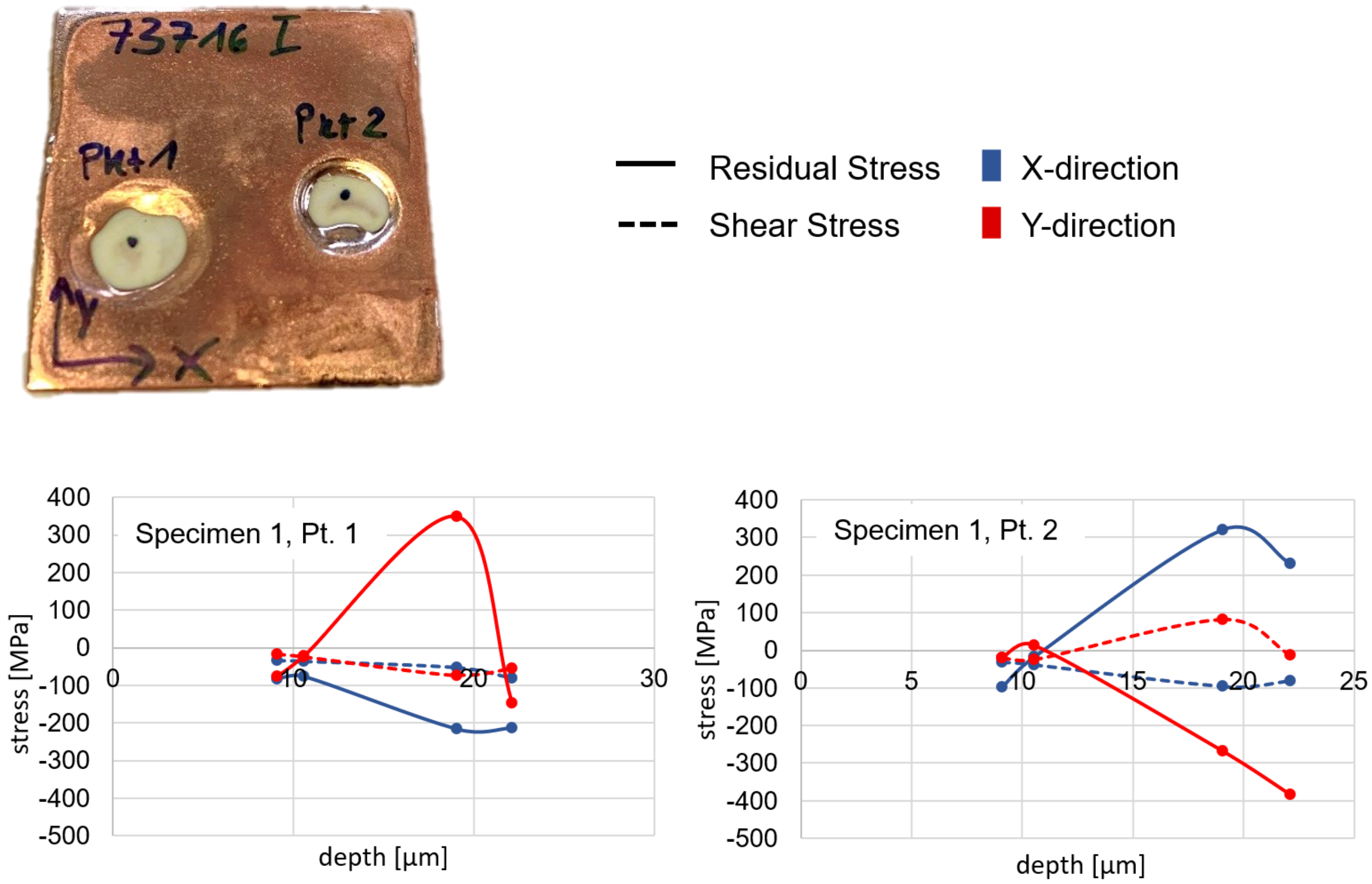

Fig. 7: *Example for depth profiles of residual stress in the ceramic layer of a project substrate.*

04. Events

GlobalAM Kick-off-meeting

GlobalAM Project officially kicked off with a productive meeting held in Brussels on 30th and 31st of January 2024.

Read more

Dissemination

Dr. Frank Sarfert from Robert Bosch presented the GlobalAM project at the EFFRA Manufacturing Partnership Day 2024 in Brussels on 7th of May 2024.

Read more

Second General Assembly Meeting

The second general Assembly Meeting was held in Lyngby, Denmark on 11th and 12th of June 2024 hosted by DTU.

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Dissemination

In August 2024 Isabelle Günther from Robert Bosch published a blog article including a YouTube clip on hybrid additive manufacturing and the work in GlobalAM.

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Third General Assembly Meeting

The third General Assembly Meeting was held in Prague on 2nd and 3rd of December 2024 hosted by Safina.

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