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Hans-Christian MOEHRING*[1], Clemens MAUCHER[1],
Dina BECKER[1], Thomas STEHLE[1], Rocco EISSELER[1]

THE ADDITIVE-SUBTRACTIVE PROCESS CHAIN – A REVIEW

In recent years, metal additive manufacturing developed intensively and became a relevant technology in industrial production of highly complex and function integrated parts. However, almost all additively manufactured parts must be post-processed in order to fulfil geometric tolerances, surface quality demands and the desired functional properties. Thus, additive manufacturing actually means the implementation of additive-subtractive process chains. Starting with the most relevant additive processes (powder-based PBF-LB, LMD-p and wire-based WAAM and LMD-w/WLAM), considering intermediate process steps (heat treatment and shot peening) and ending up with post-processing material removal processes (with defined and undefined cutting edges), this paper gives an overview of recent research findings with respect to a comprehensive scientific investigation of influences and interactions within the additive-subtractive process chain. This includes both the macroscopic geometric scale and the microscopic scale of the material structure. Finally, conclusions and future perspectives are derived and discussed.

1. INTRODUCTION

Additive manufacturing (AM) technology enables the realisation of component structures that are technically very difficult, ecologically or economically inefficient or physically impossible to produce with other manufacturing processes [1, 2]. Thus, additive manufacturing technology opens up new degrees of freedom in the design of products and systems. In addition, AM enables the fast-reacting, flexible and hence resilient production of small batches and individual single items [3]. In medical technology, for example, implants can be designed and produced with geometries and bio-compatible surfaces that are optimally adapted to the patient's needs [4–8]. Lightweight design potential can be tapped by means of component structures optimised in terms of their topology as well as density, so that, for example, mobility systems with lower energy consumption can be realised [9, 10]. In addition, material combinations in components can also be produced using AM [11–14]. A review on hybrid and multi-material additive manufacturing as well as additive manufacturing of functionally graded metal materials is provided by [15–18]. Due to the ability to create

[1] Institute for Machine Tools – IfW, University of Stuttgart, Germany
* E-mail: hc.moehring@ifw.uni-stuttgart.de
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internal structures in components as well, AM contributes to the realisation and utilisation of a wide range of possibilities for function integration. In this way, for example, it is possible to produce component-integrated cooling systems which increase the effectiveness and thus the energy and resource efficiency in many different fields (e.g. in high-temperature applications, in hydrogen technology, in energy conversion systems) [9, 19]. Free form geometries manufactured by AM help to reduce flow losses and realise optimised fluid systems [20, 21]. Function integration can also consist of using AM to specifically adjust the stiffness and damping properties of components that are particularly advantageous for the respective application [22, 23]. By using AM, it is also possible to produce function-integrated sensor and/or actuator components with specific respect to their application [24, 25]. Finally, AM enables the generative building of structures on existing or prefabricated substrates [26] and thus, among other things, the repair and regeneration of complex, cost-intensive functional components. Consequently, the main areas of application for AM are in the automotive, aerospace, medical, consumer goods and electronics industries, in production technology and general engineering industries, as well as in many other branches of industry. AM is used to create three-dimensional objects directly on the basis of CAD (computer-aided design) data by building up material layer by layer [27, 28]. A wide variety of materials can be used here [29, 30].

2. ADDITIVE MANUFACTURING AND POST-TREATMENT

Common AM technologies are the classic 3D printing (binder jetting) [31], material deposition by means of extrusion processes (fused deposition modelling – FDM) [8, 32], stereolithography [33] as well as processes based on the input of energy into powdery or wire-shaped materials by means of laser, electric arc, electron beam or ion beam [2, 34, 35]. Figure 1 depicts the schematic of a laser based powder melting process (e.g. Powder Bed Fusion – Laser Based (PBF-LB) following DIN EN ISO/ASTM 52911–1) with its fundamental characteristics and parameters. Besides Powder Bed Fusion (PBF), Laser Metal Deposition (LMD) based on the melting of powder material (LMD-p) or wire material (LMD-w) as well as Wire Ard Additive Manufacturing (WAAM) are most important with respect to an industrial additive manufacturing of metal parts.

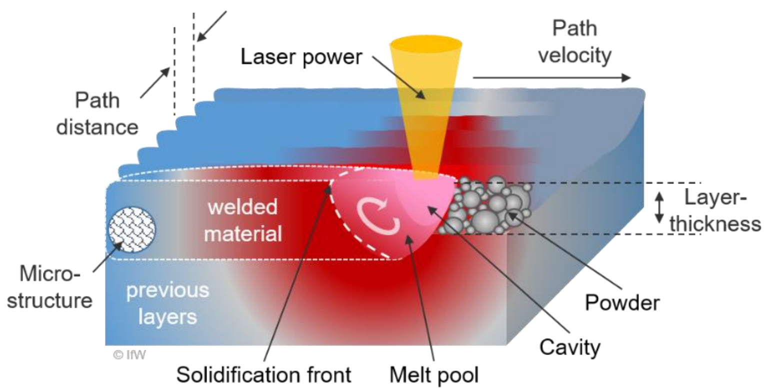

Fig. 1. Principle schematic of laser based powder melting in additive manufacturing

Apart from a large number of different plastics [36, 37], fibre-reinforced plastics [38] and ceramic materials [39], various metallic materials can also be processed [9, 29, 40] of which aluminium alloys, stainless steel grades, titanium alloys and nickel alloys are the most relevant for technical and medical applications. For the vast majority of additively manufactured components (unmachined AM parts), secondary operations or remachining is necessary in order to achieve the required geometric accuracy and tolerances (e.g. assembly tolerances for the installation in higher-level assemblies and systems), functional surface and rim zone properties (e.g. for achieving tribologically favourable functional properties) as well as the required strengths (e.g. against fracture, compressive and/or reversed bending loads). The production of unmachined AM parts is often followed by heat treatment and mechanical material-removing (subtractive) machining processes. For example, shot peening processes are also applied for cleaning and surface solidification, which may cause rim zone influences, hardening and the input of compressive residual stresses [41]. In Fig. 2, the surfaces of differently blasted AM parts, produced by laser based powder bed fusion (PBF-LB) are shown.

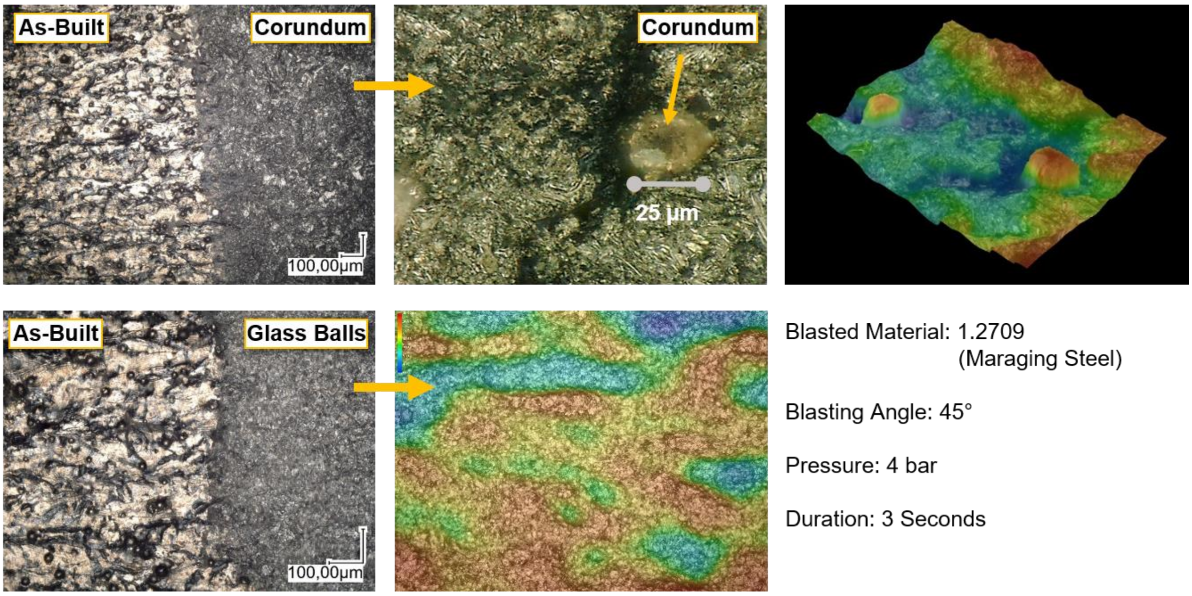

Fig. 2. Surfaces of AM parts made of 1.2709 maraging steel blasted with corundum or glass balls [41]

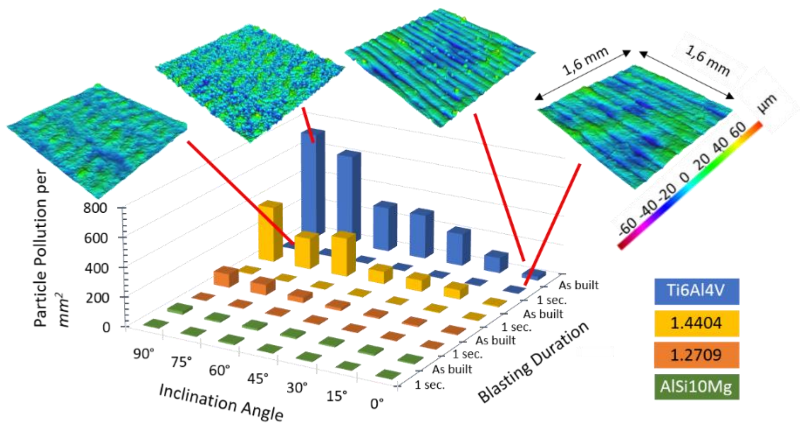

Fig. 3. Influence of blasting parameters on the particle pollution of different AM workpiece materials [41]

As can be seen, in the case of blasting with corundum, some trapped blasting particles can be found within the workpiece surface which could be harmful for cutting tools in subsequent machining. Figure 3 presents the surface pollution by powder particles of AM parts made of different materials before and after blasting. Blasting with glass balls leads to significant cleaning of these surfaces depending on the blasting parameters even after a processing time of only 1 second, showing the beneficial influence of this intermediate process step. As can be seen in figure 4, the blasting duration has a clear influence on the weight reduction by material removal but its effect on the surface roughness is relatively small. Also the inclination angle affects the blasting results with respect to surface roughness values and weight reduction. Furthermore, the blasting process has an impact on the hardness properties of the workpiece, as shown in Fig. 5.

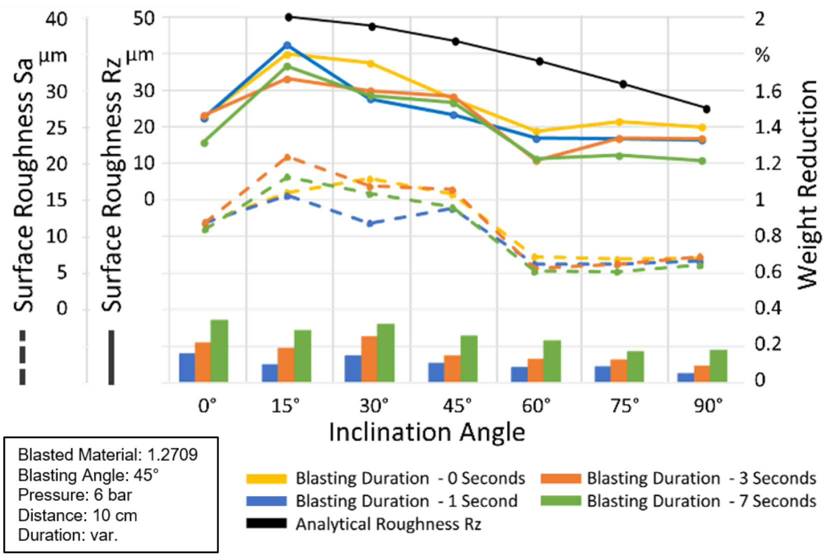

Fig. 4. Influence of blasting parameters on the surface roughness and weight reduction [41]

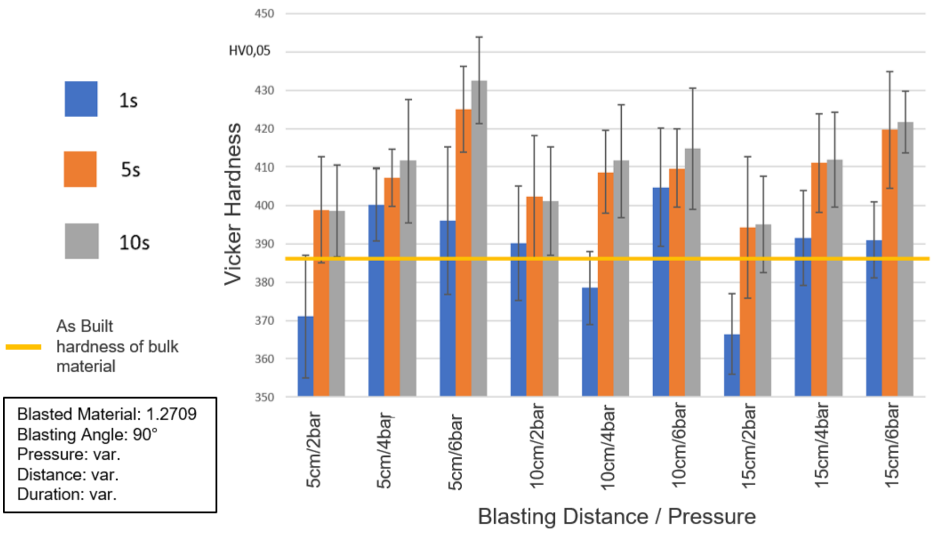

Fig. 5. Vickers hardness values 20 µm below the surface depending on the blasting time

The influence of heat treatment on the microstructure of an additively generated 1.2709 maraging steel specimen can be observed in Fig. 6. The heat treatment was conducted either as solution annealing at 860°C over a duration of 2 hours and subsequent fast cooling in stationary ambient air or as age hardening at 460°C over a duration of 6 hours with slow cooling at closed door of the heat chamber. In solution annealing, an increase of the grain size can be observed.

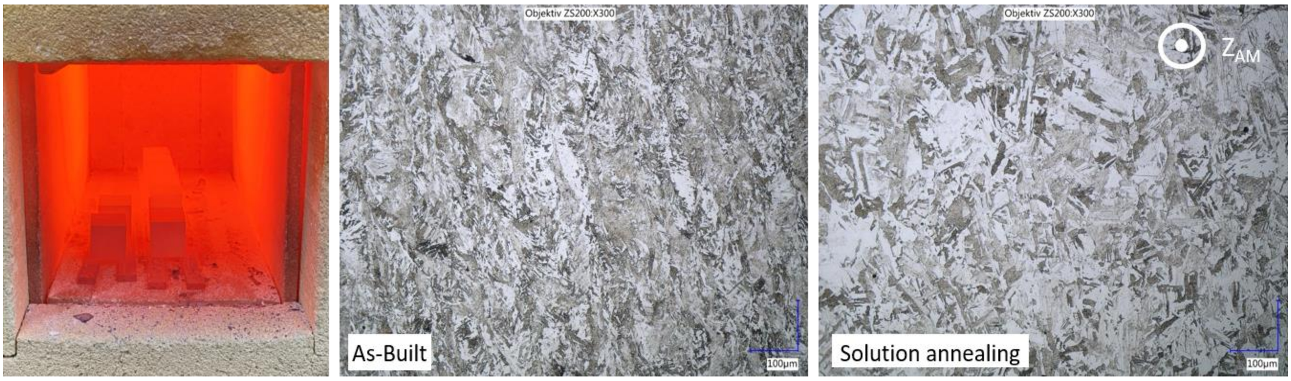

Fig. 6. Influence of heat treatment on the micro structure of additively manufactured (PBF-LB) 1.2709 maraging steel

An additive-subtractive manufacturing process chain (ASM) is usually used in AM to produce components with predefined functional properties and performance characteristics (Fig. 7). Grzesik already described hybrid additive and subtractive processes in [42] and gave an overview of processes and systems for the implementation of hybrid additive and subtractive manufacturing in [43]. An overview of additive-subtractive hybrid machine tools is provided in [44]. As a consequence, the component characteristics finally achieved result, on the one hand, from the influence on the material and component properties by the respective individual processes and, on the other hand, from physical interactions between these individual processes.

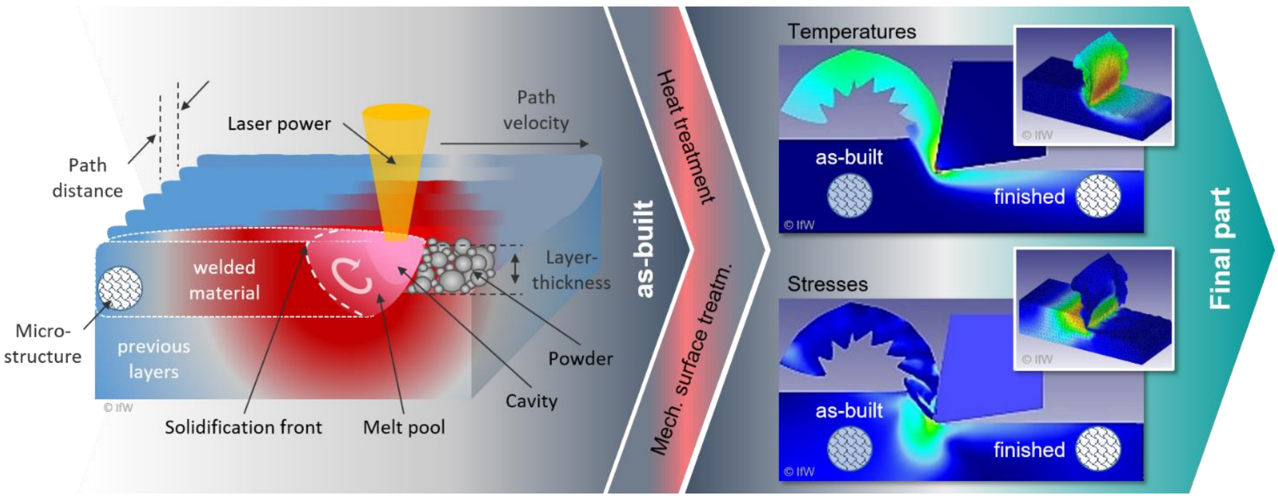

Fig. 7. The additive-subtractive manufacturing process chain (ASM)

The AM-based production of metallic components is mainly based on the use of metal powder or metal wire [45–48]. Metal powder is largely processed in powder bed processes (selective laser sintering, selective laser melting (PBF-LB/M)) but also increasingly by means of direct powder deposition processes (directed energy deposition (DED) in terms of Laser Metal Deposition (LMD-p)).

In PBF-LB processes, the powder material is heated locally with high resolution using a laser beam to cause melting and thus bonding of the material (see Fig. 1 and Fig. 7). Immediately after exposure to the laser beam, the material cools very quickly and solidifies [2]. Wire-based AM processes also use laser (wire-based Laser Metal Deposition (LMD-w) also known as Wire Laser Additive Manufacturing (WLAM)), arcs (Wire Arc Additive Manufacturing (WAAM)) [49], or a combined energy input [50] for melting the material supplied as a wire. This technology offers high material deposition rates [51, 52] but is limited in terms of the geometric resolution of the components to be manufactured. The powder-based LMD-p process offers a compromise with a comparatively high deposition rate and geometric resolution as well as a high utilisation degree of the substrate material used.

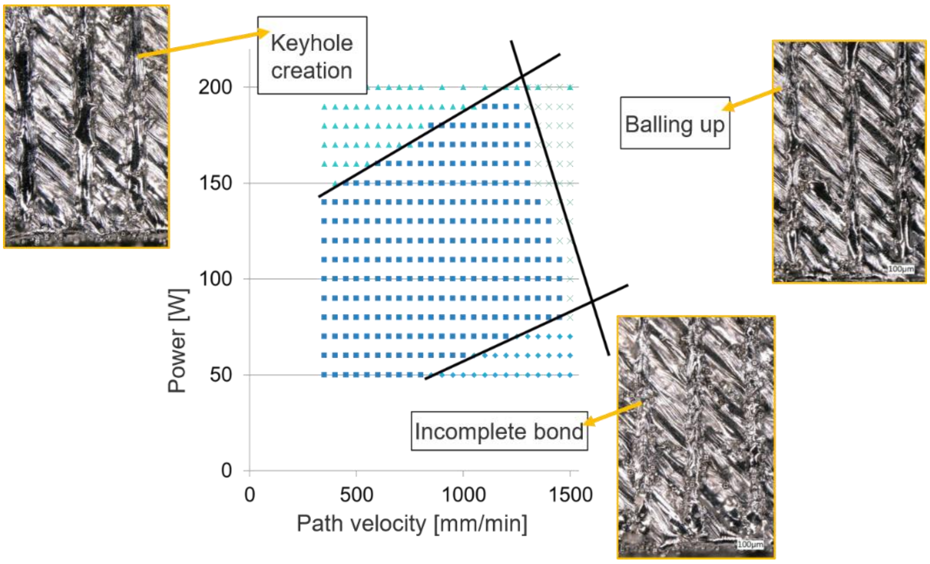

Fig. 8. Limitations of powder bed based additive manufacturing

Compared with the technical possibilities, AM processes also present technical and physical challenges (Fig. 8). When exceeding a certain power limit, the keyhole effect leads to material voids within the material of the part. Depending on the converted power (e.g. laser power) and the deposition or track speed (especially the speed of the laser spot, the so-called scanning speed, in PBF-LB processes), a considerable amount of energy is introduced into the component to be produced. Excessively high track speeds and/or an insufficient power lead to defects, cavities, porosities or areas in the component material that have a lower density and strength. In contrast, excessive energy input leads to a local increase in hardness, high residual stresses, component distortion and crack formation [47, 53–55]. In powder bed-based processes, such effects can be reduced, for example, with the help of heated building platforms and/or temperature-controlled working spaces as well as by heat treatment and/or shot peening of the generated components [56–58]. In LMD and WAAM processes, thermally induced stresses can be mitigated by adapted build-up sequences [59, 60], preheating of the substrate [61], heat treatment [62] and/or rolling or surface hardening processes [63]. The process quality can also be increased by optimising the process parameters [64, 65]. The material properties of additively manufactured workpieces depend sensitively on the process conditions during material deposition [66–68], on the material characteristics [69] and the AM device used.

3. THE NEED OF MACHINING OF AM-PARTS

In the majority of cases, additively manufactured components do not have the required geometric accuracy and surface quality with regard to functional and assembly requirements [51, 70, 71], so that subtractive post-processing is necessary [72, 73]. This post-processing is predominantly carried out by means of material removal with cutting processes (e.g. turning, milling, drilling) [74], abrasive processes (e.g. grinding, honing, micro-finishing) [75], free abrasive processes (e.g. abrasive blasting, lapping, flow grinding) [76, 77] or electrochemical machining. Flow grinding is a finishing process for deburring or polishing surfaces and edges [78]. Due to the hardness of additively manufactured workpieces, increased process forces and accelerated tool wear occur compared with conventional machining [79–81]. Since unmachined AM parts often consist of thin-walled elements, special attention must be paid to critical component vibrations and unstable process conditions during post-processing, as they have a detrimental effect on surface quality and tool life [82]. Due to the thermomechanical stress on the workpiece material caused by the machining process, the post-processing influences not only the geometry and the surface properties but also the component sub-surface layer and causes changes in the residual stress states of the components [83–85]. Thus, among other things, the strength properties can be affected [86, 87]. In addition to conventional machining processes, ultrasonically assisted processes have great potential in terms of increasing tool life, process stability, machining quality and productivity [88]. The surface and rim zone properties of unmachined AM parts can also be purposefully modified, adjusted and optimised by the post-processing processes [89, 90]. Hence, the final properties of the components manufactured by means of the additive-subtractive manufacturing process chain (ASM-components) result from the influences and the interaction of both the additive and the subtractive process steps.

Intermediate machining operations, such as heat treatment in particular, have an additional significant influence on the material and rim zone properties of the ASM components [91]. However, the working mechanisms and interactions occurring within the ASM have not been systematically researched to a sufficient degree until now. Thus, there is a substantial lack of knowledge and methods with which the specific design, parameterisation and implementation of the ASM and its individual processes can be carried out with regard to predefined and required functional and performance properties of the ASM-components. The quality of AM [92] as well as post-processing processes [93] can be increased by using process monitoring methods. At present, improvements in AM and post-processing processes are achieved independently of each other. Consequently, a combined examination and holistic optimisation of the process steps within the ASM are missing. This leads to inefficient use of materials, energy and resources [72, 94, 95]. The total production effort and the costs incurred depend on all process steps involved and their optimal coordination with each other [96, 97]. Thus, the result of the AM processes decisively influences the effort and costs of post-processing. The same applies to the energy requirements of the process chain [98–100].

4. THE INFLUENCE OF DESIGN

The required characteristics of the ASM-components finally produced by the process chain are initially determined by their design. AM opens up completely new degrees of freedom with regard to the geometric design and function integration of high-performance components [101]. Thus, for example, weight- and topology-optimised components with bio-analogous, mechanically highly efficient structures can be produced [102, 103]. By incorporating the necessary process understanding, purposeful adjustments of the material properties can be incorporated into the design of AM components [104]. Based on the component geometry and by simulation and data-based estimation of the material influence within the AM process, predictions regarding the component material properties are used to implement a specific AM process design. For example, the strength properties of AM components depend on the geometry-related design of the AM processes [105]. The purposeful design of porous structures is also possible, which can only be realised using AM and are suitable, for example, for the flow of fluids or gases in later applications [10, 106]. However, restrictions of the process technology must also be taken into account in the design of AM components [1]. For example, overhanging structures which are generated up to a certain angle of inclination (approx. 40°), need support structures to dissipate the process induced heat into the substrate plate. Especially in the production of topology-optimised component geometries, the use of support structures must already be considered in the design [107, 108]. Therefore, the arrangement and parameterisation of support structures is often the responsibility of the designer. Apart from the pure component geometry, it depends on the orientation of the component in the working space of the AM machine during the AM process. However, the orientation of the component during the AM process is also directly related to the layer structure of the material, which results in a certain anisotropy of the subsequent component material properties. In addition, a heat transport (heat conduction), influencing the temperature gradients within the component and thus its heating and cooling, occurs via the support structures during the AM process. The configuration of the support structures also has a significant influence on the subsequent component properties via this effective correlation. With regard to the later use of the AM components, the support structures used must be removed after completion of the AM process and the AM components must be separated from the build platforms applied during the AM processes [109]. At present, this is mainly done in practice by manual work. In principle, however, the support structures can also be removed by machine tools, which are also used for a functionalising post-processing. With regard to the configuration of the support structures, however, their accessibility must be taken into account in comparison to machining [110]. Finally, AM components are often characterised by the fact that a lattice-like “filling structure” (lattice structure) is created within a “component envelope" that constitutes the outer component geometry [111]. In this way, a further structural optimisation and weight reduction of the AM components can be achieved beyond the topology optimisation. Depending on the stiffness and strength requirements, these filling structures are designed with different densities and arrangements. The design of these filling structures also has an influence on the heat distribution in the AM component during the AM process as well as on occurring mechanical stresses, which result in particular from inhomogeneous heating and cooling processes. For n optimal design of AM components and the layout of the AM processes to be used for their production, a component-process co-design is therefore indispensable [1, 72, 112]. The definition of the component shape is also accompanied by the determination of tolerances. With regard to the achievable complexity of AM components, this tolerance definition represents a challenge. One approach to solving this problem is to define geometric tolerances for each layer of the material structure and to use these tolerances to predict the genesis of the component accuracy [113].

5. THE INFLUENCE OF PROCESS LAYOUT

In addition to the described configuration of the AM process, the track and process planning has a significant influence on the resulting properties of the AM components [114]. In this context, it is particularly important to consider that beyond the single energy input into the component during local material deposition or material consolidation, each further approach of the process zone (area in which the material is melted by the specific energy input) causes renewed heating of a component area (Fig. 1). Thus, an excessive heat input into the component and its destabilisation can occur if the process zone remains too long or concentrated in a component area. In contrast, a more uniform energy input and a more homogeneous heat distribution in the component can be achieved by a systematic sudden shift of the process zone (e.g. in the PBF-LB process). However, remelting caused by renewed energy input can also be used to increase the surface quality of AM components [115]. The formation of high temperature gradients in the component in turn contributes significantly to the development of residual stresses in the component and thus to a subsequent component distortion or crack formation. The energy input into the AM component depends not only on the track planning but also on the track speed of the process zone and the programmed power of the energy source (e.g. laser source). With regard to a productive but also stable material build-up by avoiding critical residual stress states in the component, an optimal combined track and process planning, depending on the respective local component geometry, is therefore required [116, 117]. Processes such as WAAM and LMD also enable multi-axis AM process control, in which the component is inclined and rotated during material deposition. In this way, support structures can be largely dispensed with, as the pivoting movements of the AM component can be used to vertically align overhanging component areas [118]. Taking into account the correlations with regard to heat input and heat distribution in the component, this results in further specific requirements for the track planning. Special track planning methods were developed for the production of AM components with intentionally generated porosity [119, 120] (Fig. 9).

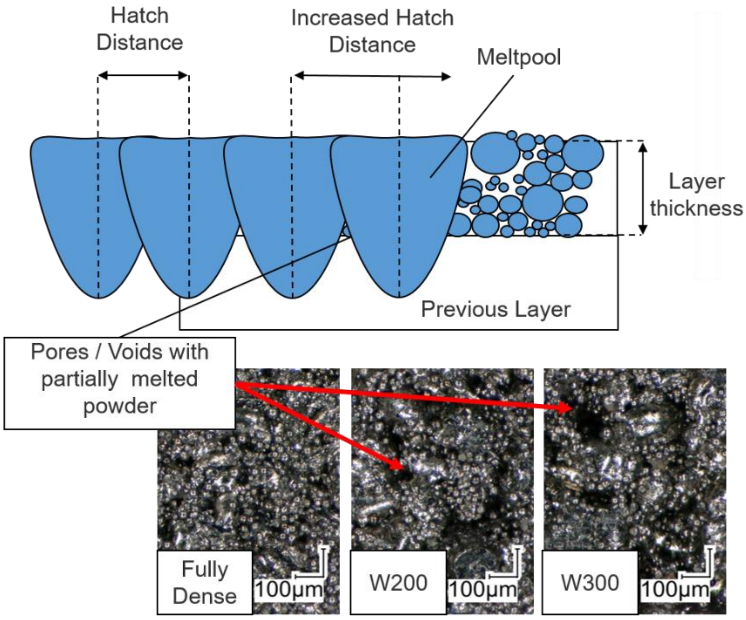

Fig. 9. Intentionally generated porous structures in PBF-LB additive manufacturing [120]

Likewise, the implementation of AM processes in combination with prefabricated substrates requires adapted track and process planning, which does not only take the geometry of the interface between substrate and AM structure into account but also the energy input and heat transport into the substrate. Finally, so-called "hybrid machines" enable both the generative production of AM components and their subtractive post-processing within one working space and in the same component set-up [44]. This also allows the implementation of alternating or iterative AM and post-processing processes e.g., to generate internal component geometries with high accuracy and surface quality [43]. This technology requires track and process planning methods that encompass both process steps [72, 121].

As comparative analyses of PBF-LB processes show, deviations between process results occur when manufacturing AM components with different AM machines under the same process conditions [122, 123]. The reasons given are differences in the atmospheres in the respective machine working spaces, electrostatic charging, type of powder recoater, working space size and the resulting time of recoating, dimensions of the building platform, component arrangement in the working space and different laser-optical systems. In LMD-p processes, the powder feed also has an influence on the AM process [124]. Investigations of the effective correlations within the ASM must therefore be supported by a characterisation of the machine technology used.

6. THE INFLUENCE OF POWDER MATERIAL

A very significant influence on the properties of AM components from powder-based processes is exerted by the type and composition of the powder [125–127] as well as its flow and processing properties [128]. Thus, particle size distribution and powder composition, particle geometry, oxidation and/or particle coatings affect the powder-metallurgical melting process, microstructure, porosity and micro-hardness [129]. It was also found that the energy input via the laser power and the track speed must be adjusted to the characteristics of the specific powder in order to avoid imperfections in the AM component [130]. This requirement is complicated when using inhomogeneous powder compositions by the fact that there are different powder-metallurgical characteristics of the individual components, which prevent homogeneous alloy formation in the local molten pool [131]. Nevertheless, powder-based metal AM can be used to implement alloy formation [132, 133]. It has also been found that mechanically produced metal powders can be a cost-effective alternative to conventional gas-atomised powder materials [134]. With regard to the development of a circular economy, approaches that use powder from recycling processes are also important [12, 135].

The properties of the powder material directly interact with the process parameters with regard to material deposition or melting and consolidation. Basically, sintering in the solid state or in the liquid phase, partial or complete melting as well as chemical bonds are to be considered as consolidation mechanisms [136]. Non-consolidated material is partially vaporised by the energy input. This sometimes leads to the formation of “weld spatter” on the surface of the AM components [137]. In addition, the type of laser source has an influence, as the energy absorption of the materials depends on the respective wavelength of the laser and the effective consolidation mechanisms depend on the energy density. Also, the size and shape of the molten pool is influenced by the laser power or energy input, the track speed as well as the temperature of the substrate, previously applied layers or the substrate material [138, 139]. A reduction of temperature gradients within the component, e.g. by active heating of the building platform and the working space of the AM machine, has a beneficial effect on process stability and component quality [140] as well as on the avoidance of critical tensile residual stresses in the component and the resulting crack formation [141]. A high energy input can be used to increase the layer thickness during the generative build-up of the component [142]. However, increased layer thickness results in increased pore formation. In addition, the microstructure (especially the grain size distribution and grain shape) of the built-up material is influenced by the energy input, so that anisotropy and inhomogeneous microhardness are caused. The layer thickness, the energy input, the track speed as well as the inclination of the component surface also have an effect on the roughness of the consolidated surface, which serves as a basis during further material deposition [143, 144]. In [145] it was shown that the tensile strength and breaking elongation of specimens produced by the PBF-LB/M process from gas-atomised powder of a nickel superalloy (Inconel 718) depend on the layer thickness as well as on the build-up direction (horizontal or vertical). Another strategy for producing high-strength AM components is to use pulsed laser radiation with high power peaks. In [146], the use of pulsed laser power for laser sintering of 316L (stainless steel) in a powder bed was investigated. The aim was to achieve the highest possible surface quality. For this purpose, the displacement of the melt and the effect of the rapid evaporation of the powder layers were analysed. For the LMD-p process, it was shown that the consolidation can be purposefully influenced by adjusting the energy density distribution of the laser beam in combination with an axial powder feed [147]. The energy input into the component by means of laser radiation can be used beyond the AM process for a direct local heat treatment up to a remelting of the component material [148]. This can additionally influence the surface, porosity or residual stresses near the surface and microstructures. In [62], correlations were shown between the laser power, track speed and build-up direction as well as the layer height adjustment on the porosity, microstructure and strength of AM components made of the titanium alloy Ti-6Al-4V in the LMD-p process. Furthermore, the problem of component distortion due to internal residual stresses in the component after the AM process was analysed. By means of a secondary operation of the AM components by hot isostatic pressing (HIP), these distortions could be reduced. The generation of residual stresses and resulting component distortion by the AM process interacts with the porosity and density of the AM component produced, which are influenced by the laser power and track speed [149].

7. MEASURING METHODS

To develop a deeper understanding of the process and evaluate present process conditions, measuring methods are required that ensure, as far as possible, an in-situ determination of the physical working mechanisms during the running manufacturing processes [150, 151]. Since the geometry of the molten pool and the surrounding heat distribution are decisive for the microstructures created in the AM process, thermal imaging cameras, pyrometers and high-speed camera systems are often used for process monitoring [152–154]. Coaxial camera systems integrated into the AM equipment are particularly suitable for the investigation of process parameter influences on the molten pool geometry [138]. Research work at the IfW (Stuttgart) includes the development of a thermo-sensory building platform for monitoring the powder bed PBF-LB process (Fig. 10) [155]. By measuring the local heat input into the sensory system, it is possible to determine, e.g. crack formation or detachment of the AM components due to residual stresses during the AM process.

A method for measuring the actual layer thickness in the PBF-LB process was presented in [156]. A recoater with an integrated optical measuring system was presented in [157]. With regard to a process control to ensure the layer height in a LMD-w process, a coaxial OCT (optical coherence tomography) system was used in [158]. In [159], laser measurements were used for optical powder flow analysis as well as coaxial molten pool detection to identify powder feed irregularities in the LMD-p process. A special in-situ microscope for observing selective laser sintering was presented in [160]. With regard to the strength properties of AM components, the remaining porosity and the involved stress concentration are of importance. Computer tomography (CT) is the preferred method for detecting component porosity [161, 162]. The knowledge about the porosity distribution in the component allows in particular the derivation of FEM calculation models for the prediction of the component strength. CT technology also enables a detailed analysis of the surfaces of AM components [163]. A measurement method that has already been used several times to analyse the molten pool dynamics and pore formation during the AM process is based on the in-situ use of X-rays [164,165]. With the help of this method, even alloying processes of different material powders can be observed. An overview of common surface and microstructure analysis methods for the investigation of AM components was given in [166]. In addition to X-rayographic methods for determining residual stresses in AM components, the use of ultrasonic measuring technique was investigated [167].

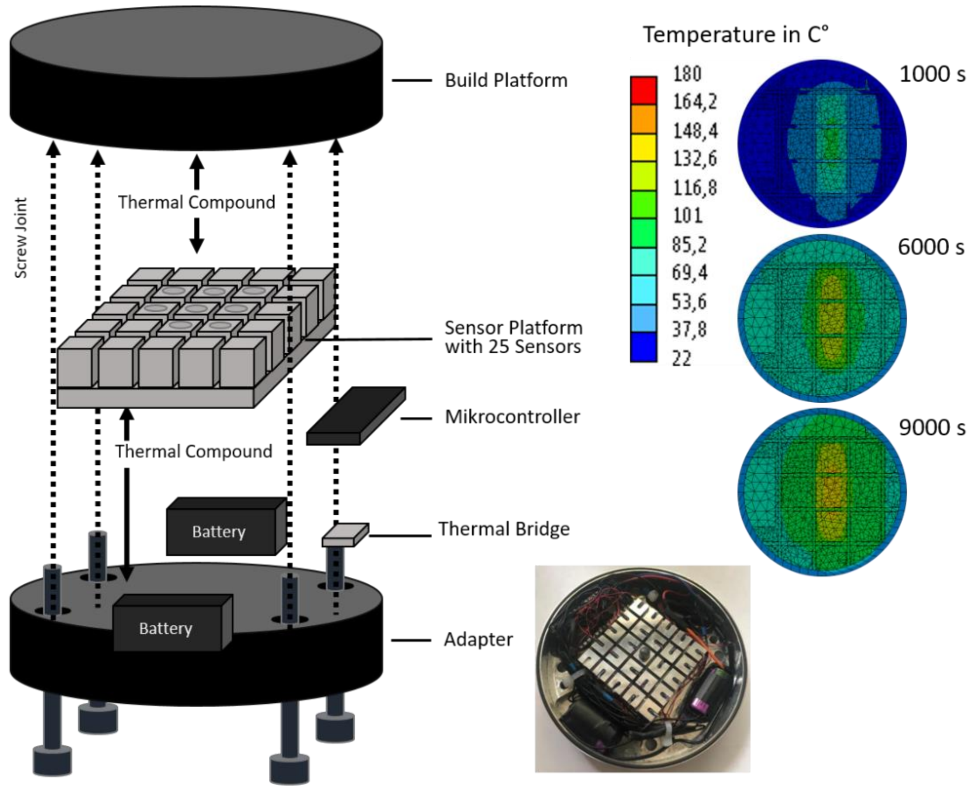

Fig. 10. Sensory build platform for process monitoring in PBF-LB additive manufacturing [155]

8. SIMULATION OF AM-PROCESSES

The scientific literature contains a wide range of papers on the simulation of individual AM processes. Most frequently, finite element (FE) models have been developed (see e.g. [168–171]). The aim is to be able to describe the thermal process conditions, the molten pool geometry, the liquid-solid phase transition, the volume shrinkage and the residual stress states, deformations, microstructures and strength properties resulting from the process conditions [172]. With the help of simulation, the influence of different laser track designs can be estimated, for example [173]. A very comprehensive overview of mechanistic modelling methods was given in [174]. In [175], a finite difference approach was presented, which takes account of physical effects such as dynamic laser absorption, buoyancy, Marangoni and capillary effects, evaporation, recoil pressures and temperature-dependent material properties. In [176, 177], methods for mapping dendritic solidification in the PBF-LB/M process were shown. For the calculation of thermally induced stresses up to crack formation, a coupling of FEM and CFD (Computational Fluid Dynamics) simulation was carried out in [178], which takes the solidification and a renewed melting of neighbouring tracks into account, among other things. In [179], a Lagrangian-Eulerian computational approach for the meso-scale simulation of the PBF-LB/M process was described. Thermal diffusion and hydrodynamics were combined here and temperature-dependent material properties were taken into account. Based on the powder-particle distribution, a meso-scale thermofluiddynamic model was created in [180], which allows conclusions to be drawn about the microstructure. Compared to micro-scale approaches, meso-scale models promise shorter computing times and a more consistent link with macroscopic models for track planning and geometry generation. Although manifold research work has already been conducted with respect to the modelling of metal additive manufacturing processes, a comprehensive multi-scale simulation of all important influences and effects has still not been achieved.

9. THE INFLUENCE OF MACHINING

Increasing interest in the industrial production of additively manufactured metallic components has been accompanied by more intensive research into the mechanical processing of AM components (see e.g. [181]). The first fundamental point to note is that the machining of additively manufactured metallic materials differs considerably from that of conventionally produced (e.g. cast, rolled or forged) materials [85]. For example, the process forces that occur in the machining of additively processed materials differ from those in the machining of conventional materials [74, 80]. Additively processed metallic materials tend to exhibit a rather hard-brittle separation behaviour during machining, which has a negative effect on the achievable surface quality. Due to repeated remelting processes in the near-surface rim zone during AM processes, an increased hardness and strength occurs in comparison with the deeper material areas. The resulting influence on the elasto-plastic properties of the AM components is again influenced or removed by the material removal during mechanical processing [158, 182].

In [158], the influence of different process control strategies in laser metal wire deposition (LMD-w/WLAM) of aluminium alloy combined with subsequent material removal by turning operations was investigated. Figure 11 shows some additively manufactured test specimen and the characteristics of the related LMD-w process control parameters. A coaxial OCT (optical coherence tomography) system was applied in order to monitor the track height of the deposited material for control purposes. The resulting shapes and roughness values of the inner and outer surface of the specimen are depicted in Fig. 12. Obviously, the process results react very sensitively with respect to the applied process parameters. Furthermore, the micro-structure of the produced specimen is affected significantly by the different process conditions (Fig. 13) [183, 184]. The material removal process can be used in order to remove porous material layers close to the surface of the part. However, this has also an influence on the micro-structure of the near-surface material layers (Fig. 14) as well as on the corresponding hardness of the material [183, 184].

The microstructure generated by the AM process and the residual stress state of the components can be influenced by heat treatment processes [185], which in turn affect the machinability of the material [186, 187]. The specific material properties and in particular the microstructural characteristics of AM components result in increased tool wear compared with conventional machining [81, 188, 189].

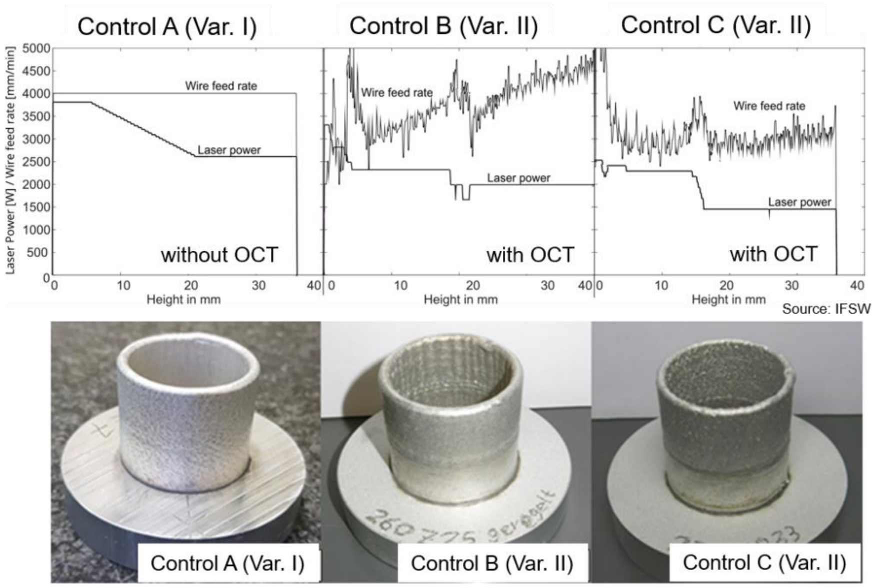

Fig. 11. Specimen produced by laser wire deposition of aluminium alloy [158]

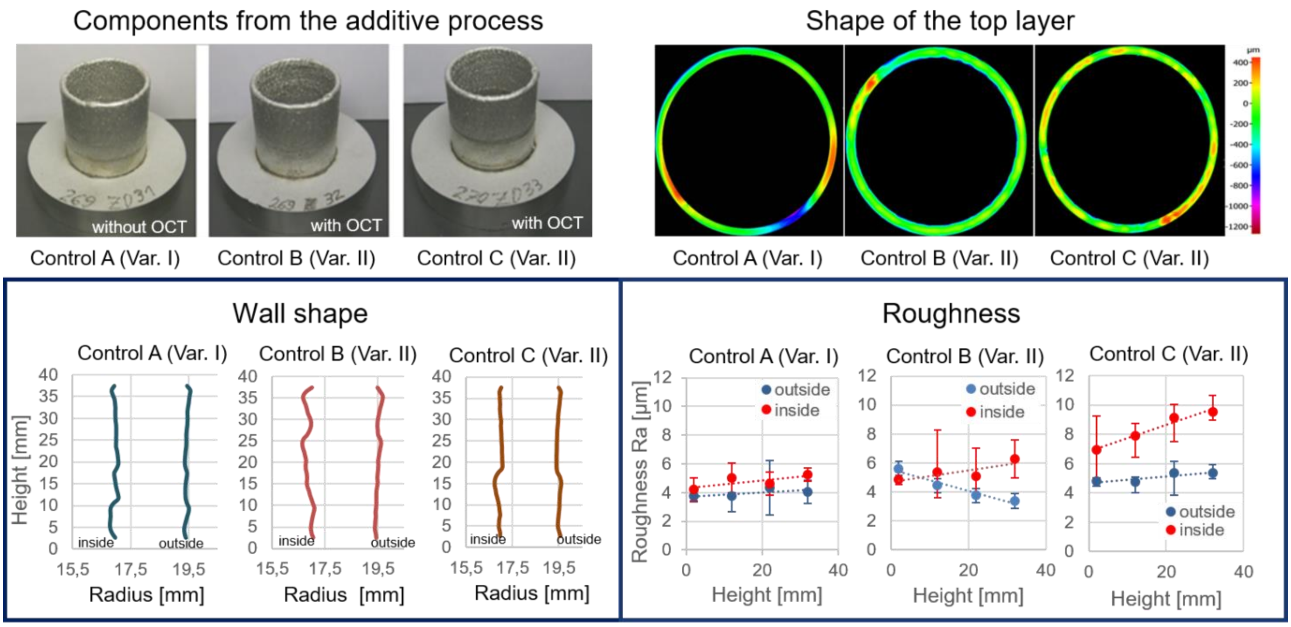

Fig. 12. Results of the laser wire deposition process in terms of shape and roughness [158]

The anisotropy of the material properties that arises in the AM process influences chip formation in post-processing [190–192]. The interdependencies of the layer orientation in PBF-LB additive manufacturing and the subsequent machining in terms of orthogonal cutting are investigated at the IfW intensively [192, 193]. The analysis is based on systematically varied orientations of the test specimen during the layer-wise part generation that can be described by the orientation angles α and β (Fig. 15). On the microscopic scale, the part orientation coincides with the orientation of the dendritic micro-structure of the material (1.2709 maraging steel).

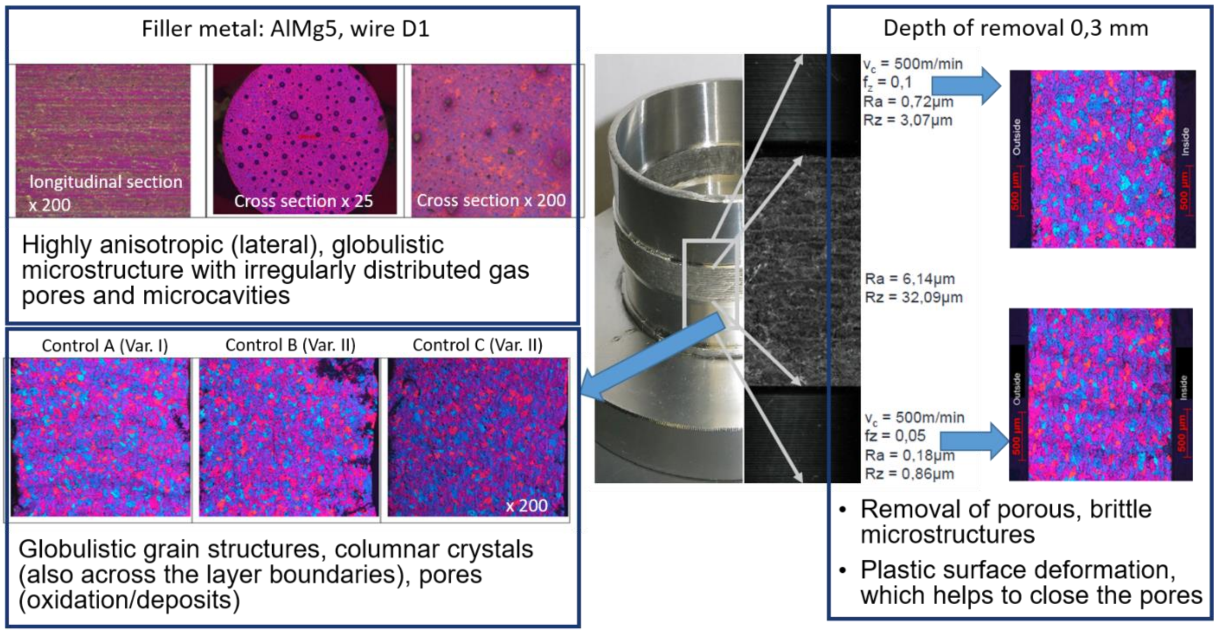

Fig. 13. Micro-structure of specimen produced by laser wire deposition of aluminium alloy [183, 184]

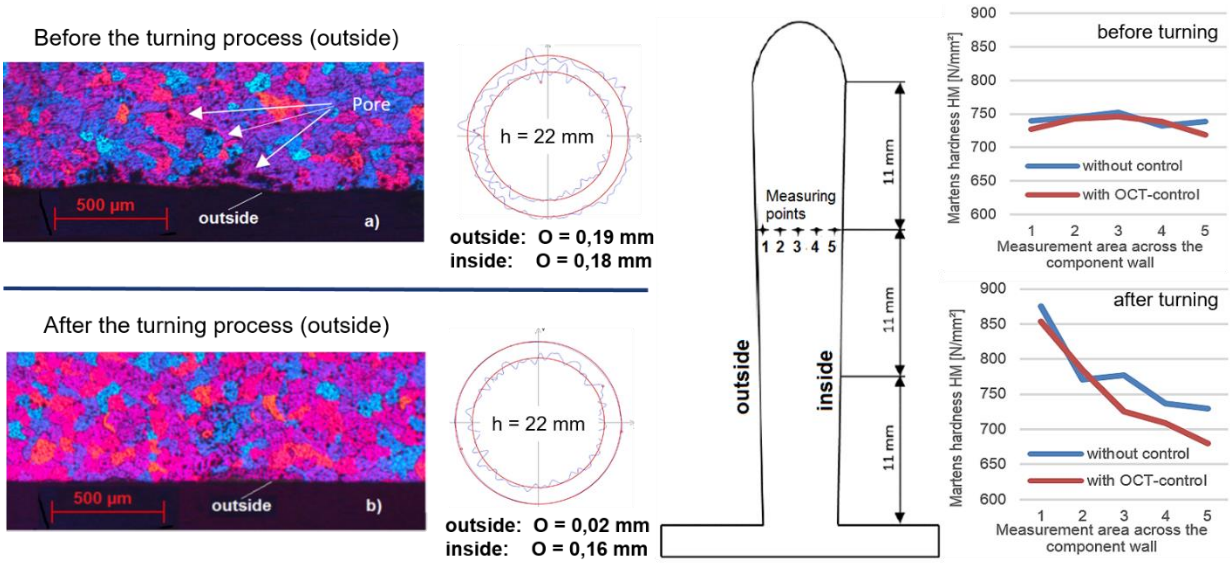

Fig. 14. Influence of material removal by turning on the micro-structure and hardness of LMD-w specimen [183, 184]

Regarding the chip formation, the relative orientation φ of the direction of cut in relation to the layer orientation is particularly relevant (Fig. 16). In order to separate this influence from other process conditions, experiments were conducted by means of a special one-axis test rig for orthogonal cutting with cutting speeds of up to 190 m/min.

The chip formation was observed optically from the back side of the chip (Fig. 17). As can be seen, a kind of flaking becomes visible at the chip rear face in chip flow direction whose structure obviously depends on the relative orientation φ of the cutting direction. This already reveals that the inhomogeneity of the additively generated material significantly affects the mechanisms of the material removal processes.

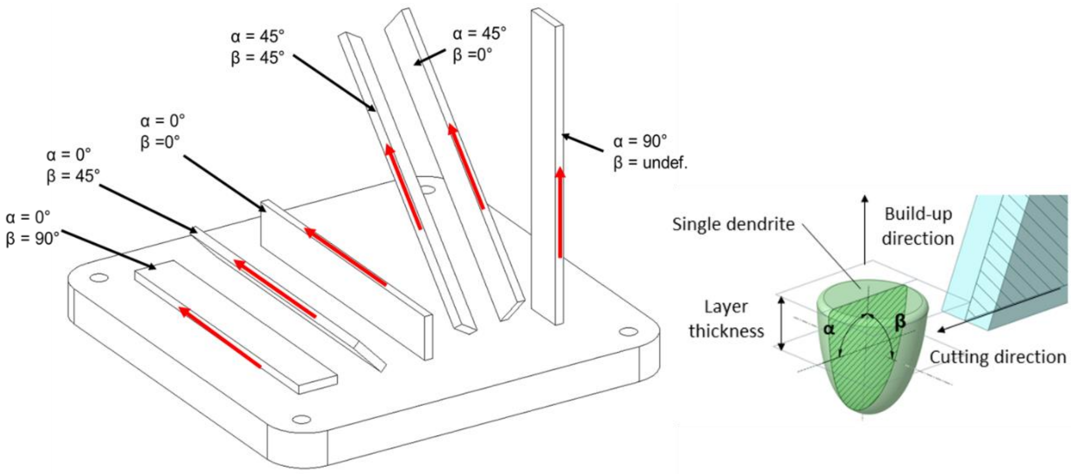

Fig. 15. Systematics for the analysis of influences of the build-up orientation on subsequent machining [193]

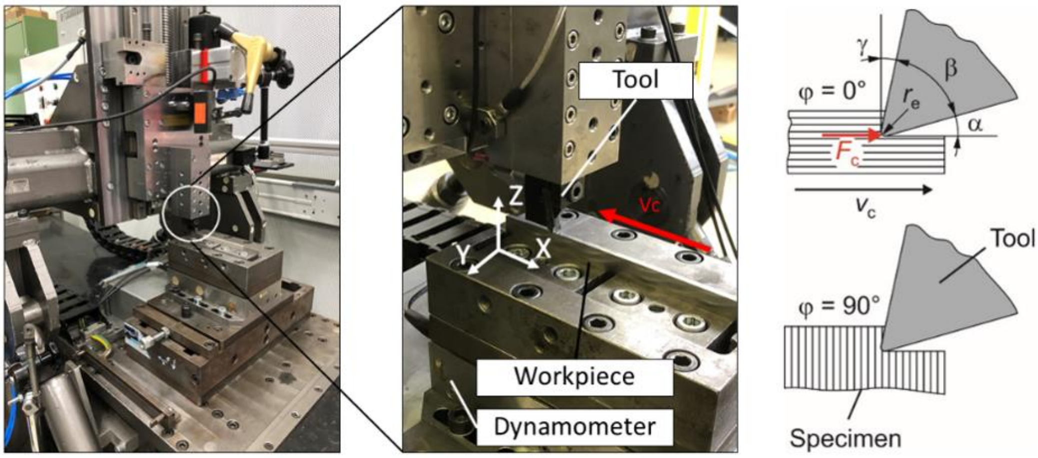

Fig. 16. Analysis of the influence of the cutting direction on chip formation and process characteristics [192]

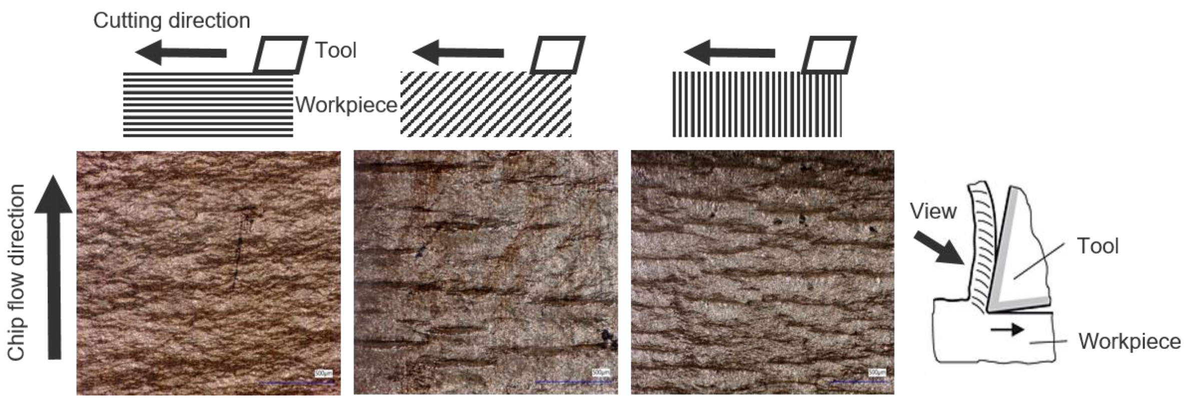

Fig. 17. Influence of the cutting direction in relation to the layer build-up on the chip formation

Figure 18 shows the relative dependency of the cutting force on the layer orientation (characterised by the orientation of the specimen given by α and β) in orthogonal cutting.

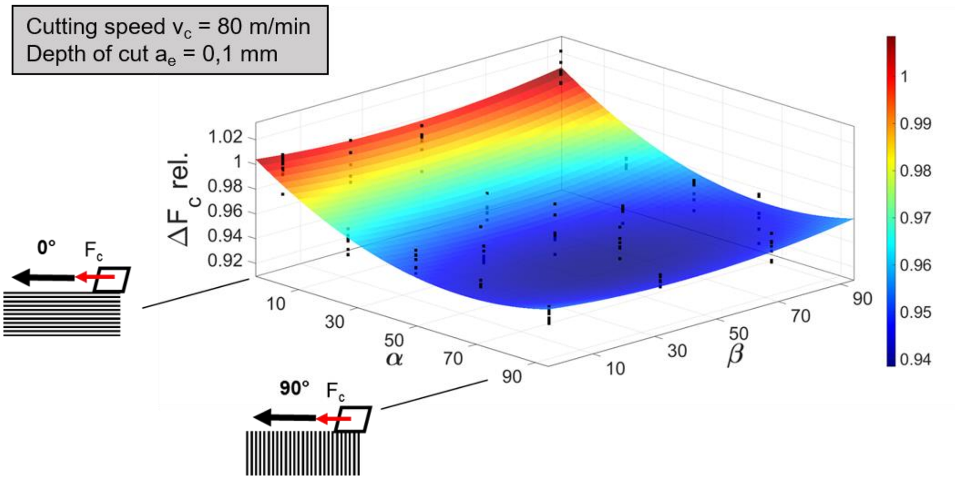

Fig. 18. Regression model describing the relative cutting force dependency on the build-up layer orientation [193]

A deeper insight into the chip morphology depending on the relative orientation of the dendritic micro-structure and the direction of cutting is provided by Fig. 19 [193].

Comparing the first orientation ($\alpha = 0°$, $\beta = 0°$) with the last one ($\alpha = 90°$, $\beta = 0°$) reveals significant differences in chip thickness and lamella distance. A more detailed analysis of the cutting mechanisms indicates an influence given by the number and arrangement of the grain boundaries within the material that are intersected by the cutting process (Fig. 20) [193]. However, in order to understand the highlighted phenomena more comprehensively, further research work is still necessary.

Unfavourably designed support structures also have a negative effect on machining [109]. When removing the locally arranged support structures, e.g. by means of milling operations, strongly fluctuating engagement conditions of the tools and consequently considerably varying process forces occur, which lead to tool displacement and vibration excitation. This impairs the quality of the machined surface [194].

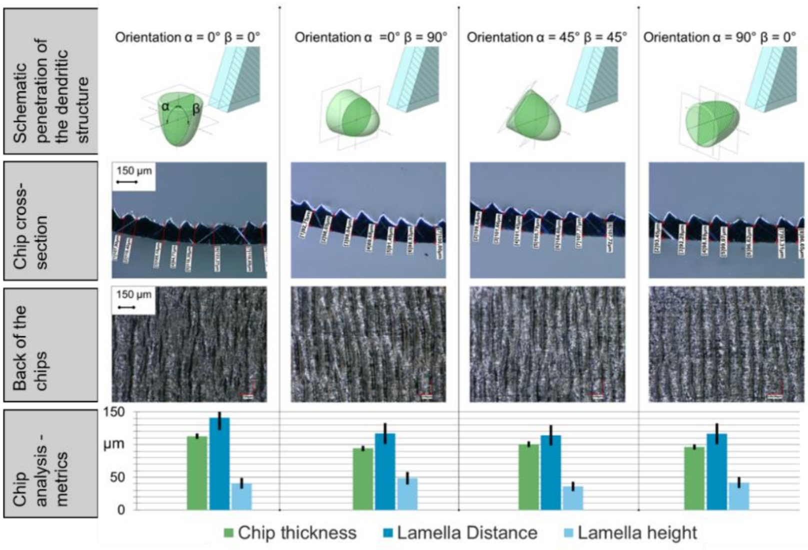

Fig. 19. Chip formation depending on the orientation of the dendritic material microstructure in cutting [193]

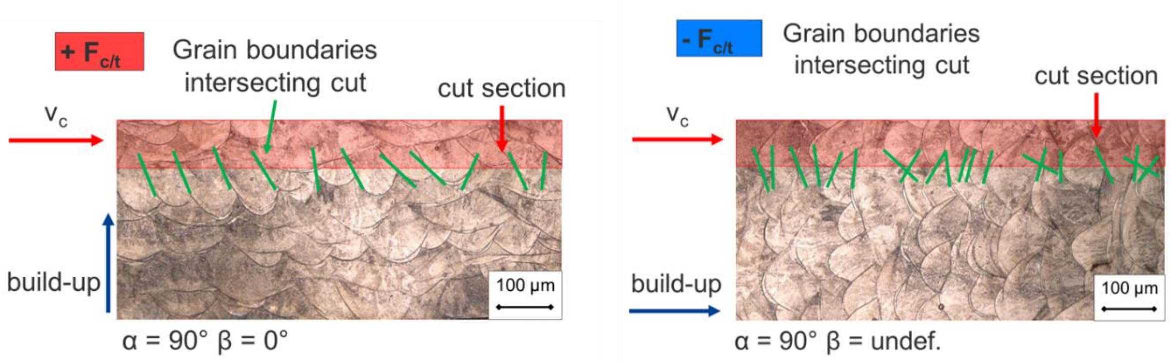

Fig. 20. Grain boundaries in relation to the cutting process [193]

Accordingly, the conditions of mechanical machining should be taken into account in the design of the support structures. Support structures and allowances made of specifically porous material areas can contribute to a homogenisation of the machining forces and considerably improved surface qualities [120]. In Fig. 21, the influences by heat treatment (HT) and different intentionally generated material porosity (see also Fig. 9) on cutting forces are presented, considering 1.2709 steel as workpiece material.

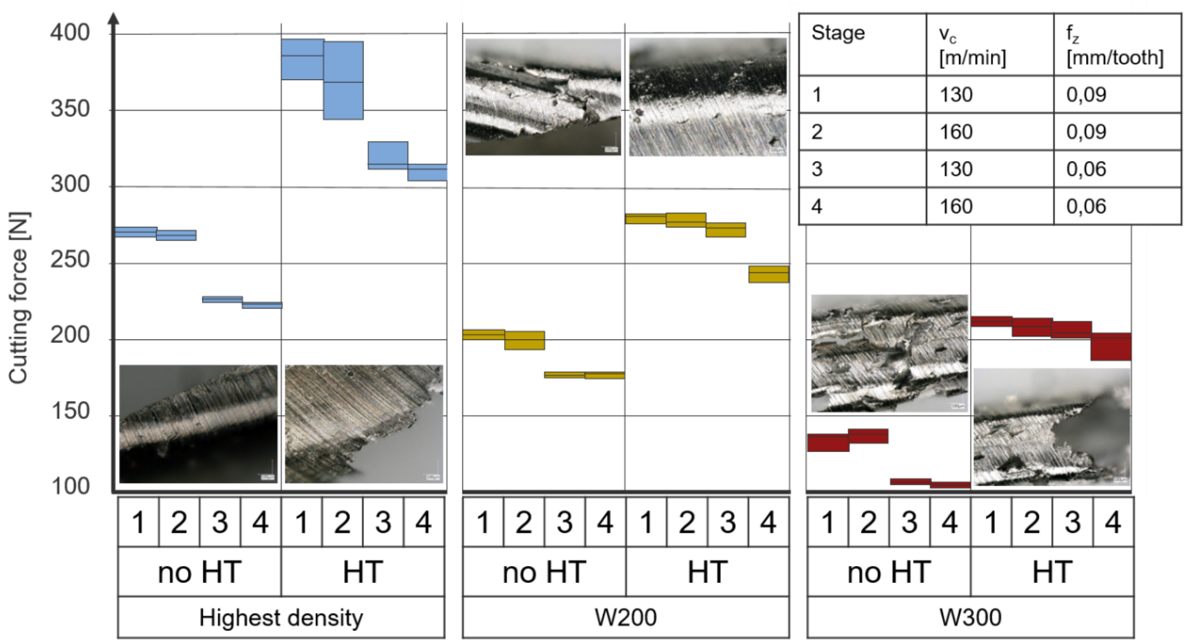

Fig. 21. Influence of heat treatment and intentionally generated porosity on cutting forces [120]

With regard to the removal of inhomogeneous surface layers on AM components, the compensation of component distortion resulting from AM processes as well as the renewed deformation of the components during mechanical post-processing due to residual stress effects, stock allowances on AM components must be provided from which the desired component geometry can be precisely worked out [195]. However, since the causal chain of effects is not fully understood and describable, oversized stock allowances are usually implemented. This leads to significantly longer process times in additive manufacturing and to a significant loss of material in machining. The efficiency of ASM is thus significantly limited [196]. Recent work has shown that there are correlations between the scanning strategy during the AM process, the process planning and parameterisation in mechanical machining and the resulting machinability as well as the component properties produced [197], which can be attributed to the respective influence of the material microstructure. The direction of build-up in the AM process and the relative direction of machining, the respective process parameters and heat treatment conditions have a decisive effect on the surface properties of the components [198, 199]. Properties such as the fatigue, wear and corrosion behaviour of the components are significantly influenced by the interactions of the individual process steps [200]. Further investigations dealt with the use of cryogenic cooling lubrication and dry machining of AM components with regard to environmentally friendly manufacturing [201, 202].

10. THE SIMULATION OF MACHINING OF AM-PARTS

The simulation of machining processes has been a field of intensive research for a long time. Basically, analytical or semi-empirical machining models can be distinguished from FEM-based models and geometric-physical models, where different degrees of detail are available in the process descriptions [203]. The aim of the simulation calculations is usually to predict the forces acting during the machining of a material, the temperature fields occurring and the resulting stresses in the component, in order to minimise, for example, displacement and vibrations of the tools and workpieces and to avoid damage to the component surface layers. A prerequisite for a realistic machining simulation is the availability of material models that represent the material behaviour under machining conditions sufficiently accurate [192]. Figure 22 shows an example for the identification of Johnson-Cook material model parameters for further use in cutting simulations [192].

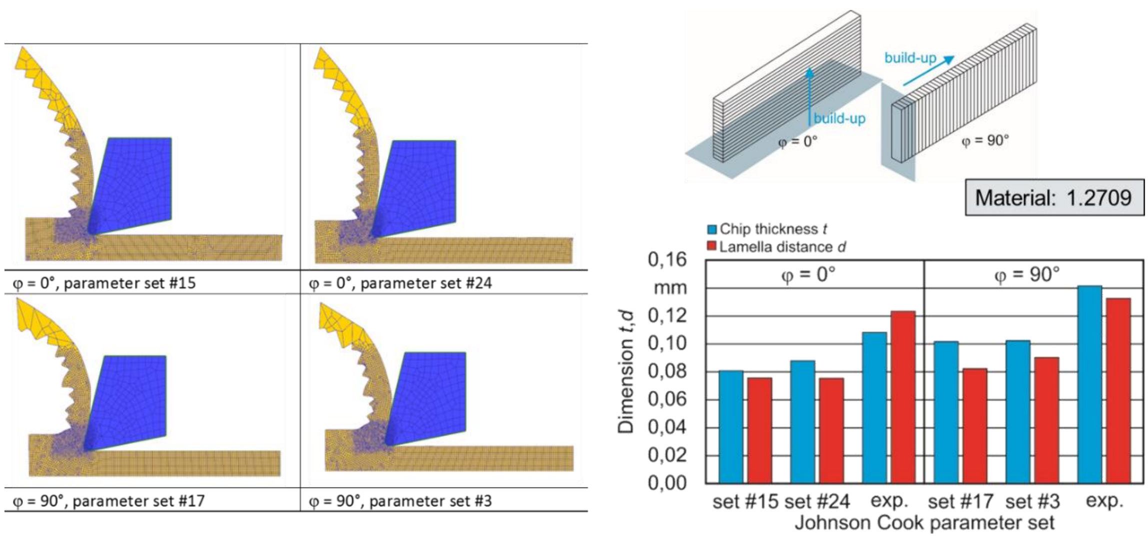

Fig. 22. Influence of different parameter sets of the Johnson-Cook material model on cutting simulation [192]

For additively manufactured materials, however, only few material models are available so far. Consequently, very complex experimental parameter identifications are required if the machining of additively manufactured components is to be simulated.

11. THE FUNCTIONAL PROPERTIES OF AM-PARTS

The functional properties of the components manufactured by means of the ASM can be characterised on the basis of the geometric, dynamic and tribological properties as well as the strength and fatigue properties. With regard to the geometric component properties, in addition to the geometric accuracy of the individual processes (especially the AM process and the machining process) [204], it is particularly important to consider that residual stresses induced in the AM process, influenced in the heat treatment and released in the machining process lead to deformations (component distortion) [56, 83, 205–207]. The formation of microstructure and residual stresses in AM components during the AM process result from the local thermal gradients and cooling rates and are influenced by the applied thermal power (e.g. beam power), the spot geometry, the track speed and the substrate temperature [208–210]. Also, the build-up direction [67], the component geometry [105] and the internal lattice structures [211] have an influence on the structural properties of AM components. The microstructural and mechanical properties of AM components are connected with each other [186]. AM components often have a higher micro-hardness than, for example, conventionally cast components. Higher tensile strengths are also achieved. Phase transformation processes during heat treatment can in turn lead to a reduction in these characteristics and to inhomogenisation. Since the microstructure of AM components also has an impact on machinability [55] and the thermomechanical material load in machining again affects the microstructure in the component surface layer and thus the component properties [212], there is a strong interaction between the individual process steps [57, 158]. The material structure of the AM components and, in particular, the defects present in it have a significant effect on the strength and fatigue properties of the components [213–215]. It must be taken into account that multiaxial load conditions are decisive with regard to the later utilisation behaviour and are thus decisive for the evaluation of the component properties. With the help of meso-scale models, an attempt was made to describe the influence of the build-up direction and porosity on the crack initiation and fatigue strength of AM components [216]. Likewise, elasto-plastic approaches to fracture mechanics have been analysed with respect to an assessment of fatigue damage tolerance [217]. Finally, surface roughness affects the vibration cracking of AM components. However, this can be reduced by machining.

12. SUMMARY

In summary, this article illustrates that there are complex interactions between the design and process parameters of AM processes, local thermal conditions, cooling rates and temperature gradients, the resulting material microstructure, porosity and residual stress state, the use of intermediate and heat treatment processes, and the process conditions in machining, which have a decisive effect on the final material and component properties in terms of strength, tribology and corrosion resistance [218]. A summary of the dependencies of several process steps in additive subtractive manufacturing chains is provided by Fig. 23. Figure 24 depicts the major influences within the additive-subtractive process chain schematically.

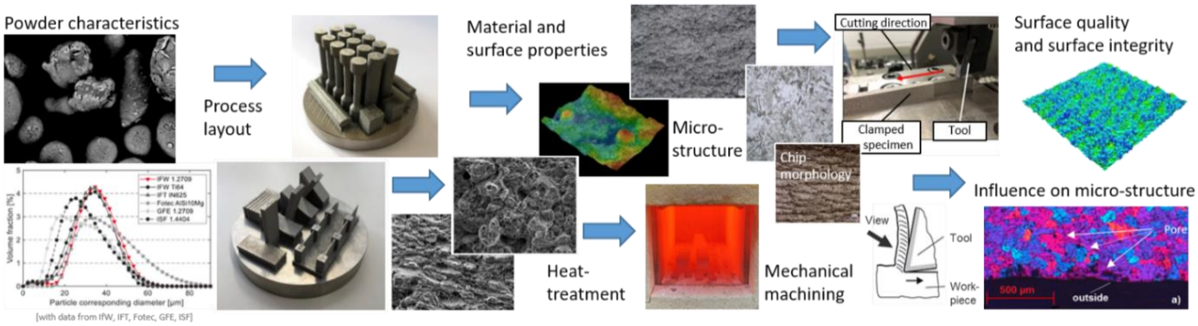

Fig. 23. Summary of dependencies within the additive-subtractive process chain

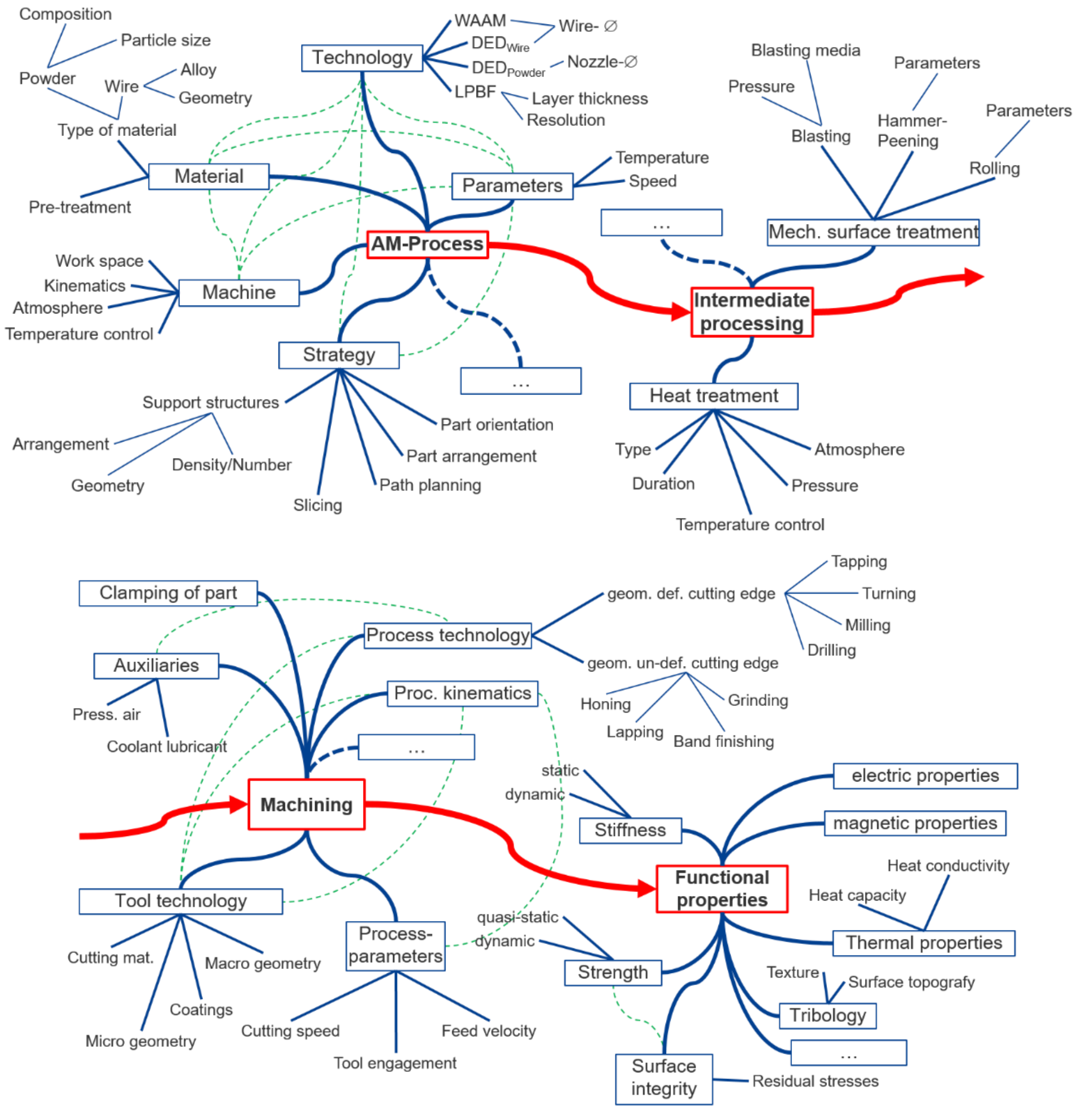

Fig. 24. Schematic illustration of the influences within the additive-subtractive process chain

The most important conclusion is that the final properties of the produced parts regarding geometrical accuracy, surface integrity, strength and performance result from the generation and gradual alteration of the material micro-structure by the subsequent process steps and that the single influences of these process steps interact significantly. Although impressive research work has already been conducted with respect to the detailed analysis of the various process technologies separately, intensive research is still necessary in order to achieve a comprehensive understanding of the complex process interactions. The final goal is to enable a targeted implementation of the process chains in single piece production of parts with pre-defined functional properties.

Following the vision of achieving a comprehensive methodology, which allows to lay out, implement and control additive subtractive process chains for a flexible and fast reacting "first-part-right" production, the following challenges have to be solved in future:

- An even more detailed understanding of the physical phenomena of each process step on the macro and micro level as well as an in-depth knowledge about physical interactions between subsequent process steps.
- Comprehensive physics-based and/or data-driven multi-scale modelling and simulation methods that allow the description and prediction of parameter influences as well as the detailed interpretation of measuring values in terms of soft sensors and digital twins.
- In-situ measuring techniques and monitoring systems that enable real-time observation of each process step as a basis for process control, adjustment and correction in order to assure the achievement of (intermediate) process results throughput the entire additive subtractive process chain and to allow an adaptation of subsequent process steps as a consequence of process conditions in previous steps.
- Fundamental understanding on the dependencies of functional part properties on process influences with the aim to provide target values for process control and objective functions for process chain optimisation.

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