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Vision on metal additive manufacturing: Developments, challenges and future trends

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A R T I C L E I N F O

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A B S T R A C T

Additive Manufacturing (AM) is one of the innovative technologies to fabricate components, parts, assemblies or tools in various fields of application due to its main characteristics such as direct digital manufacturing, ability to offer both internal and external complex geometries without additional cost, and the potential of varying materials at the voxel level. However, despite high anticipations, AM as a real revolution for serial production of metal components has yet to be seen, mostly due to lacks of fundamental understanding, design engineering tools, and the global robustness of the value chains. This paper aims to provide a vision about the future of metal AM based on the collective knowledge of all ten scientific and technical committees of the International Academy of Production Engineering (CIRP).

Introduction

Additive Manufacturing (AM) covers a set of technologies that has had a rapid and diverse development. During the 1990s, the initial denomination was Rapid Product Development [34] because AM technologies were mainly dedicated to product development and prototypes. During the last 30 years, new ways of manufacturing metal parts by AM have been developed and gradually adopted by industry as an alternative production technique [200,202,216]. However, until recently, only a few examples of sustainable value chains were demonstrated with respect to specific application fields [204]. There was a need to continue investigating through research and development, with interesting and demonstrative case studies, such as hydraulic blocks, heat exchangers and medical prostheses and scaffolds. Only few real AM-based serial production scale manufacturing applications do exist today. Two real practice cases are depicted in Fig. 1.1 and Fig. 1.2. An even more impressive case is the well-known serial production of AM fuel nozzles (Fig. 1.3) produced by GE Aviation for its LEAP jet engine, 30,000 of which having been produced between mid-2015 and September 2018; and this was only a production ramp-up [117]. Yet, serial AM production remains today an exception.

To be successful for serial/mass production, AM has to be integrated in complete value chains (Fig. 1.4), taking into account the capabilities of each step of that chain. Starting from ideas and concepts, the different stages − design, work preparation, manufacturing, post-treatment, finishing, control (in- and post-process), material lifecycle management, and all production and business management issues including usage and end-of-life − have to be considered in a complete and systemic way [37].

This paper relates to **a vision on metal additive manufacturing** with AM-based value chains. It is issued from a group of experts from the International Academy of Production Engineering (CIRP)

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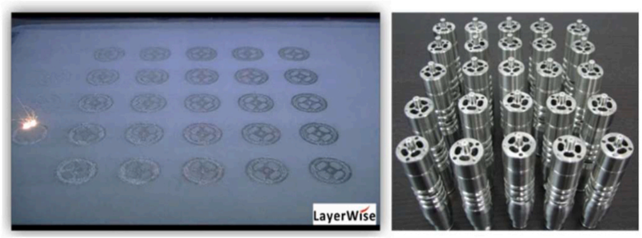

Fig. 1.1. 30 stainless extruder cylinders build in one time/build.

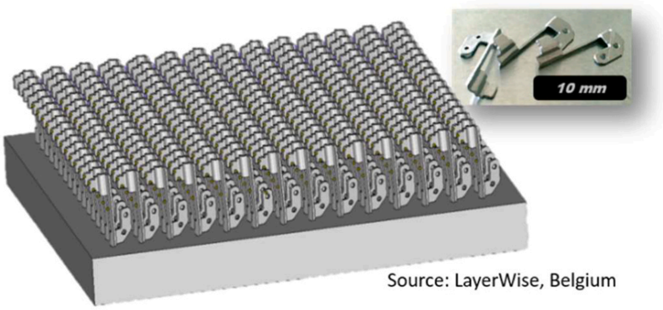

Fig. 1.2. 238 titanium braces build on one platform.

Fig. 1.3. AM fuel injector for GE LEAP jet engines.

community. It differs from other review papers related to AM in that all the major related issues/steps, shown in Fig. 1.4, will be considered and discussed in this paper with a systematic coverage divided into three main parts: a) problems and challenges to be addressed, b) state-of-the-art, and c) vision on future ways to address these problems and challenges. Specific global aspects, like sustainability, interoperability, cybersecurity, education and training, are also covered in this paper. The paper also includes a variety of Key Performance Indicators (KPIs) related to different points of view on what could be expected and taken into account when considering AM to, for example, create, develop, manufacture, use, repair, and recycle products. Even if these different points are not independent, the authors have chosen to address them sequentially to give a better and clearer understanding of what could be expected at each stage of the AM-based process chain.

Consequently, and based on Fig. 1.4, each of the following sections provides a particular vision in complete coherency with the other aspects that have direct relationships with respect to the proposed vision for the future. At the end of the paper, the authors provide an extensive section that synthesizes these perspectives into a summary of the proposed directions for the future. A large list of references is provided to support the arguments proposed in the paper.

The paper covers direct metal AM processes (no two-step processes with e.g. a sacrificial polymer binder). Most attention goes to powder bed fusion (PBF) processes, as this is by far the process with the largest market penetration. Where appropriate it also explicitly refers to direct energy deposition (DED) processes, unless with statements that hold for DED as well as PBF.

Occasionally other metal AM processes are also discussed, like ultrasonic sheet lamination, cold gas dynamic spray deposition, etc. A comprehensive overview of AM processes and related terminology is given in ISO/ASTM 52900 [165].

Design

The present problems/challenges

The layered nature of AM-based production processes allows for the design of complex geometries. While AM processes tend to be more costly for producing parts of low complexity than conventional production processes like injection molding or computer numerical control (CNC) machining, for complex parts this cost difference reduces, as for example CNC costs also depend on number of fixtures needed, material volume to be removed, feature geometry and the size of the mills that can be used. However, AM related economic benefits are often realized when also strategic or functional performance is enhanced [90]. Use of AM in industry is growing based on business opportunities (low-cost prototypes, efficient small series production, spare parts, market responsiveness, etc.) and on the increased product functionality that can be achieved by non-standard/complex geometries. In addition to the functionality of the part, the part also needs to be optimized for other life cycle stages such as processing, post-processing, and inspection and certification. For overview purposes, part design for AM has been subdivided in two main subcategories: i) optimizing geometry for functionality, where the optimized geometry has a complexity that (only) can be produced efficiently by AM technologies and ii) optimizing geometry for (cost) efficient production and inspection purposes [366,377].

State of the art and current developments

Part design for functionality

Part design for functionality can be subdivided into five main subcategories:

- **Improved functionality through complex geometry**: The design for improved functionality is directly linked to complex geometry, such as lightweight structures or three-dimensional (3D) scanning based designs. The resulting shapes are often difficult or expensive to produce with conventional production methods. Topology Optimization (TO) is the best-known design support method and focuses on optimizing geometry with predefined goals and constraints. Classical TO methods focus on the distribution of material within a volume to obtain the lowest mass/stiffness or mass/strength ratio. State-of-the-art TO tools may for example optimize scan strategies to improve on mechanical properties like strength and fatigue [310]. Finally, TO methods have been developed that take other goals (e.g., large deformation, optimal part orientation, required resonance behavior, and high resistance against buckling) and constraints (fast production, minimal post-processing costs, etc.) into account. Other design strategies and methods, such as generative design and lattice structure filling strategies, are also emerging. Lim et al. [222] provide an overview of multi-objective topology optimization strategies for structural applications.
- **Surface structure optimization**: Optimization of product surfaces regards the complex, recurring patterns of small artifacts or features on a complex surface form. Benefits of optimally-designed surfaces include modified flow profiles, bone ingrowth support for tissue engineering scaffolds and other biomimetic

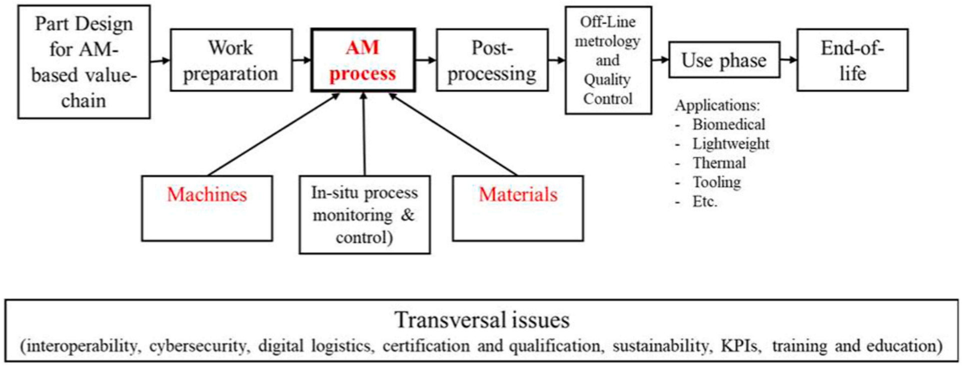

Fig. 1.4. Global vision as a base for the structuring of this paper.

applications. Direct/Indirect reproduction of natural topologies via reverse engineering and generic bio-inspired design are the methods used in this subcategory [377].

- **Internal features:** The ability to create features within a product that are generally inaccessible to traditional manufacturing processes allows for new functionalities, for example for the internal transportation of energy, liquids or gases. Research focuses on design and validation of internal cooling channels (manifold design, conformal cooling), determination of minimal printable internal features (walls, channel geometry) and process settings that result in required levels of porosity for transport of matter through printed features [172,361,365].
- **Redefinition of parts versus assemblies**: AM processes also allow for the redefinition of the way designers think about the subdivision of products into parts. For AM, the constraints for manufacturing, assembly, or inspection are different from that of conventional manufacturing. They even allow for the direct manufacturing of adjustable assemblies. Also, methods for the subdivision of parts that exceed the build volume of the manufacturing equipment have been developed [280,317]. The opposite, the consolidation of parts into one structure, is often applied as it reduces assembly costs and might also result in additional advantages (reduction of stresses, increase of product life, etc.) [277];
- **Multi-material and hybrid techniques**: Since the functionality of parts also depends on the material used, local deposition and control of these materials open up new opportunities for product design. Multi-material and hybrid AM processes allow for the production of multi-material objects while other process variants allow for control of the local microstructure of the materials [28].

Part design for efficient production and inspection

Part design for efficient production and inspection integrates tasks that are otherwise tackled during work preparation (see Section 3.1) within the part design stage for improved synergy between those tasks. This type of part design is generally subdivided into four major stages: pre-processing, production, post-processing, and qualification and certification. Part design for efficient production and inspection deals with knowledge, tools, and methods to overcome challenges associated with a particular stage.

During the pre-processing stage, the part is located and oriented in the build volume, supports are designed, slicing is applied and process settings (layer thickness, hatch pattern and settings, laser power, scan speed, etc.) are defined. A large body of work is focused on application of TO for the definition of lightweight structures for which the need for support structures is minimized. Langelaar [209] offered a method to optimize the part topology while also minimizing the required supports while varying product orientations. Cheng and To [62] proposed a method to optimize the part orientation to minimize support requirements and residual stresses. In general, it can be said that part orientation is a multi-criterion optimization problem, as it is linked to many quality features, e.g., part quality (shape, dimensional accuracy, surface quality), building time and costs, support requirements, and the accessibility of support structures. Leutenecker et al. [214] showed that over 55% of design rules for major AM technologies are, directly or indirectly, linked to part orientation. Although much research is directed to definition of process settings for AM processes, relatively little work has been focused on the relation of combined optimization of product geometry and process settings.

For all AM process variants, design rules have been developed that define the features and products that can be produced. They are mostly used for the definition of geometry in a manual design process. Furthermore, databases have been developed of applicable AM features [235]. In the context of this section, automated geometry definition is mostly focused on TO-based methods that take into account various constraints such as sharp angles, permissible angles for down-facing surfaces, minimum hole sizes and minimum strut sizes. Furthermore, research has focused on automated methods for manufacturing analysis, including a state-of-the-art overview on this topic (See [243]. As an example, Shi et al. [342] developed a method to recognize geometrical features within a part and automatically assign their manufacturing complexity. [173] presented an approach that is also able to handle freeform approximations of geometric features and proposes design changes to overcome manufacturability problems.

While many design methods take manufacturing into account, methods that also take post-processing, testing and qualification into account are rare. Product design methods, also focusing on post-processing, have mainly considered issues like supports (accessibility for removal [244], stability [86] and collision avoidance [57] during finish machining of functional surfaces, or design tools to minimize finish milling operations [171]) and thermal post-processing steps. As the production of end-use parts for critical applications is on the rise, testing, qualification and certification becomes more and more important. For low production volumes, as found in AM, non-destructive testing is the norm, but these testing methods all have their own requirements on the product to be tested. For example, for computed tomography (CT) scanning, the minimum size of the pores that can be detected scales linearly with the thickness of the part [299]. Finally, recent research [331] described a framework that considers both post-processing and testing-oriented design for additive manufacturing.

The vision on future needs and expectations

Many examples of product design strategies for various life cycle stages have been presented in this section. Some aspects

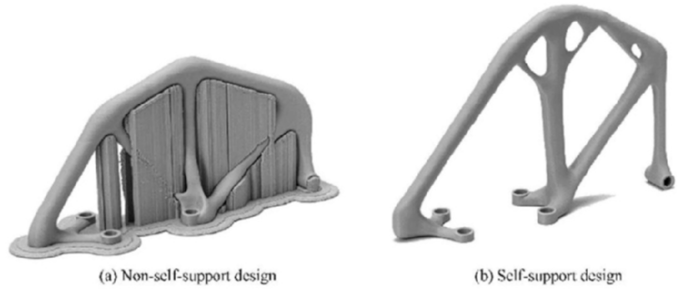

Fig. 3.1.1. Use of Topology Optimization to define self-supporting product geometries.

are, however, still under-represented and are expected to be addressed in future research. One of the drawbacks for AM is the high cost of manufactured parts. Research addressing the link between production costs and design features is required to allow for early cost prediction and design optimization. Furthermore, methods for qualification and certification of AM parts are seen as the next step required for the further integration of AM in such sectors as aerospace, automotive and biomedical. Although the impact of product design on the printing success is known, methods to predict certification potential as a function of product design are still missing (for example, lattice support design inside a conformable channel for structure support and fatigue performance). Further topics to be addressed include artificial intelligence (AI) and machine learning-based methods for product design and optimization. Finally, if real-time monitoring for closed-loop quality control is realized, this might have a profound effect on the geometries that can be manufactured using AM, thus further relaxing design constraints.

Work preparation

Work preparation deals with actions to ensure that the optimal design of the product is realized both from technical and economical viewpoints. It includes tasks such as two dimensional (2D) and 3D part nesting and orientation, design of support structures, slicing and hatching strategies, and selection of optimal process settings. Optimization strategies within work preparation depend on the product design and process chosen, directly interact with other work preparation steps, and co-define part characteristics and required post-processing steps (see Fig. 1.4). As such, research addressing work preparation for metal AM focuses on understanding and optimizing work preparation steps as well as developing rapid and accurate simulation tools for process planning at both the product and build levels.

From Computer Aided Design (CAD) model to numerical control (NC) program

The present problems/challenges

When additive manufacturing moved from prototyping to the production scale creation of products, the requirements on production processes and resulting products have become more rigorous. The steps from the CAD model, over the design of the supports and the build, to the actual machine instructions contribute significantly to quality and economic success of the resulting parts. Many of the steps associated are interrelated and new methods and tools need to be developed to gain insight into those relations that help the designer and the process planner make the right choices.

State of the art and current developments

AM file formats

A number of file formats have been developed for CAD vendor independent representation of part/product information [307]. The Standard Tessellation Language (STL) file format is still the *de facto* standard for transfer of geometric data to the AM machine operating software. It defines geometries by tessellation of the model surfaces using triangles and is applicable for monochrome, mono-material designs. 3D Manufacturing Format (3MF) and Additive Manufacturing Format (AMF) are newer formats that are able to cope with more advanced AM objectives like textures, multi-color, multi-material and material gradients. Both have not reached the penetration level within industry to replace STL. However, as an indication from the membership of the industry consortium, 3MF seems to have better support from industry [1]. Next to product data, file formats have been proposed to support interoperability of processing related information. These mainly focus on exchange of 2D slicing related data, such as Layer Exchange American Standard Code for Information Interchange (ASCII) format (Leaf), Slice (SLC), Common Layer Interface (CLI), Hewlett-Packard Graphics Language (HP-GL), and Multi-Material AM file format (MAMF), and storage and exchange of data related to all additive manufacturing process steps [256].

Design of support structures

For some AM processes, a level of natural support functionality is available within the process, as, for example, powders providing support for layers built above [119]. In many cases however, support structures are required by the designed geometry or the AM process and these can affect product quality, material utilization, (post) processing time, and cost.

Within laser powder-based fusion (PBF-LB) of metals, support structures are required to be thermally conductive so as to reduce the buildup of thermal stresses, while rigid supports are required to help buttress overhanging faces, and to constraint the part while being produced or during post-processing (machining or thermal treatment). Research on support structure optimization focuses on reduction of printing time, costs, and post-processing effort [174]. Part orientation strategies focus on the reduction of support volume, printing time and beneficial support locations over product faces, while meeting the requirements of geometric dimensioning and tolerancing. Many strategies on the optimization of support structure geometry have been developed, focusing on reduction of support volume while maintaining the functional characteristics of these structures [[174]] or, for example, reduction of vibrations during post-process machining [86]. Contact free supports have shown a positive effect on reduction of part curl and dimensional accuracy compared to non-supported geometry [70]. Finally, much research has been conducted to optimize the product geometry to reduce the need for support structures (see Fig. 3.1.1) [420].

Part orientation

The orientation of parts in the build space impacts surface and shape quality (including dimensional tolerances and warping) as well as build characteristics like costs, time, build volume utilization and suitability for post-processing [214]. Furthermore, in powder-bed based processes the correct orientation of the part relative to the recoater movement may reduce the forces on the printed part and increase the success of the process [306]. As such, part orientation is considered a multi-objective optimization problem and many, mostly genetic algorithm based, solution strategies have been proposed. Leutenecker-Twelsiek [214] proposed to include optimal part orientation early in the part design process and developed a method for optimization of orientation at the feature level. Langelaar [209] proposed a topology optimization strategy that combines part topology, support structure optimization and part orientation, showing the applicability of the strategy in 2D. Lastly, support-free parts can be realized by local part orientation relative to the build direction using 5-axis deposition strategies [400].

Process settings

Depending on the type of AM process, many process settings can be selected to optimize the AM process. For metal AM, the use of energy to locally melt the material is among the most important process parameters.

In PBF-LB processes, the laser is used to supply an additional dose of energy to locally sinter/melt powder particles, resulting in solid material after cooling down. At high processing speeds, a required dose of energy thus transforms the powder to consolidated solid material with the associated microstructure and mechanical properties, with some residual stresses. Although there are various definitions related to volumetric, areal, or linear energy density, the energy dose is typically expressed as the Volumetric Energy Density (VED):

$$VED = \frac{LaserPower(W)}{ScanSpeed\left(\frac{mm}{s}\right)*HatchSpacing(mm)*LayerThickness(mm)} \tag{1}$$

The optimal energy dose depends on the material used and local conditions, such as location within the build, local part geometry and local thermal history. The VED is typically set for a finite number of regions of the part (for example core, top surface, side surface/contours, supports, and lattices). There is a large body of work defining VED settings for many powdered materials. Variations in scan speed and laser power at constant VED values have been shown to affect the width and depth of the melt pool, which in turn affect the amount of key holing pores and particle fusion [74,236,416].

Slicing and hatching

In most AM processes, parts of a build are sliced into layers to be produced sequentially. For each (planar) slice, a pattern is defined. The controller interprets the patterns and defines commands that ensure that the laser or print head locally solidifies the material. The design of these so-called 'hatching patterns' has an impact on printing accuracy, speed, cost, material properties, and residual stresses. For AM processes that only deposit material where required (for example Directed Energy Deposition (DED) or Material Extrusion) research is focused on more advanced slicing and hatching algorithms. Liu et al. [228] decomposed the product/build in a way that allows for staggered processing of parts. This reduces the non-productive movements of the tool but requires continuous collision detection/avoidance during production (Fig. 3.1.2a). Pelzer and Hopman [294] used a nonplanar path planning algorithm, with a material extrusion rate dependent on variable layer height, to produce freeform top surfaces (Fig. 3.1.2c). In another work, slicing was recalculated, based on scan data of the previously deposited layer, during wire-arc AM (WAAM) [326]. They indicated that as-printed dimensions are better approximated, resulting in reduced post-processing efforts. Others have developed a part decomposition strategy to minimize surface roughness per section by intermediate reorientation of the part (Fig. 3.1.2b) [269]. Finally, the part may be divided into interior and surface sections, and different slice settings may be used for the different regions (Fig. 3.1.2d) [232].

The vision on future needs and expectations

Development efforts on software that focus on (integrated) product design and work preparation steps will continue to intensify. Design freedom of parts will be further used to optimize for subsequent processing steps while software focused on work preparation will support decision makers in better balancing the often opposing effects related to design and work preparation.

State-of-the-art research is directed at AI and machine learning in combination with real-time sensing (acoustic, thermal, optical, among others) for parameter prediction and optimization, manufacturability prediction, and in-situ quality monitoring [176,345]. For example Phua et al. [297] propose the usage of a digital twin that combines surrogate modeling, in situ sensing, machine control systems and intelligent control algorithms to overcome printing defects and quality issues while enabling qualification and certification. He et al. [145] states that AI enables closed loop process control of WAAM, which is stated to be critical for ensuring process stability and repeatability. The paper furthermore presents an extensive overview of research focusing on the application of AI related to the design stage, to deposition control and to offline parameter optimization.

Developments to strengthen the strategic position of AM (batch-based production, closed loop quality control and start-stop control for embedding devices) will also impact the requirements and tools associated with pre-processing in ways that have yet to be investigated.

Modeling and simulations

The most common metal AM processes start from either a powder or wire form of metal alloys or elementary materials. Due to the fact that materials are built at every local point while making a product, and the fact that it is extremely expensive, if not impossible, to physically sense or examine material microstructure evolution at locations of interest, the ability to model and simulate AM processes and post-processes is essential for moving the technology forward. While the remaining of this section mainly focuses on the simulation of laser powder-based AM processes, the fundamental mechanics, such as solidification and residual stress prediction, applies also to other types of metal additive manufacturing processes.

The present problems/challenges

The main challenges of AM modeling and simulations are the multi-physics nature and the multi-scale dimensional and temporal nature shown in Fig. 3.2.1 summarized by Cao and Wagner of Northwestern University for the 2019 National Academies workshop on Data-driven Modeling for Additive Manufacturing of Metals [270]. Therefore, one needs to consider different mechanisms and scales in building up the corresponding simulation models depending on the intention of the model, e.g., understanding the fundamental mechanism of keyhole formation, understanding the effects of material compositions and thermal history on the final mechanical properties, considering the design of a laser scanning path for a local area or for a large component, considering use of the model for closed-loop process control, and considering simulation of the residual stress or surface finish for analyzing fatigue behavior of built components.

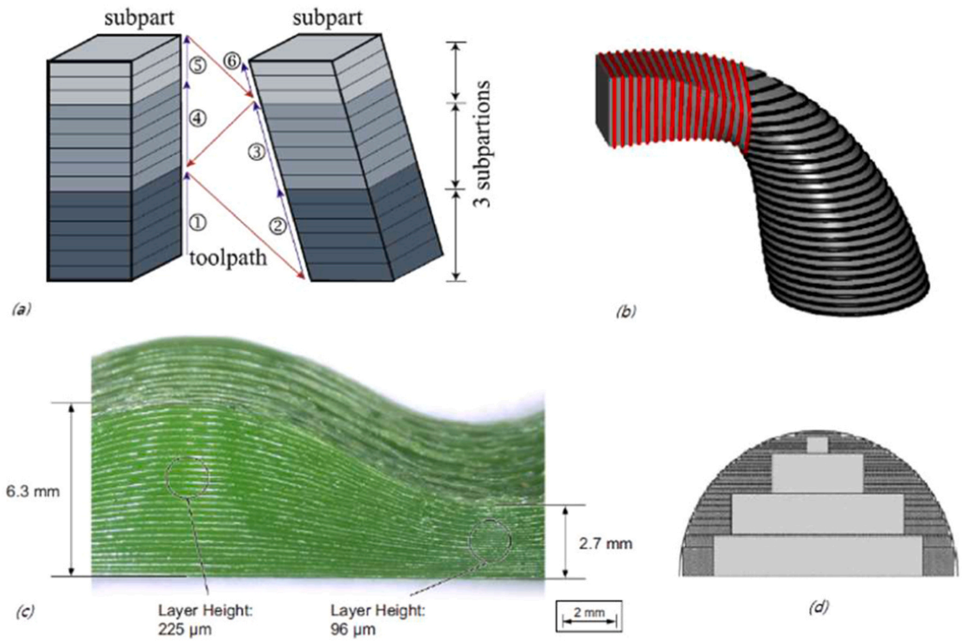

Fig. 3.1.2. (a) Staggered processing of parts [228], (b) Surface roughness reduction [269], (c) Extrusion rate dependency [294], (d) Variable layer height [232].

State-of-the-art and current developments

The state-of-the-art is summarized into two categories: understanding of the primary process mechanics, and rapid process simulation tools for process planning.

Understanding of the primary process mechanics

For powder-based AM processes, models and simulations for understanding process mechanics include:

- Interactions among solid powder particles in the powder bed coating (spreading) process are often simulated using the discrete element method (DEM) [82], Chen et al., [56] to capture the essential mechanisms, while considering the powder's rheological behavior, shape, and size distributions. Fig. 3.2.2 shows a snapshot of the resulting porosity after one coating pass [56]. Note the stochastic nature of powder morphology after powder spreading, which indicates the need of having advanced simulation tools to take this phenomenon into account particularly when multiple layers are simulated. Fan et al. [102] considered the dynamic contact and deformation mechanism in a multiple layer powder bed using the discrete element method in the incremental updated Lagrangian framework. However, DEM is computationally expensive and neural network-based machine learning methods have been used to create a powder spreading process map [414].
- The interaction between powder particle and gas-liquid interface in DED, considering particle speed, has been simulated using the Volume-of-Fluid (VOF) method [411], which shows that particles carry the gases into the melt pool. Furthermore, the interaction between particles and the melt pool was simulated using a coupled multi-physics particle-scale approach utilizing the DEM for particle trajectory prediction, the computational fluid dynamics for free-surface thermo-fluidic modeling and the cellular automaton method for grain growth evolution (see Fig. 3.2.3) [4]. They found that the role of the Marangoni convection is less significant than the momentum imparted by the impinging powder particles in the melt pool.
- Melt pool dynamics have been extensively studied, particularly, for PBF-LB, based on computational fluid dynamics to model multiphase flows and fluid-structure interaction, including significant developments by commercial software firms in recent years, such as ANSYS Fluent, ESI's OpenFOAM, and Flow-3D® by

	Critical Length Scale (*m*)	Normalized Length by that at the part scale
Part	10^{-2} - 1	1
Feature size	10^{-5} - 10^{-3}	~10^{-3}
Powder	10^{-5} - 10^{-4}	10^{-2} ~ 10^{-5}
Doping	10^{-9}	~10^{-8}
Beam spot	10^{-6} - 10^{-3}	~10^{-3}
Melt pool length	10^{-4} - 10^{-2}	10^{-4}-10^{-2}
Melt pool depth	10^{-5} - 10^{-3}	~10^{-3}
Mushy zone	10^{-6} - 10^{-4}	~10^{-4}
Grain	10^{-6} - 10^{-2}	10^{-6} - 10^{-2}
Dendrite	10^{-7} - 10^{-6}	~10^{-5}
Crack	10^{-6} - 10^{-2}	10^{-6} - 10^{-2}

	Critical Time Scale (*sec*)	Normalized Time by that at the build scale
Part life	10^{7} - 10^{9}	~10^{4} - 10^{7}
Build time	10^{2} - 10^{4}	1
Layer time	10^{0} - 10^{2}	~10^{-3}–10^{-2}
Solidification timescale	10^{-4} - 10^{-3}	~10^{-6}
Thermal diffusion timescale	10^{-5} -10^{-3}	~10^{-7}
Thermal convection timescale	10^{-5} -10^{-4}	~10^{-7}

Currently not simulated at the part level
Needed at the part level
Desired to be simulated

Fig. 3.2.1. Critical length scales and time scales in AM.
Adapted from Tables 4.2 and 4.3 of NAE workshop [270]

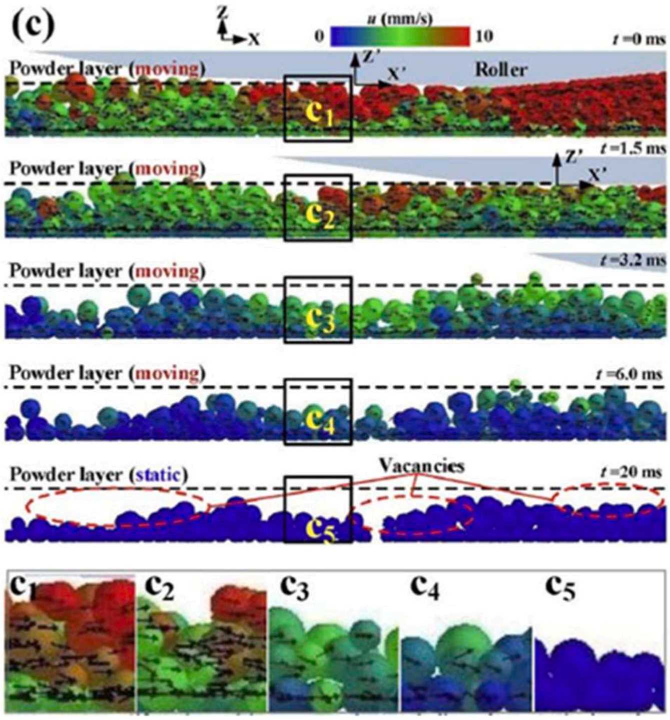

Fig. 3.2.2. Simulation results of powder spreading. The black arrows in the enlarged views (c1-c5) denote the velocity directions of particles [56].

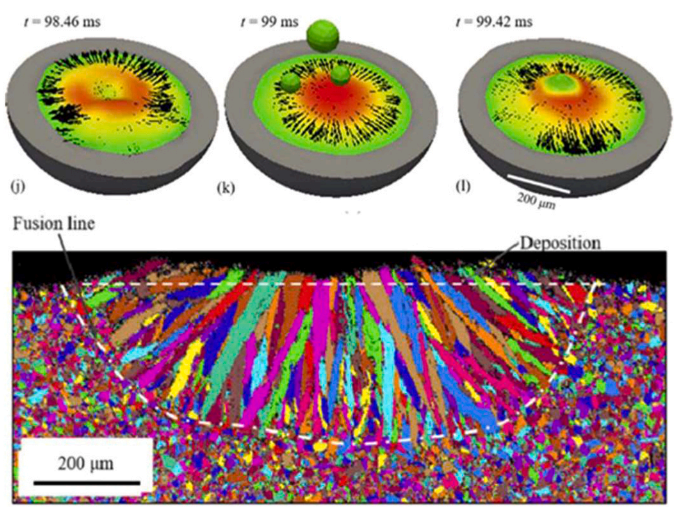

Fig. 3.2.3. Upper row – Simulation results of the melt pool evolution, particles impingement, ripple formation, and temperature contour in DED, and bottom-row: one sample resulting grain color map from EBSD at a central cross-section of a single spot deposited by DED. [4].

Flow Science. A 2020 review article on this topic [69] not only presented the main approximations and assumptions in common modeling methods, but also illustrated the capabilities of the leading simulation groups around the world, which provides readers a good means to continue tracking the latest developments in this field. A different approach was taken in a 2021 review article of simulation methods [30], which organized literature based on the involved length-scale and physics.

- Additionally, it is noted that the evolution of the solid phase and fluid-solid interactions in the melt pool has not been captured in the particle methods for PBF-LB, and there still lacks a realistic and stochastic heat source model with experimental validation. The success in modeling of melt pool dynamics for multi-layer cases and the adhesion of partially melted powder particles to the solidified surface can provide the needed predictions of surface topography at various geometric setups (horizontal, vertical, upskin or downskin) [341].
- Microstructure evolution, including grain growth, grain orientations, grain morphology, phase changes, is critical to the resulting mechanical properties and product performance. The phase-field method, a diffuse-interface method for modeling interface evolution, has been used in modeling microstructural evolution [183]. A phase-field model suggests strong dependency of dendrite orientation and surface roughness on scan speed [2]. A new recursive scheme was derived for efficiently capturing the complex grain morphologies in AM that often have a mixture of columnar and irregularly shaped grains, as shown in Fig. 3.2.4 [50]. The resulting microstructures can then be used in crystal plasticity simulations for predicting the resulting mechanical properties [118].

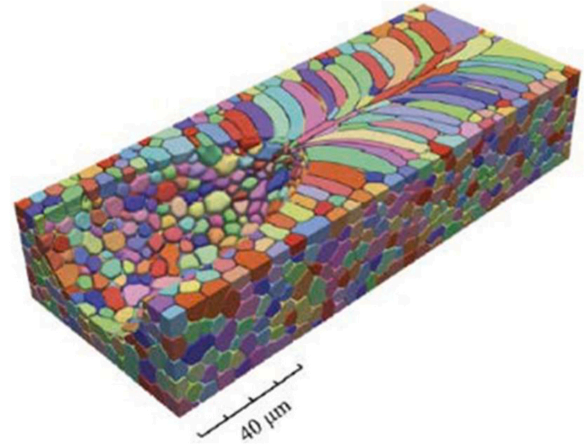

Fig. 3.2.4. 3D simulation showing the inverse pole figure of the microstructure of 316 L stainless steel [50].

Rapid process simulation tools for process planning

While the physics-based modeling as discussed above provides many insights about various mechanisms happening at different length scales and time scales associated with complex AM processes, they require massive computational resources and time, making them infeasible for most time-sensitive applications.

For example, for the volume shown in Fig. 3.2.4, the simulation had a wall time of 20 h [50]. A physics-embedded graph network (PEGN) is proposed to leverage an elegant graph representation of the grain structure and embed the classic phase field theory into the graph network and achieved 50X speed acceleration [402]. Rapid part-scale modeling is necessary for process planning. An explicit AM finite element simulation package, Generalized Analysis of Multiscale and Multiphysics Applications (GAMMA), has been described [348] specifically for AM to solve the transient heat transfer equations incorporating the nonlinear behavior caused by the thermodynamic properties of the material during the non-equilibrium solution. The GAMMA code was further accelerated using Graphical Processing Units (GPU) [264]. Speed-ups of about 100x – 150x compared to an optimized single CPU core implementation were achieved, making it feasible to simulate the temperature history of the entire build in less than 1/10th of the physical build time [264]. Similar works have been conducted in other research groups as discussed in two review papers [30,69]. Additionally, many analytical and semi-analytical solutions have been proposed to offer a trade-off between computation cost and accuracy of high-fidelity models. Some models were extended for multi-track and multi-layer cases [156,278,339]. Despite the recent progress in the field,

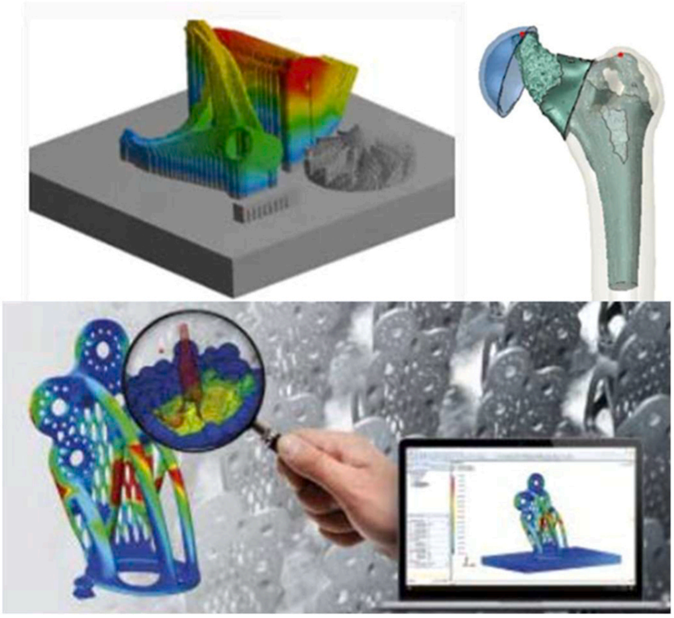

Fig. 3.2.5. Sample AM simulation using commercial packages [Ansys [8]; Simuleon [344]; ESI [422]].

analytical solutions deviate from realistic responses even in moderately complex geometries as the analytical solutions include numerous simplifications and/or assumptions. Commercial software firms [Ansys [8]; Simuleon [354]; ESI [98]] with traditional strength in CAD and/or finite element method (FEM) have been actively developing their AM simulation solutions with promising results, some with the integrated computational materials engineering (ICME) approach as shown in Fig. 3.2.5.

While simulation tools have shown the promise and the capability to rapidly predict thermal history at the part-scale, predicting residual stress, geometry, surface finish, and resulting fracture and fatigue performance remains a challenge. Due to inherent rapid heating and cooling cycles during AM, significant residual stresses are generated, that can result in build failure and dimensional inaccuracies if not addressed properly. Unlike the temperature field, experimental measurements of residual stresses and distortion are time-consuming and very expensive [268]. Therefore, developing robust and efficient models to predict residual stresses are of paramount importance. Thermomechanical FEM simulations have been widely used to predict the residual stress in AM processes. In most of the existing models, the thermomechanical simulation is performed in two steps: 1) thermal simulation for calculating the temperature field; and 2) substituting the strain due to thermal expansion into the stress equilibrium equation, such as the inherent strain method to efficiently and accurately predict residual stress and distortion in PBF parts [58]. To speed up the simulation, step 2 is executed layer-by-layer rather than following the laser path point-by-point (see Fig. 3.2.6) [268].

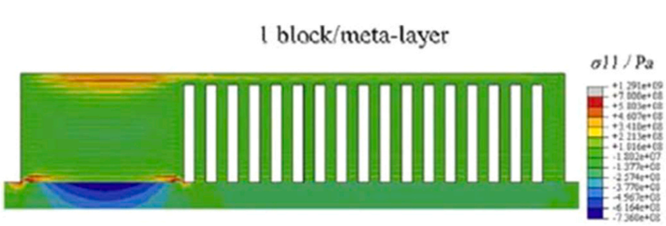

Fig. 3.2.6. The predicted residual stress right before the cutting step using flash heating with 1 block/meta-layer [268].

The vision on future needs and expectations

Temperature-dependent anisotropic material properties

Material properties, particularly temperature-dependent properties, are critical to the accuracy of numerical simulations. For example, to represent melt pool dynamics accurately, temperature-dependent surface tension and wetting forces, Marangoni effects, and evaporation-induced recoil pressure need to be taken into account. Under the constraint of experimental measurements, it is recommended to develop a model system and utilize an advanced in-situ monitoring system with an extra high sampling rate to develop an open database of both temporal and spatial anisotropy dependency of properties. The combination of both in-situ and ex-situ experimental data with numerical simulations should be explored to calibrate critical material parameters using the latest data-driven methods. Once these critical material properties parameters are determined for a simple model system, to achieve the generalizability over unseen complex geometries, a recently developed Recurrent Graph Neural Network (RGNN) architecture may be used [263].

Physics-based data-driven models

In recent years, data-driven modeling has received significant attention for contributing to the modeling, design and control of advanced manufacturing processes [43,405], as summarized in a 2022 review article [265]. It was noted that the majority of recent machine learning (ML) methods have been implemented for additive manufacturing [65,87,89,188,223,274,286,296,305,351,422]. Those approaches were developed to train the ML model to establish a function mapping between input and output data, that is, it learns a specific model whose performance is determined by the training data properties. Deep learning-based approaches stand among the most studied and applied methods due to their strong capability for handling complex modeling and decision tasks. Hybrid models that utilize both experimental and simulation data have merged to improve the prediction accuracy and to reduce the computational cost. For example, Moges et al. [260] proposed an unbiased model-integration method combining physics-based, simulation data, and measurement data for approaching a more accurate prediction of melt-pool width. Du et al. [89] proposed the hybrid model for detecting balling in laser powder bed fusion. Liao et al. [221] developed a physics-informed neural network combining a partially observed temperature data measured from an infrared camera with the physics laws to predict full-field temperature history and furthermore, to discover unknown material and process parameters. However, further study of architectures and engineering implementations is needed for handling noise/uncertainties, feature extraction, and transient boundary conditions that will be critical to qualification and certification [120].

Optimization at the level of work preparation and process chain

The present problems/challenges

To enable economic production of large product volumes through metal AM, work preparation and post-process chain planning need to be considered. Several subtasks of the work preparation for the AM process are already (or at least partially) automated, such as part orientation for minimizing build height or amount of support material, generation of supports, part slicing, layer hatching, scanning strategy, process parameter determination, etc. However, the integration of those subtasks into a global automated AM work preparation system is missing: see e.g., Section 2 for integration with part design, Section 3.1 for optimization of the whole trajectory from part model to NC programs, and Section 3.2 for physics-based modeling of the AM process. However, currently many process planning and work preparation tasks still must be done manually.

Yet, further automation and optimization of work preparation are likely to yield substantial economic benefits. In particular, the following work preparation activities offer promise:

- Combining and nesting of different AM parts in one build job,
- AM-specific scheduling for a mix of heterogenic products,
- Selection and scaling of AM production processes,
- Extending the work preparation for the AM process to include the pre- and post-process chain planning.

The idea of **nesting** describes technology-specific orientation and positioning of several products within one build chamber of an AM-machine [10], which takes the advantage of the geometrical design freedom of AM. The possibility of creating complex geometries results in the idea of building several parts within one build job, or even within each other part [10].

To fully utilize the potential of nesting for AM production, an integration of nesting approaches with production scheduling is necessary [63]. Optimizing the **production schedule** for an industrial AM machine park is an ongoing challenge, which is based on two key phenomena, especially for metal AM. Firstly, the low process stability requires an experience-based control of scheduling decisions. Quality control is necessary for each new combination of build job and AM machine. Secondly, the above-mentioned nesting of different products within one build job yields the potential for optimizing the production scheduling and thus needs to be integrated in AM-specific production scheduling optimization problems.

Aside from scheduling and nesting products, a challenge for metal AM concerns **process selection and scaling**, based on product requirements and economical production volumes. Due to the different process characteristics, among metal AM processes, and limited knowledge about emerging AM technologies, a holistic decision regarding the best metal AM technology for a part is difficult. The usually limited availability of materials for metal AM processes restricts the possible technologies and the achievable material properties [410].

Finally, in addition to selecting the ideal AM technology for a given product, the **pre- and post-process chain planning** remain challenges [194]. Based on the product requirements, specific pre- and post-processes are obligatory, e.g., hot isostatic pressing (HIP) for turbine blades or machining for precision parts. Moreover, certain industrial branches require safety and health related certification and quality control, e.g., for airplane parts or medical endoprostheses [330]. In addition to product related requirements, AM technologies usually require specific post-processing steps, such as de-powdering for powder bed fusion (PBF) based processes or binder dispersion for certain binder-based processes.

State of the art and current developments

In general, the process of **nesting** can be divided into two methods. The positioning in one spatial plane, called 2D nesting, is possible for all metal additive technologies. 3D nesting, which also enables the position of parts above or within each other, is currently a focus of research in academia and industry.

All powder bed based multi-step-metallic technologies are able to position green bodies of products on top of each other during their consolidation process. In contrast, technologies based on DED as well as sheet lamination technologies are not able to use 3D nesting because of their fundamental process characteristics. In addition, 3D nesting is not desirable for some processes because of the cost of removing support structures in the post-processing phase or because of the influence of heat diffusion [415]. For PBF-based processes that use an electron beam as source of fusion (PBF-EB), 3D nesting maybe possible. For powder PBF-LB, 3D nesting is currently not possible due to residual stresses induced by the laser beam requiring connection to the base plate for each product in the build job [330].

Several approaches exist to optimize the number of possible parts within one build job [10,47,63]. Canellidis et al. [47] as well as Zhang et al. [415] suggested genetic algorithms for the 2D nesting of parts on the platform of the machines, which can be transferred to metal AM. Arndt et al. [10] developed and implemented a conceptual algorithm for 3D nesting that employed multi-criteria optimization. Chergui et al. [63] proposed a novel heuristic for 2D-nesting.

In regard to **production scheduling**, one of the first work on efforts to integrate 2D or 3D nesting problems into scheduling algorithms was published in 2018 [63]. This work mostly focused on tardiness and machine utilization. Current solutions usually center on 2D or 3D nesting problems to increase machine utilization through minimizing empty build volume. The optimized build jobs are consecutively used as input for the scheduling problem, which tries to minimize the delay of all orders as was shown by Chergui et al. [63].

Several approaches exist to support **process selection** [237], but due to the fast development of technology improvements and the emergence of new AM technologies, wide adoption of those proposed approaches is difficult [410]. Planning complex AM-based production sequences, such as combining conventional forming processes with AM technologies in one process chain, is an ongoing research issue [170,316]. For **production scaling**, AM offers high flexibility based on tool-free production. For a larger production volume, careful planning and process selection for production ramp-up and ramp-down becomes increasingly important. One example of combining PBF-LB, binder jetting, metal injection molding, and conventional powder metallurgy from a manufacturing company, GKN Ltd., is depicted in Fig. 3.3.1 [178].

Lastly, the selection of the best process and machine for **pre- and post-processing** steps is a complex and largely neglected area of research [194]. Rapid development of new AM technologies and domain specific development of support processes by AM-machine producers offer a dynamic variety of possibilities. First, planning approaches not only focus on selecting the ideal support process sequence for a given AM technology, but also balance the machine specific capabilities to improve the throughput of AM based process chains [194]. Exemplary PBF-LB process chain concepts are shown in Fig. 3.3.2. They are characterized by the use of multiple chambers (2) or modular, transportable chambers (3 and 4), so that non-value-added pre- and post-processes can be removed from the build chamber and can be run in parallel with the value-adding build process.

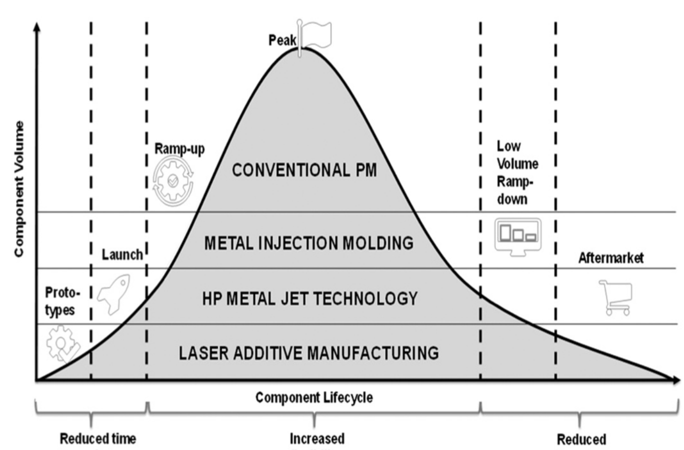

Fig. 3.3.1. Combination of metal AM and conventional technologies over the life-cycle of large volume powder metallurgy parts.
Adapted from [178].

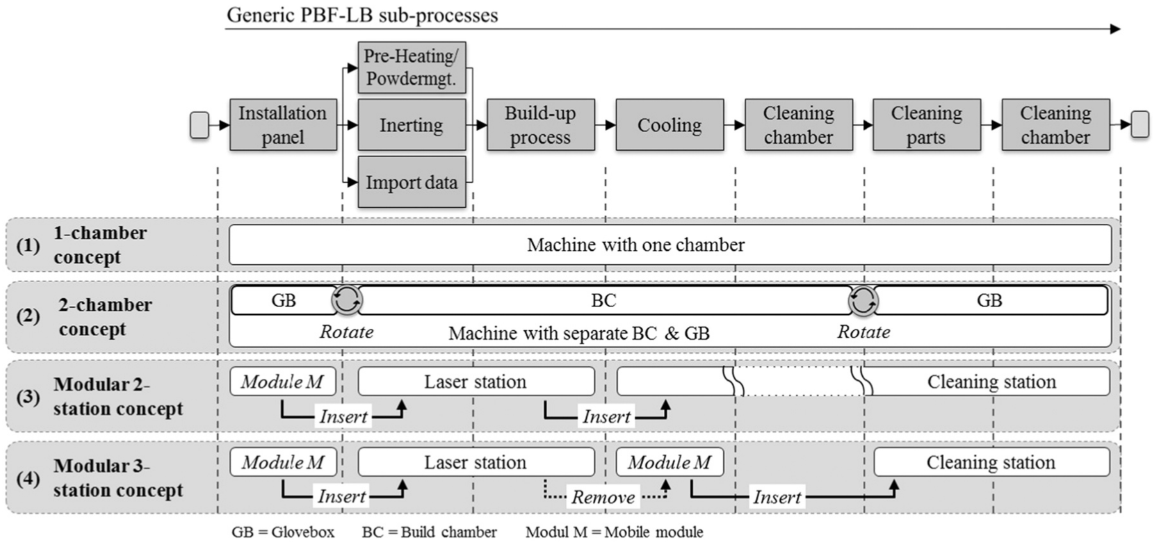

Fig. 3.3.2. PBF-LB process chain concepts for improved throughput [193].

The vision on future needs and expectations

Nesting is expected to lead to an improvement of the economic performance of AM by increasing machine utilization [298]. This is achieved by better utilization of the available build space as well as by reducing the number of non-value-added loading and unloading steps of AM machines. Further improvements are expected based on more advanced manufacturing technological capabilities as well as improvement of nesting algorithms. Nonetheless, technology-specific challenges for nesting parts exist (e.g., due to residual stress induced in metal PBF-LB processes and therefore required support structures) and have to be solved.

A fully integrated solution of nesting and **scheduling** has not been developed yet, but is expected in the near future due to the need of more economic AM production. Combining **process selection and scaling** approaches will lead to an improvement of economic AM production by fully utilizing its technological flexibility. Finally, optimizing the **pre- and post-processing** in combination with the AM technology will enable increasing competitiveness of AM production in comparison to other production technologies.

Overall, the work preparation for AM application yields high potential to enable the economic production of higher product volumes in the same amount of time. It is expected that research in this area will continue to support a growing number of industrial applications and increasingly complex planning.

Production by AM

This section deals with AM itself or production using AM. AM production calls on an AM process that requires an AM machine and AM material to be processed on the machine. This is represented as a triangle in the middle of Fig. 1.4 (see three boxes with red text): the top vertex represents “AM processes” resting on “AM machines” (bottom left vertex) and “AM materials” (bottom right vertex): this triangle represents the interaction and intertwining between AM “process”, “machine”, and “material”. In what follows, subsections will be devoted to each of these three items. However, the subsection on “AM processes” will be split in two to discuss first the AM processes themselves, followed by a separate subsection discussing how AM processes can be combined with other processes into what is referred to as “hybrid processes”. At the end, a separate section is devoted to “in-situ process monitoring and real-time control”, a trendy AM subject that is, again, very interlinked with the process (that is being monitored and controlled), the machines (required sensors, hardware and software), and the material being processed (and possibly being observed and controlled during processing).

Individual metal AM processes

Metal AM processes are becoming more and more technically mature. AM parts are no longer just used as mere prototypes but are being utilized in various fields in industry and medicine. A comprehensive overview of (metal) AM processes and related terminology and abbreviations is given in ISO/ASTM 52900 [165]: please refer to this standard for the extended abbreviations given below.

Metal laser powder bed fusion (PBF-LB/M) and laser directed energy deposition (DED-LB/M) are the most widely used processes [396] and are therefore discussed into more details in the following sections. The basic principles of these processes are described in previous work [330]. Besides the above-mentioned ones, there are numerous other relevant metal AM-processes ranging from electron beam processes (PBF-EB/M, DED-EB/M) [113,130,409], wire-based or directed-arc DED (DED-Arc) [190], ultrasonic sheet lamination (SHL-UC/M) [190,215]. The later paper [190] also describes some more exotic or ‘unconventional’ metal AM processes (like friction or resistance AM) which are not further discussed here.

Besides the previous single-step processes (SSt processes according to [165], there are also two-step or multi-step approaches (MSt processes according to [165] comprising printed green parts and subsequent polymer debinding and sintering or infiltration (e.g. BJT-MSt, PBF-LB-MSt/M/PA, MEX-TRB-MSt/M/ABS, VPP-UVL-MSt/M) [123,309]. Such multi-step processes will only be discussed shortly in this Section 4.1 (on AM processes) and will not be discussed in Section 4.4 (on materials for metal AM) as this paper focuses on one-step or direct metal AM.

Some newer processes – that are hard to classify using the present ISO/ASTM 52900 process classification structure and abbreviations – are occasionally discussed as well: e.g. cold gas dynamic spray deposition (a cold-spray variant of material jetting AM or MJE-CS/M) [311] or wire-based molten/liquid metal deposition (a metal-wire-based material extrusion or MEX process) [376,399].

The present problems/challenges

Despite the wide range of different metal AM processes, the underlying principle is identical: an automated system uses layer-wise deposition of material, based on digital data, to form a part geometry [330]. This facilitates the high degree of design freedom and flexibility that is attributed to additive manufacturing. However, compared to conventional manufacturing technologies like casting or forming, the layer-wise generation of parts has some disadvantages that must be overcome to open up new applications.

The first and foremost point that must be addressed to support further growth of AM technologies is to increase productivity and to lower costs. This includes improvements of the processes themselves and also automation of pre- and post-processing steps (see Section 3 and Section 6).

Second, further research regarding AM-specific materials (see Section 4.4) and the influence of the conditions during AM processing on the resulting material properties is necessary. This does also include multi-material and tailoring of material properties by controlling the process conditions (e.g., solidification and intrinsic heat-treatment).

Third, the reliability of AM processes must be further improved. Since parts are generated in numerous steps layer-by-layer, the chance for defects or anisotropy is accordingly high. A further challenge for quality control is that AM parts are often manufactured as unique pieces or in small batches, and iterative process development – which likely includes destructive testing of the parts – is consequently not an option. Hence, effective online process monitoring and process control systems (Section 4.5) have to be developed to increase reliability and part quality. This point goes also hand in hand with the build data preparation and simulation (Section 3), while processing (this Section 4) and post-processing (Section 6) are crucial for process stability.

State-of-the-art and current developments

Existing AM processes are continuously improved and new processes are constantly being introduced. While the basic process principles of important metal AM processes like PBF-LB and DED-LB are described elsewhere (e.g., Schmidt et al. [330]), the following section provides an overview of recent developments and research activities that address at least one of the above challenges and have the potential to further promote the application of metal AM technologies in the future.

Beam shaping. Typical laser beam sources for the PBF-LB/M process are single-mode fiber lasers with a Gaussian beam profile and powers between 100 W and 1000 W [157]. However, other beam profiles can be beneficial for processing hot-cracking sensitive alloys, reducing spattering or increasing surface quality and process speed. Currently, different approaches for metal PBF-LB with modified beam profiles are being researched. Matthews et al. [242] investigated the effect of elliptical and Bessel beam profiles on the metal PBF-LB process and confirmed a strong impact of the beam profile on the process and the resulting microstructure. In their experiments the beam profiles were realized by specialized lens systems. Further possibilities for tailoring beam shapes are diode lasers, combinations of multiple laser beams, diffractive optical elements [314] or special optical fibers [33,144]. While these approaches still included scanning of the part cross-section, the next visionary step would be an areal exposure to fuse part sections or even complete layers in one step. This approach is already used for polymer-based AM (including HP's metal jet fusion process involving a polymer binder) to cure UV-resins. In most cases a digital micro-mirror device is used for light distribution. Current technology is however limited to laser powers in the 100 W range. Provided that corresponding beam shaping technology for multi-kW applications is developed, areal exposure has the potential to significantly speed up metal AM. Currently, the application of tailored beam profiles has been demonstrated only in laboratory-scale experiments. However, in future PBF-LB systems, tailoring the beam profile can provide an additional lever for controlling the metal PBF-LB process and can therefore contribute to an increase in part quality, process stability and productivity.

Multi-material and spatially resolved material properties. The principle of AM holds not only the potential to tailor the desired part geometry but also the material properties within a part. This facilitates manufacturing of optimized parts, with for example, a wear-resistant hull and a ductile core or with favorable anisotropic properties that are adapted to the load case. This, however, requires the adjustment of machine technology (Section 4.3) and correspondingly additional process development. While multi-material processing within DED processes [388] and even more in cold gas spraying [311] can be realized comparably easily, it requires heavy modification of PBF systems, since the deposition of multiple powder components is more challenging [383]. Possible solutions that have been demonstrated at the laboratory scale are either vacuum removal of powder layers and subsequent recoating with a second material [36] or nozzle-based deposition systems [27,386,387,388,406]. An recent and original development is the raster- and pixel-based powder deposition system developed by Aerosint, Belgium, a company acquired by Desktop Metal in July 2021. This system will be further described in Section 4.3 on 'machines for metal AM'.

In addition to powder deposition, metallurgical effects must be considered, as some metal combinations tend to form an undesired brittle phase in the transition zone (e.g., Cu and Al). This problem is avoided in cold spray deposition AM, since no material is melted. Besides multi-material, microstructural features in single materials, such as grain size and grain orientation, can be controlled by the conditions during AM and harnessed for locally tailored material properties in metal AM parts. This has been demonstrated for aluminum alloys by Rasch et al. [315] or for titanium and nickel alloys by Pobel et al. [300]. While recent scientific progress has demonstrated the potential of multi-material metal AM parts or single material parts with tailored microstructure, these approaches are in their infancy and require further development.

Process monitoring and online quality control. Effective process monitoring systems for metal PBF or DED processes hold the potential to increase part quality and reduce the effort for process development by establishing a closed-loop process control for increased process stability. Possible approaches for process monitoring include thermography [208], photodiodes and pyrometry [135], camera-based methods [96], and acoustic emissions [195]. For PBF-EB, backscattered electron detection has been proposed by Pobel et al. [301]. To establish closed-loop process control, real-time data processing is required, which necessitates powerful hardware and software and further research to correlate sensor signal with actual process events. This topic will be covered in detail in Section 4.5 (in–situ process monitoring & control).

Two-step AM processes. In contrast to direct AM methods, two-step methods generally comprise printing of a green part employing feedstock material consisting of metal powder and a polymer binder or solvent with subsequent debinding of the polymer and sintering or infiltration of the remaining porous additively-shaped metallic part. For printing of the green part, low cost AM methods like extrusion-based AM (ISO MEX-MSt/M) or binder jetting AM (ISO BJT-MSt/M) can be used, since no fusion of high melting metals is required. Furnace debinding and sintering processes are already well established for metal injection molding and are easily scalable. Comprehensive reviews of extrusion-based printing with regard to two-step AM are provided by Rane and Strano [309] and Gonzalez-Gutierrez et al. [123]. Furthermore, advanced system technologies are available for powder bed approaches, e.g., binder jetting (BJ), and droplet-based methods such as material jetting. These processes are within the scope of current research activities and gain interest due to their high flexibility and cost-saving potentials.

Another promising two-step approach to lower manufacturing costs of metal parts is indirect AM. This approach comprises printing of sand molds and subsequent metal casting [308]. The elaborate melting process for the production of a dense metal body is outsourced from the actual AM step to a subsequent casting process. This has the potential to lower costs, as no expensive equipment like high-power lasers or electron beam guns are required during AM and the energy to melt the metal is provided by a simple melting furnace. By assembling multiple printed sand cores, complex geometries can be realized. Since the metal part in these indirect processes is not produced by AM itself, no attention is paid to those processes in the other sections of the paper.

The vision on future needs and expectations

Current and future needs with respect to metal AM processes include cost reduction, increased productivity, and process stability as well as a tighter control of the resulting material properties that may involve multiple materials. Evolutionary enhancement of existing technologies, such as multi-laser systems, or an increasing level of automation of pre- and post-process tasks, e.g., adjustment of build platforms or removal of finished build jobs, will contribute to these goals. However, more fundamental progress in the following areas is required to bring AM processes to the next level:

- Novel methods of energy delivery to the process zone that facilitate improved control of the spatial and temporal intensity distribution to increase process speed and stability; this includes, among others, beam shaping and areal exposure specifically for high-power processes like PBF-LB and DED.
- AM processes that facilitate tailoring of material properties by a high level of control of the temperature fields during processing or by the introduction of multi-material processes.
- With respect to the former issues, we expect further developments regarding the cooperation of multi-laser or energy source AM processes. Cooperating lasers (or energy sources like electron beams) mean that the lasers no longer operate independently (typically in distinct and separated areas of the layers) for the mere purpose of increasing productivity, but rather they are synchronized to cooperate (e.g., by following one another or moving concentrically), for example to impose a specific spatial or temporal energy profile to the material.
- Novel cost-efficient approaches with good scalability for manufacturing large AM metal parts without expensive equipment by two-step or indirect processes.
- Effective methods for process monitoring and related algorithms to extract process information from raw data in real-time; this enables closed-loop control, thus facilitating increased part quality and reduced process development effort.

Hybrid (AM) processes

When AM-processes alone do not meet the requirements, hybrid processes can be an attractive solution to overcome typical AM-related restrictions. In this context, process chain correlations and impacts have been investigated [137]. AM hybrid processes are defined as the use of AM with one or more secondary processes or energy sources that are fully coupled and synergistically affect part quality, functionality, and/or process performance [333]. This description is derived from the general definition of hybrid processes in manufacturing given by the CIRP collaborative working group on Hybrid Processes [211]. A general objective of hybrid manufacturing is the “1 + 1 = 3” effect, meaning that the positive effect of the hybrid approach is more than the sum of the advantages of individual single processes [332]. Based on that, AM hybrid processes enable adjustment of part properties or processing of materials, which cannot be realized by conventional manufacturing approaches or AM alone. The main goals are the improvement of part quality and performance [333] or an increase in productivity. Potential process combinations are AM plus forming of metal material, AM plus traditional machining processes like milling or grinding [413], AM on sintered substrates like alumina ceramic plates [360] and AM in combination with other laser-based processes like laser re-melting and polishing [252] or laser heat treatment. Some AM processes also combine several non-conventional processes: e.g. combination of laser and ultrasound processing, laser and electric arc processing, etc.

The present problems/challenges

The main challenges of AM hybrid processes are the control and utilization of interactions between the processes to achieve the desired part properties. This requires understanding of the process mechanisms and interaction between the processes that are combined.

Design of hybrid processes. The design of hybrid processes includes the selection of the respective processes to realize the desired part properties. Most of the hybrid AM approaches consider subtractive manufacturing processes such as milling or grinding. Combinations of metal AM and laser-based processes for surface treatment like remelting or laser surface hardening are the subject of current research, as well as the combination of laser additive (e.g., PBF-LB/M) and laser subtractive processes (e.g., laser ablation/erosion). Combinations with forming operations have seen few applications, although there is a high potential of combining forming with additive manufacturing. This includes the specific benefits of forming operations like work hardening, surface smoothing, and geometric precision. To use these potentials, a fundamental knowledge of process mechanisms is necessary.

Control of interactions and process mechanisms. Hybrid processes imply the application of different manufacturing processes to a processing zone, which interact with different process mechanisms. The mechanisms underlie the physics of the singular processes and their combination as a whole. Therefore, the interactions must be understood for each single process and for the hybrid processing approach. To exploit the process mechanism to realize the desired part properties, a time- and position-resolved application is necessary. This can make the integration of measurement equipment into the process space necessary. Besides understanding process mechanisms, it is important to adjust the process to control the mechanisms and use them for manufacturing industrially relevant parts.

State of the art and current developments

The approach of hybridizing AM processing in combination with forming is the subject of several research activities. These focus on different technologies of AM and forming, design of machine setups, investigation of interactions in process chains, and characterization of resulting part properties.

A great potential of AM and forming is that the technologies are applied where necessary to reduce changeover time [250] or shorten production times of AM processes [21]. The integration of different technologies into one machine setup has been patented in some case. These include a device for incremental forming, DED-LB and milling [152], which is integrated for example, in a commercially available hybrid machine (from DMG Mori company), or the application of bulk metal forming directly after depositing a layer of material [22]. Several investigations also focus on process chains consisting of forming and subsequent additive manufacturing to create a hybrid component. Early investigations in this field have been done for titanium alloy (Ti-6Al-4 V) sheet metal forming and PBF-LB [328] or PBF-EB [327], as well for steel alloy (316 L) PBF-LB and forming [287]. The AM process can also be used to manufacture semi-finished products for subsequent forming [346]. Such parts could also be post-processed by milling after AM to receive a defined initial geometry for a subsequent forming operation as shown for incremental forming [302] or rolling [255]. The application of forming and AM can also be more energy efficient than processing the whole part by conventional processes [26]. The AM process could be used for increasing the stiffness of formed sheet metal components by applying additional material on the surface of the formed part [23] or to manufacture semi-finished sheet metal with material accumulation for a subsequent forming operation [24]. The properties of parts manufactured by process combinations of AM and forming have been investigated in different contexts such as bonding strength [329], residual stresses, deviation [138] and distortion [157], formability of sheet metal with additively manufactured material [373] as well metallographic structure [44] and hardness distribution [150].

The concept of a hybrid machine that combines additive and subtractive technologies is suitable to address specific disadvantages related to the AM process, such as residual stresses, low accuracy and unsatisfactory surface finish quality [71]. More than ten companies offer machine tools that combine laser AM processes (often DED) and milling (often 5-axis) [340]. Because subtractive processes are often used as post-processing technology, more details are presented and discussed in Section 6.

Other hybrid approaches combine laser-based AM with other laser processes, like laser-based surface treatment processes [333]. Laser remelting (after each layer is deposited and melted, or after every n^{th} added layers, or after only the final/top layer) is more and more applied on PBF-LB and DED parts to improve the relative density and mechanical properties (by remelting after each n^{th} added layers), or improving surface finish (by remelting only the upfacing surfaces) [252,408]. Laser additive (mostly PBF-LB) and laser subtractive (laser ablation or erosion) manufacturing is another interesting combination that allows for the improvement of accuracy laterally (by laser milling the contours of the layers) or vertically (by reducing the thickness of a deposited and melted layer using laser ablation/erosion). Recent work applied this technique to remove the elevated edges that often occur in PBF-LB at the border of melted layers [254]. Additionally, laser-shock peening has been applied to induce beneficial compressive residual stresses in the material. Thus, the resistance to fatigue and stress corrosion cracking is increased [179].

Researchers have already demonstrated the many benefits of combining several laser processes. For example, surface roughness could be reduced, density raised, geometric accuracy increased, tailored microstructures and mechanical properties can be realized (by hardening or surface treatment) and new possibilities are made feasible (e.g., micro-machining of small holes, slots and ribs, using laser ablation/erosion). Early examples of laser micro-machining are given in Fig. 4.2.1 and Fig. 4.2.2 [408].

The vision on future needs and expectations

AM hybrid processes is a subject of ongoing research. Secondary processes in hybrid AM can be based on forming, machining, laser processing (heat treatment, remelting/polishing, shock peening, ablation/erosion, etc.) or other non-traditional processes (ultrasonic, electric arc, plasma processing). However, with a few exceptions (like combinations with milling or laser remelting), most other combinations are only in an early development stage. Laser-based secondary processes are especially interesting as they can be easily integrated in laser AM machines, possibly using the same laser and scanner mechanism. Future needs include the following:

- New machine concepts need to be developed to utilize the benefits of hybrid manufacturing processes to the fullest by a targeted improvement of the material properties.
- Advanced in-situ sensing technologies are needed to collect process data and derive associated control strategies and adjust manufacturing parameters to fabricate products in a final or close to a ready-to-use state (see Section 4.5).
- Design and product development guidelines need to be rewritten to fully exploit the benefits of singular additive and hybrid manufacturing processes (see Section 2).
- Inevitably, simulation tools and models will be required to avoid cost-intensive iteration in designing the manufacturing processes and getting closer to the “first-time-right” principle (see Section 3.3).

Machines for direct metal AM

The present problems/challenges. The AM machine is one, if not the most, important factor for guaranteeing final part quality. Main machine challenges are productivity and repeatability executing the AM process, resulting in excessive variations in part density, microstructure, and surface roughness. Early years of PBF and DED processes were characterized by their aim of providing high power energy systems to assure the processability of basically any material. The default near-infrared (NIR) laser systems with a wavelength around 1030 nm to 1070 nm are mainly suitable for additive processing of materials like steel, aluminum casting alloys, and titanium; for high reflectivity materials (like Cu, Al, Au, …) visible laser light (500–600 nm) might be preferable. In recent years, with high power energy sources being available at reasonable costs, the trend has shifted towards more process-specific developments and solutions.

For instance, PBF processes require a different system architecture compared to DED processes due to the different working principles. Furthermore, shielding inert gas environments needed for PBF and DED systems are achieved differently. While PBF-LB machines require the build area to be covered with inert gas, DED-LB systems provide inert gas locally at the interface of the laser with the material. With PBF-EB (also called EBM) and DED-EB (also called EBAM) machines, a vacuum environment is required; the generation of such a vacuum atmosphere within the entire build envelope is time and cost-intensive, especially for larger parts.

A goal of these manufacturing machines should be to minimize the influence of the machine layout on the part quality. Efforts along these lines should be considered depending on the direct AM technique used: PBF-LB, PBF-EB, DED-LB with powder (DED-LB-Powder), DED-LB with wire, DED-Arc (always wire-based), DED-EB and nozzle/extrusion-based metal deposition techniques (liquid/semi-liquid material extrusion, droplet deposition, cold spraying).

State of the art and current developments. As mentioned above, one of the main challenges in PBF processes is productivity (the build time), which is highly influenced by the number of energy sources used. In PBF-LB/M, multi-laser systems have been an area of interest in recent years. SLM Solutions AG (Germany) even provides a machine equipped with up to twelve high power lasers [251]. These laser machines are mainly aiming at higher productivity, whereby the lasers operate in parallel mode, each covering a different area/patch of the build platform. The lasers can also operate with different spot sizes: small spots for accurate fusing of contours and small features, and large spots for fusing the inside of larger areas. Whereas lasers used for PBF-LB/M are still mostly continuous wave lasers, some commercial machines integrate lasers that can operate in pulsed mode [253,371]. This could be beneficial for a wide range of applications like surface polishing, material densification by laser shock peening [207], or the fabrication of structures with complex small-scale features such as mass-saving lattices.

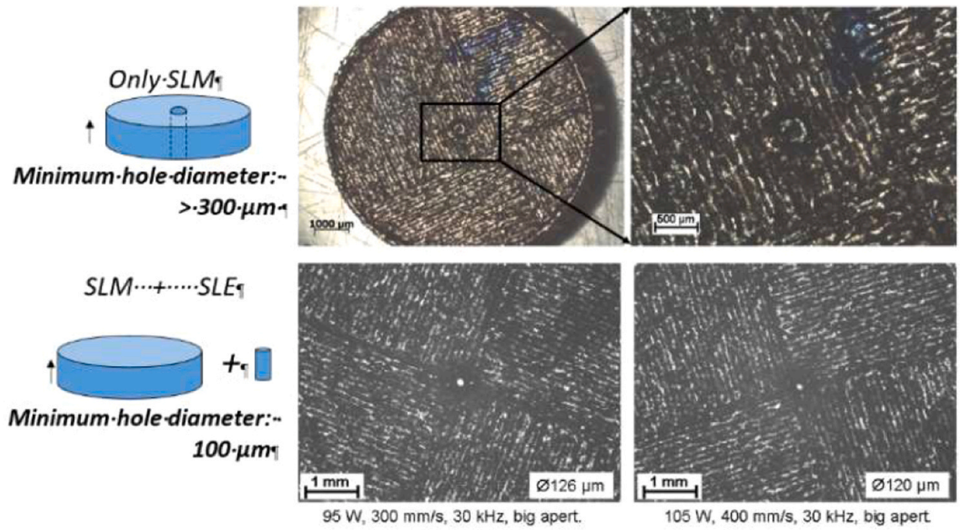

Fig. 4.2.1. Top: making a hole ⌀ < 300 µm in pure additive mode is not possible (no true hole). Bottom: two true holes of ≈ 100 µm produced by first AM building a massive part without hole and then laser drilling/trepanning the hole(s) in that massive part using the same Nd:YAG laser in pulsed mode with intermediate vertical part shift after each n layers.

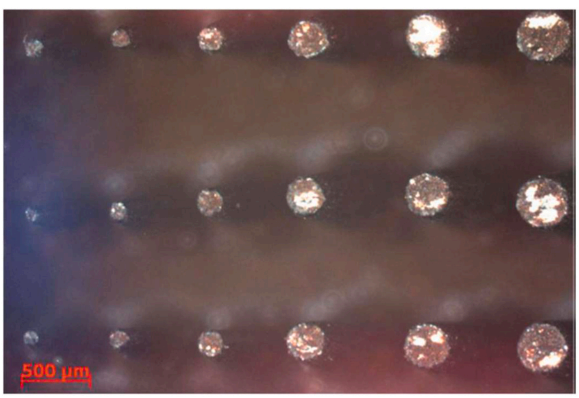

Fig. 4.2.2. Cylindrical micro-pins, down to 100 µm diameter, produced by additive building a larger pin (diameter 500 µm), then laser eroding the contour to reduce the diameter.

Another important aspect is the size of the build platform because it is decisive for the maximum size of the final part. Therefore, larger systems have been designed and fabricated over the last few years. Spreading the powder material homogeneously over the entire powder bed has proven crucial for reducing the overall scrap rate [181]. However, as a feedstock-specific inhomogeneity of the powder bed cannot be fully eliminated, the use of in-situ optical monitoring systems (see Section 4.5) is suggested.

The shielding gas atmosphere is another key influencing factor on the final part quality. Research is focused on adjusting the gas flow within the build envelope to avoid contamination of the powder feed stock and defects due to spatter or powder agglomeration within the part [107]. Further studies focus on the ideal position of the products within the build envelope to reduce defect-probability [75] due to, for example, powder bed contamination. Increased process chamber sizes result in larger amounts of powder required for performing the PBF processes. Thus, automated and optimized solutions for powder handling, part cleaning [78,352], and even support structure removal [318,356] are introduced to avoid unnecessary idle times of the machines during production. Some machine developers even went further in integrating metal AM machines, powder handling systems, and automated guided transportation systems (AGVs) in an integrated production line [88,95].

Manufacturing products from single material may not meet product requirements to the fullest. Advances in multi-material deposition will help to tackle this challenge by locally modifying the material or alloy composition, thereby leading to altered or graded material properties, e.g. [64,357,375,386].

In contrast to PBF, DED processes are highly detached from build envelope specific influencing factors as the processing nozzle typically generates a local shielding gas atmosphere, eliminating the need for a closed processing chamber filled with special gases. Larger parts can be fabricated using DED systems with greater axes reach.

One great potential of this technology is the fabrication of multi-material-parts without great effort by using either different powder hoppers or processing nozzles for supplying the powder material into the processing zone (see Multi-Metal DED machine of company Meltio). By adjusting the mass flows of the respective components (powder hopper or nozzle), graded structures can be generated. Correspondingly, the development of new powder supply systems to minimize the temporal delay when switching powders is inevitable. Recent developments in DED heads accommodate both powder flow and wire feed allowing for more material combinations.

The start-up company Aerosint (Belgium) recently developed a multi-material "Selective Powder Deposition" (SPD) system that can be retrofitted to a variety of powder-based AM machines (https://aerosint.com). So far such system was integrated into PBF-LB/M machines of Aconity, a PBF DMP printer of 3D Systems and in binder jetting machines of Desktop Metal who acquired Aerosint in 2021. The SPD deposition system consists of one or more rotating drums (typically 3 drums, each delivering a separate powder material). Each drum has thousands of tiny peripheral powder dispensing holes representing a grid of 300 µm pixels, each pixel being programmed to deposit a specific material at a specific pixel location.

The company Sciaky developed an original electron beam DED machine characterized as Electron Beam AM or EBAM [304]. This machine uses an electron beam to melt an off-axis fed metal wire. One of its advantages is that using material in wire form is much cheaper than the price of the same material in powder form [304].

NIR lasers have proven to be the state of the art in laser-based metal AM over the last two decades. Recent developments, however, led to high-power laser sources in the visible wavelength range. For instance, using green [368], or blue laser sources [210] can result in drastically improved energy efficiency during manufacturing due to the higher optical absorptivity of many materials like copper or nickel at these visible wavelengths. Laser systems with output powers around 1.5–2.0 kW are available for both green and blue wavelengths, which is sufficient for PBF but only partially meets the need for DED processes.

Part-to-part differences in additively manufactured specimens hinders the industry-wide use of this manufacturing technology. To reduce the effects of machine-specific influencing factors and harmonize testing of the functional performance of PBF machines (e.g., shielding gas flow), an international standard regarding the machine acceptance was recently published [166].

Another important challenge is the real-time acquisition of process information like thermal or geometrical data [367]. First, relevant data needs to be recorded during the process. This is especially challenging for PBF processes due to fast movement of the laser spot and the necessity to follow and refocus optical measurement devices to generate spatially resolved information on, for example, temperature evolution. This particular issue will be covered within the scope of Section 4.5.

The vision on future needs and expectations. To turn metal AM into a more accepted serial production system there are still some machine-specific issues that need to be tackled in the near future:

- To fully exploit the benefits of beam shaping, technical devices for beam shaping, e.g., diffractive optical elements (DOEs) or laser sources capable of dynamic beam shaping, need to be integrated in commercial PBF and DED machines;
- Visible wavelengths have shown tremendous potential in laser-based AM for materials like copper. These laser sources might also be suitable for more materials, depending on the respective optical absorption. Extensive research will be required in the future regarding energy efficiency and corresponding part qualities;
- Rather than using multiple lasers operating in parallel and independently in different areas of the part or layer being manufactured, cooperating lasers (e.g., one laser following the other, or a large-spot laser surrounding the smaller spot of the second laser) could be used to optimize the temperature profile around the melt pool in order to, for instance, achieve a desired microstructure or reduce residual stresses.
- The creation of suitable interfaces and advances in local powder deposition concepts will support the fabrication of graded or multi-material products in the future.
- New techniques for laser beam focusing might be required in the future if lasers are to be used in a parallel way, if larger build envelopes are targeted, or if a fast defocusing of the laser beam would help in increasing the build rate.
- New concepts for metal PBF-EB machines will be needed in the future which only generate a local vacuum so that bigger parts can be manufactured without the need for extremely large manufacturing enclosure.
- A better control of the temperature within the work volume of the machine (e.g., using infrared or inductive pre- or post-heating systems) will be helpful in controlling the temperature profile and reaching targeted material properties already in the as-built-state.
- Repeatability needs to be addressed as part-to-part variations significantly hinder a wide industrialization of AM processes as unpredictable changes in material properties hinder certification. One potential way to meet this challenge could be provided by closed-loop control systems (see Section 4.5) which automatically counter deviations.
- Closed-loop control systems, however, demand high-precision and high-speed acquisition and analysis of process information anywhere within the build envelope. New machine concepts will be necessary to allow a local and high resolution capturing of data like melt pool temperatures or geometrical part properties in all AM processes.
- User-friendly software solutions, incorporated into AM machines, will be required in the future to help unexperienced operators and end-users in designing build jobs to reduce part scrap rate and down times.
- Integrated and automated manufacturing chains are needed to connect the single software solutions available in the field of AM with the manufacturing machines and the corresponding post-processes to reduce lead times and boost efficiency and enable rapid qualification of AM process chains and AM parts.

Industry-wide standards will be essential for ensuring the product quality independent of the fabrication location, the machine, or the powder material used. This topic should be tackled by established committees at International Organization for Standardization (ISO) and ASTM International in the future.

Materials for metal AM

The present problems/challenges

The challenges regarding AM materials are well known [39] as only a limited palette of materials can be processed or are commercially available today. This group mainly contains castable aluminum alloys, titanium- and nickel-based alloys, stainless steels as well as low-carbon tool steels. Good weldability is generally a decisive factor when selecting material for AM. Additionally, common problems with residual porosity, micro-cracks, residual stresses, inhomogeneous/non-equilibrium micro-structure, anisotropy, problems with undesired oxide layers on powder, or oxidation of printed material result in further uncertainties when manufacturing parts additively.

On the other hand, AM offers unique possibilities as to the introduction of new (metallic) materials with unique properties. In contrast to subtractive and forming production technologies where the material is formed first in the form of a blank, billet, or sheet, and is then 'machined' or 'manufactured' into the desired part geometry; in AM the part material and the part shape are often created/produced at the same time layer after layer. This offers unique possibilities like applying a local variation of the material properties by adjusting the microstructure or the addition of alloying components to locally modify the material system.

State of the art and current developments

Until recently, the palette of common commercially available PBF/DED metal AM alloys was limited to pure titanium (cpTi), titanium alloy (Ti6Al4V), stainless steels (316 L and 17–4PH), maraging steel (18Ni300), aluminum alloy (AlSi10Mg), cobalt-chromium alloy (CoCrMo), and nickel based superalloys (IN718 and IN625) [39]. Recently several powder producers and research laboratories have developed dedicated metal powders for AM. They have developed new variants of the traditional AM powder compositions mentioned above, optimized powder particle size distribution, added special coatings, or nano-decoration particles to the surface of the powder particles, etc.

Major improvements can often be achieved by slightly modifying the composition of the material. For example, it turned out that adding few percent of Si to aluminum alloy (Al7075) not only enabled AM to achieve densities over 99%, but also almost completely eliminated the occurrence of micro-cracks [261]. Rather than producing powders with that new composition, the researchers mixed up typically 1–4 wt% Si powder particles to the Al7075 powder and used that powder mixture directly in the PBF machine where in-situ alloying happens. Working with mixtures of (elemental) powders of different chemical composition gives an incredible freedom to vary the final composition of AM components. Others have modified Al-Mg alloys by adding Sc and Zr for better PBF processing and better material properties [355]. Some of those modified Al-Mg powders are now commercially available under the trade name Scalmalloy®.

The fact that AM offers the possibility to create the materials during the part manufacturing process, e.g., by in-situ chemical reaction, offers the opportunity to apply or generate new material compositions at hardly any extra cost (e.g. by just changing the mixing ratio of mixed powders). It also opens the path to totally new metal matrix composites (MMC) or reinforced materials. For example: Dadbakhsh et al. [77] applied an in-situ reaction between Al and ZnO to alloy Zn and an aluminum alloy (Al6061) (bringing it closer to Al7xxx) and to reinforce the aluminum with nano-scale aluminum oxide (Al_2O_3) particles. Other Al, Ti, and steel MMCs have already been tested, starting from mixtures like Al/Fe_2O_3, AlSi10Mg/SiC, Ti/C, Ti/SiC, Ti/Si_3N_4, Ti/Mo_2C, Fe/SiC. A survey is given in Dadbakhsh et al. [76]. Han et al. were able to produce (TiB + TiC)/Ti composites by in-situ PBF of Ti and B_4C powders [140]. Another upcoming group of AM materials are high-entropy alloys that can be 3D printed using various AM processes (PBF-LB, PBF-EB, DED-LB, DED-EB, DED-Arc), either by starting from high-entropy powders or by in-situ reaction of elemental powder mixtures. A nice review of AM of high-entropy materials is given in [139]. It is expected that those various systems and processes will gradually reach industrial application and that the palette of new materials (MMC, high-entropy and others) will widen to cover specific material requirements.

Yet, not all metal AM techniques can be used for processing whatever material. For instance, wire-based extrusion using molten/liquid metal deposition [376,399] is today only applied to aluminum alloys that can be put in a viscous semi-solid state, as done in tixomolding. Applications to magnesium may be expected in the future. For magnesium alloys the WAAM (wire-arc additive manufacturing or DED-Arc) process [190] might still have advantages over other processes. EBSM (Electron Beam Selective Melting), i.e. a PBF-EB process, on the other hand is well suited for processing brittle materials like TiAl [130].

Over the last two decades and still today, a tremendous amount of research has been devoted to characterizing the resulting material properties and to optimizing process parameters in metal AM [6,227,417]. Currently, the potentials of locally modified processing strategies to achieve functionally graded properties are investigated [313]. This enables the spatial tailoring of the material properties. Countless papers appear in the literature on these issues. While most work still goes to properties like density/porosity, strength, and ductility, the scope of research has gradually extended to include residual stresses [359], fatigue and dynamic properties [94], and formability [25,151,288]. The latter is particularly important when considering hybrid processes that combine AM with forming technologies.

It is important to notice that studies on material properties today are not only based on experiments, but they also apply substantial modeling and simulation [116,184,285,321,381,409]. Today several companies offer commercial versions of this modeling software [353].

The vision on future needs and expectations

The future will see tremendous efforts in further expanding the palette of metallic AM materials as well as further efforts to characterize the corresponding material properties and to model the processing and to predict the properties:

- Research and development will be devoted to materials that cannot be processed well by means of AM today. Huge efforts are needed to expand the palette of steel, titanium, aluminum, or nickel alloys that can be 3D printed, but also to expand the palette to material classes (alloys or composites) that cannot be well processed today, like highly reflective, highly conductive materials based on Cu or Au [358], lightweight materials like Mg, high strength refractory materials (W, Mo, Stellites, etc.), magnetic materials [192], high entropy alloys, engineered alloys, MMCs, and many more.
- In-situ alloying will be addressed even more in the future, as it offers a unique opportunity to develop and process new material compositions.
- An increased interest in the formation of MMCs can be expected in the future. In principle, any carbide, oxide, or other particle type can be added to tailor the material properties.
- New powder systems with optimized properties need to be developed in the future. For example, improved processability could be achieved by modifying the particle size distribution or identifying suitable coatings for a better powder supply.
- Furthermore, the material portfolio will gradually be focused on materials susceptible to cracking. Advanced knowledge on countering factors may be used to reduce crack formation via beam shaping and improved system technology to implement the required methods.
- Multi-material processes need to be developed, especially with the aim of fabricating load-optimized products and functional grades. However, an adequate system technology is required, which was discussed in Section 4.3.
- Modeling the AM processing, post-processing (heat treatments, machining, forming, etc.), and resulting properties of AM materials will be a major issue of further research and development. While still in its infancy, the development of digital twins for these purposes will become a hot topic [199,393].

In-situ process monitoring and real-time control

The present problems/challenges

Processing conditions in AM often vary substantially in the short term (e.g., within a single build or single layer), as well as in the long term (e.g., from day to day). Short term variability might be due to local variations of geometry and heat flow conditions (e.g., at sharp wedges, thick or thin walls, or when scanning on powder versus solid substrate) or in view of the inclination of downfacing surfaces, the type of support structure, etc. Variability might also be due to the stochastics of powder deposition (e.g., irregular powder feed, local variation in powder layer thickness, or zones with larger or smaller powder particles), or due to gas flow turbulences. Long term effects include variations in environmental conditions (humidity, temperature, powder moisture content, purity of protective gas, leakage in processing chamber, etc.), variability among powder batches (composition, particle size distribution, moisture, etc.), degradation of the optical systems (laser power, dirt on optics, thermal lensing, etc.), cleanliness of powder filters, etc. Many short and long term effects cannot be anticipated and require in-process actions like adjusting processing parameters, or interrupting, adjusting and restarting the build.

The process variability often results in variable part quality and in unexpected defects (pores, cracks, unmolten powder particles, melt pool Raleigh instabilities, balling, distortion due to residual stresses, undesired inclusions, local part overheating affecting the microstructure and part properties, etc.) which are only detected after the part is totally built, resulting in high scrap rates. In-process monitoring with in-process feedback and/or feed-forward control may remedy this variability.

In-process monitoring

In-process monitoring may be used to assess the part's quality and/or defects while the AM process is ongoing. This could allow:

- Generating a quality or defect certificate after each part is built giving confidence on part quality without the need for extensive (often destructive) post-process quality checks.
- Stopping the process at an early stage if a severe defect occurs that would turn the part to scrap, thereby avoiding the process to proceed until the part is fully built and avoiding spending more time and cost in completing a defective part.
- Adjusting the process settings as soon as the monitoring system observes deviation from normal conditions, thereby avoiding the production of low quality or defective parts.

As summarized in the state-of-the-art section below, various in-process monitoring systems have been developed recently at research organizations or by commercial entities. Many monitoring systems apply optical sensing in the visible or infrared (IR) spectrum; the latter corresponding to thermal monitoring. The monitoring is either done with photodiodes (global/integral sensing giving one output value representing the total optical process radiation) or with cameras (resolved sensing that allows for monitoring radiation as a function of location in the powder bed or in the melt pool) [73,201,295].

A major remaining challenge is to find a correlation between in-process monitoring data (e.g., total melt pool radiation or melt pool size and shape) and post-process part defect analysis (e.g., pores). This can be done by comparing a 2D or 3D map of monitoring data [149] with a 2D/3D map of the part obtained by X-ray CT [124,212,258]: Fig. 4.5.1 and Fig. 4.5.2 compare two 2D maps by overlaying the CT and monitoring data. Notice the relatively poor match that may be partially due to poor thresholding of the monitoring and CT images, but is most probably also due to physical phenomena that will be explained at the end of this section.

Feedback control

Applying feedback control yields additional challenges. The first is in terms of speed: there is need for high image frame rate and readout speed (ensuring to catch juxtaposed images at high scan speed), fast image processing (e.g., calculating melt pool area, and length, width), fast decision making, and fast process actuation (e.g., laser, heater or blower response time). To achieve high control speed (> 20 kHz), some researchers have implemented the whole monitoring, image processing, and control logic on field-programmable gate array (FPGA) chips, rather than relying on the computer processing speed [67,72]. Another challenge is the lack of insight in the AM process and the relation between real-time process parameter adjustment and response of the process. Suppose you have established the relation of monitoring data to part defects and the monitoring system detects a situation that may result in a local defect (e.g., dross or pore), then the question arises what feedback action is to be taken to remedy to the problem: reducing or augmenting laser power, scan speed, hatch distance, or rescanning/remelting the last layer, possibly after recoating the layer, or some other action.

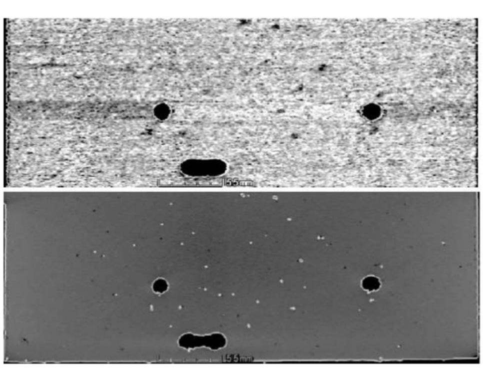

Fig. 4.5.1. Top: Mapped camera image data (melt pool size). Bottom: CT pore analysis (small black dots with white border are pores; the 3 larger black areas are cooling channels) [67,124].

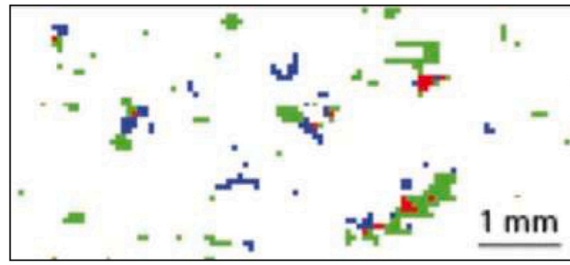

Fig. 4.5.2. Comparison between 'defects' detected from monitoring data (green pixels) and from CT scan (blue pixels). Red pixels mean coincidence between green and blue pixels [124].

Finally, establishing a correlation between monitoring data or a control action at location x and at time t and the occurrence or elimination of a defect somewhere in the part is a difficult issue:

- An abnormal melt pool at location x in layer N will not necessarily yield a pore at location x in layer N, but will rather generate a keyhole pore in layer N-4 to N-5.
- A pore that is induced at location x in layer N may not be present in the final part at layer N; the pore may indeed be remelted upon scanning layer $N+1$ and $N+2$, thereby closing the pore.
- Similar negative or positive location or time 'delays' do not only affect defect monitoring, but also affect the efficiency of control actions.

State-of-the-art and current developments

Pioneering work in process monitoring and feedback control was done by Mercelis at KU Leuven in 2004–2006 [201,249]. The monitoring system he implemented combined a photodiode (PD) and high-speed NIR camera looking at the melt pool coaxially with the laser beam and through the galvanometer scanner of a PBF-LB/M machine. As such, the PD and camera 'follows' the movement of the laser spot over the powder bed, keeping the melt pool in the middle of the picture.

The feedback control system of Mercelis was a simple proportional-integral-derivative (PID) control adjusting the laser power to maintain the total melt pool radiation (PD) or melt pool size (camera) at a constant level. That primitive system proved effective in suppressing overheating and dross formation when scanning downfacing surfaces and overhangs (Fig. 4.5.3) or when scanning narrowing geometries yielding unwanted heat accumulation. Fig. 4.5.3 shows the ability of the PID control to keep the melt pool size under control when scanning across the overhang zone.

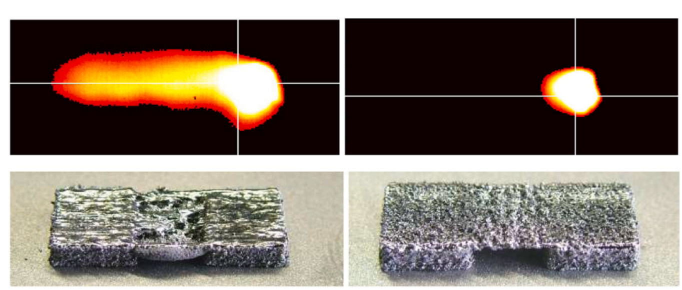

Fig. 4.5.3. Bridge structure produced with: left) fixed settings resulting in dross, pores, and sagging of overhang, (see lower picture left); right) proportional feedback control of laser power to maintain a constant melt pool intensity. Top pictures showing resp. camera images of melt pools when scanning across the overhang zone. Lower pictures showing resulting parts [249].

Recently, several research groups and machine vendors applied similar monitoring systems [101,128]. In spite of the aforementioned contribution, and with a few notable exceptions, feedback control has been insufficiently explored [73,101,128,149,180,201,257]. To cope with the problem of speed, some researchers have applied FPGAs to reach monitoring, image processing, and control cycle times up to 20–30 kHz. Others use slower PC and software-based feedback control limiting the response to only adjusting process settings for the next layer [378].

Rather than using co-axial thermal monitoring (i.e., using NIR PDs or cameras observing melt pool radiation through the galvanometer scanner), several applications use simpler off-axis thermal sensors (NIR PD/cameras) to observe the whole or partial build platform and detect hot spot defects within the layer being scanned [197].

Monitoring is not limited to observation of visible or thermal/NIR radiation. Some applications use piezoelectric sensors or microphones to monitor acoustic process emissions (air- or structure-borne) [97] or use process-integrated ultrasonic testing [319] to identify different levels of defects (porosity, cracks, delamination, broken supports) in PBF-LB. Some machines are also equipped with systems monitoring the powder deposition process or the protective atmosphere around the processing area [35].

More elaborate reviews on in-situ monitoring of metal AM have been published in [101,126,128,240]. Others [101,240] have provided a partial list of monitoring and feedback control systems that are available commercially.

The vision on future needs and expectations

AM **monitoring** and **real-time control** are both still in their infancy.

Though already applied in commercial systems, much remains to be done in terms of **monitoring**:

- Most existing optical systems monitor in the NIR spectrum, just below the laser wavelength of typically 1070 nm i.e., in the range of 750 nm − 1000 nm [67]. Monitoring in the lower visible spectrum below 750 nm [381] or in the NIR/IR spectrum above 1500 nm (i.e., above, rather than below, the typical wavelength of fiber lasers of around 1070 nm) may yield additional useful information [128].
- Another strategy would be to monitor at two or more wavelengths to obtain pyrometric temperature measurements (i.e. calibrated absolute temperature measures), instead of using hard-to-calibrate single wavelength relative temperature measurements [101,114,293].
- Some researchers are looking to in-process use of other radiation spectra: electron emission in electron beam PBF [11,397], X-ray imaging in PBF-LB (planar [133,292] or 3D CT [217] imaging, limited to small samples in specific test setups), or X-ray diffraction measurements [46]. Yet more R&D is required to reach full maturity.
- It is very likely that there will not be one sensor that can detect all relevant defects. Rather, in the future, it will be of great interest to fuse multiple data sources and sensors.
- Hardware improvements are still needed to eliminate aberrations in the optical system that yield image distortion, e.g., near the edges of the build platform.
- The largest problem is still to find a good correlation between monitoring data and real part defects, taking into account eventual positive and negative time delays between the occurrence of a monitored event (e.g., oversized melt pool) at a certain location in a layer and a defect that may appear or disappear in a lower or higher layer. This requires a profound physical insight into the melting and re-solidification process, but may also call on extended probabilistic analysis of huge amounts of experimental process data. Some researchers have already started to apply AI, Artificial Neural Networks (ANN) or machine learning techniques to identify correlations between monitoring data and pore occurrence [128]. The problem becomes even more challenging when aiming to correlate with other defects: cracks, undesired micro-structures, residual stresses, etc.
- Efforts should be devoted to find additional and better monitoring parameters containing more information on the process. Beside melt pool intensity, size, shape, and elongation (i.e., melt pool length to width ratio), other parameters may contain more information, e.g., thermal gradients at the tail of the melt pool [312], laser plumes [127], or spatter data (amount, size, direction, etc.) [29]. In this context it is of high interest to correlate the process monitoring not only to process/part defects but also to consider the effects of defects on the mechanical properties and by this the functional fulfillment of the additively manufactured part.
- In-process detection of defect generation (e.g., pores or cracks) or other induced process anomalies (e.g., overheating or balling) that will affect the final part properties can be made more efficient by combining monitoring data with process modeling or digital twins. For example, combining in-line 2D thermographic images (XY images taken within a layer) with a process model that predicts the temperature profile in the build direction (Z direction) [125] could improve the anticipation of keyhole pores or of the resulting microstructure (columnar or equiaxial grains).
- Attention should also go to in-situ monitoring of the geometry, dimensions and surface topography (roughness) of the part. Some initial work involving fringe projection has been performed recently [85]. Others are experimenting with in-situ coherent interferometer scanning/imaging [81,109].

As to **process feedback control**, almost everything remains to be done. Few academic systems have been developed and patented [68,201], but none are available on the market, not even a simple control that would definitely stop the build job upon detection of a signal that may yield an irrecoverable defect in a part, nor a control system that would temporarily stop the process to take a remediating action like powder recoating or remelting/removing the last layer before reactivating the build process [68]. Real-time adjustment of process settings will be a next development that will require better insight in interpreting monitoring data (see above) as well as insight into appropriate control strategies and actions: what to adjust to remedy to various process anomalies? Rather simple actions could be to change laser power or scan speed [249]. Developing strategies involving changing scan spacing, layer thickness, scan patterns/strategy, etc., will be even more difficult to implement, as this requires in-process real-time slicing, hatching, etc. In order to achieve efficient in-process feedback control, one may need to move to advanced control theory, process-model-based control possibly combined with feedforward control, digital twins and other advanced techniques [224].

The challenges ahead of us for realizing feedback control may be substantial, but possibly it could evolve to a situation as happened in the late 1970 s early 1980s where real-time adaptive control systems were developed for electro-discharge machines (EDM) that today equip almost all commercial EDMs [349].

Off-line Metrology and Quality Control of AM parts

Although the adoption of metal AM by industry has been continuously increasing over the last decades, its relatively low level of maturity still causes significant machine-to-machine and part-to-part variability. Therefore, off-line metrology plays a significant role for achieving necessary quality control, especially for safety-critical components used in aerospace and medical industries. On the other hand, due to specific characteristics of metal AM processes, novel off-line metrology needs have arisen, such as precursor material characterization, qualification of complex forms and surfaces like lattice structures [245], and material integrity verification [379]. A recent review paper on geometrical metrology for metal AM summarized the challenges and the latest advances in off-line metrology of AM parts [212]. The significant challenges associated with the coordinate and surface metrology of metal AM parts were identified as: "(i) complex freeform shapes, (ii) characteristic surface texture with typically high roughness, (iii) multiple occlusions and difficult-to-access features, and (iv) wide material range with different optical and surface properties." A result of these challenges is the lack of measurement traceability, which hinders quality control efforts. In addition, the lack of AM part qualification and certification standards has slowed the industrial adoption of this technology [336].

Metrology of precursor materials

The present problems/challenges

It is evident from existing literature that the properties of precursor materials have a significant effect on the AM processes and the resulting parts [39]. Precursor materials for metal AM are mostly in the form of metal powders. The characteristics of metal powders influencing the AM processes and the AM part quality are: chemical composition, thermal properties, and flow and spreading properties leading to layer density. On the other hand, particle size distribution (PSD), morphology, particle density, and cohesion are important powder characteristics affecting flow and spreading properties [347]. Many of the existing methods of material characterization were developed for bulk materials; and applying those to metal powders used in AM processes requires special considerations. Although metal particles mixed in paste form and metal wires, used FDM and DED processes respectively, are also gradually gaining more attention, powder form of precursor materials is most commonly used in industrial applications. Therefore, this subsection focuses on metrology associated with metal powders.

State of the art and current developments

Chemical composition of metal powders is determined by well-established elemental analysis methods such as X-ray photoelectron spectroscopy (XPS) [42] and Energy Dispersive X-ray (EDX) Spectroscopy [60]. On the other hand, measurement of thermal properties of metal powders are complicated due to particle-to-particle and particle-to-infiltrated gas interactions in powder beds. Recent efforts have focused on application of conventional methods of measuring thermal conductivity to power bed specimens, such as transient hot wire method and laser flash method, to powder bed specimens [61,389,412].

Thermal conductivity of five different metal powders were measured, using the transient hot wire setup shown in Fig. 5.1 located inside the pressure-controlled gas chamber, under varying gas types (argon and nitrogen), pressures (10^3 Pa – 10^5 Pa) and temperatures (300–450 K) [389].

The laser flash method is another well-established method to determine thermal diffusivity, heat capacity, and thermal conductivity of solid materials [289,412] applied this technique, in combination with a finite element heat transfer model and multivariate inverse model, to indirectly determine thermal conductivity of encapsulated nickel and titanium alloy powders used in AM processes.

They reported the ratios of conductivity of powder to that of the solid ranging from 3.4% to 6.9% for the two materials. However, the shape and material of the powder containers as well as interface between the powder and the container contribute to measurement uncertainty, which needs to be carefully assessed in the future.

An important feature influencing other powder characteristics is the particle size distribution (PSD). Although there are multiple methods of PSD measurement, three most common methods used in AM applications are sieving, laser diffraction (LD), and dynamic image analysis (DIA). Sieving is a very practical method to classify particle sizes and analyze size distribution [164,226]. However, it is not a method of size measurement. LD determines volume-based PSD using laser light scattering with the assumption that the powder sample consisting of spherical particles [160]. Nevertheless, some studies have provided ways to determine the actual particle shape using LD [233]. DIA is capable of measuring size and shape of particle silhouettes, using a high-speed, high-resolution camera, as they pass through a sample cell in front of a light source [161]. Yet, there are multiple metrics to describe the particle size and morphology, which produce different results. Furthermore, due to multiple assumptions involved, the PSD results obtained from different measurement methods are not always consistent with each other [241]. Researchers have conducted studies of the comparison of these methods to determine sources of inconsistencies [218,391]. To improve interpretation of these comparisons, assessment of measurement uncertainty has been the focus of recent studies [175,390].

Flow characteristics of powders are of significant interest for controlling the quality of AM processes. Conventional methods include the Hall funnel test, which measures the weight of powder flowing through a funnel orifice as a function of time [163]. However, gravity-induced flow in this test does not provide sufficient information about spreading performance in PBF applications. To improve the prediction of spreading performance, instruments measuring rheological properties of metal powders, which most commonly determines the shear stress–strain relationship of the material as a function of strain rate and frequency, have been used [66,142].

Other methods measuring the flow geometry (e.g., static and dynamic angle of repose) have been used for flow characterization [31,403].

Recent developments have introduced metal pastes [5] and metal-infused filaments [385] for metal AM processes. Metal pastes are deposited through a nozzle, typically fed by a type of pump. Therefore, the viscosity of the paste is an important characteristic

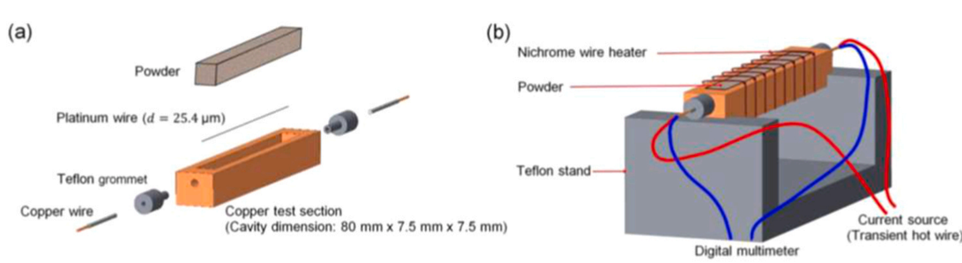

Fig. 5.1. Transient hot wire experimental setup: (a) Copper powder holder with platinum wire immersed into the powder, (b) A nichrome wire, wrapped around the powder holder to heat the powder [389].

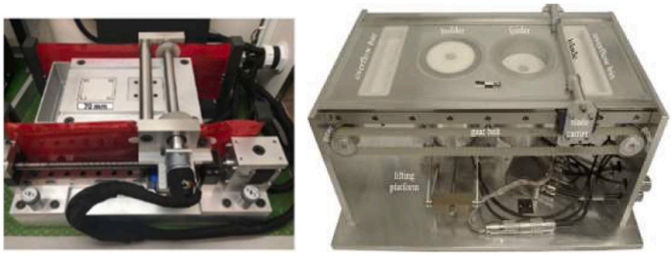

Fig. 5.2. Powder spreading testbeds [259,281].

that influences the print quality. Measurement of metal paste viscosity is accomplished by rheometry [234]. A piezoelectric rotary vibrator instrument to measure linear viscoelasticity has been described [189,225] studied rheological properties of aqueous alumina paste using a ram extrusion setup and compared the extrudate velocities with varying ram velocities to determine optimum ram velocity to avoid significant liquid phase migration.

The vision on future needs and expectations

Although the above-mentioned methods provide important information about powder characteristics, they fall short in predicting the actual spreading performance. Therefore, some researchers rely on computational models to predict such performance [55,146]. In parallel to these efforts, more direct measurement of spreading performance has been the focus of some recent studies.

Image analysis of the spread area on a spreading test platform has recently been investigated [158]. Several spreadability metrics were calculated including coverage fraction of test area and coverage fraction of bounding box of the spread layer. [122,259,281] described adjustable and modular testbeds for testing spreadability while replicating the operating conditions of commercial AM machines (see Fig. 5.2). However, currently, there is no consensus among the researchers and users of AM technology on the definition and the metrics of powder spreadability. For PBF processes, more research is needed to establish proper metric(s) for spreadability that accurately predicts the powder behavior during AM builds in different environmental conditions. Similarly, lack of metrics/requirements for powder flow in DED processes leads to the need for more research efforts in this area.

Metrology for metal AM parts

The present problems/challenges

Like all manufacturing processes, the objective of off-line measurements of metal AM parts is to ensure that manufactured parts meet the design intent as captured in final product specifications. They consist of dimension, form, surface topography requirements of internal and external features, residual stresses considerations, and defects. Other well-established off-line measurement methods used by the metallurgy community for microstructure, mechanical, fatigue, and corrosion characteristics are similarly applied to AM parts, hence they will not be covered here.

State of the art and current developments

Leach et al. [212] described in detail both contact and non-contact coordinate metrology methods to measure the complex form of AM parts. Therefore, they will not be discussed in this paper. Since this publication, there has been incremental progress in this field, but no major breakthroughs. Among those metrology methods, X-ray computed tomography (XCT) has been identified as one of the most promising methods to measure both internal and external features as well as surface topography. However, uncertainty of XCT measurements is still a weak link in such measurements. The lack of international standards to provide guidelines to develop task-specific uncertainty for XCT measurements results in the use of existing guidelines developed for coordinate measuring machines (CMMs) in XCT applications [162]. However, according to the Guide to the Expression of Uncertainty in Measurement (GUM), correction of all systematic errors of XCT systems is needed [168]. This is very difficult in XCT measurements due to the existence of a large number of influencing factors that cannot be accounted for quantitatively. The metrology community has been working to develop alternative formulations addressing this problem [103,143]. A recent study provided a comparison of the proposed alternatives in the dimensional measurement of internal features as well as flexible objects and reported the differences in uncertainty estimation within 5 µm [380].

For AM surface characterization, there is often debate about which surface texture parameter and filter settings to apply. But, as has been reported by Leach et al. [212], surface texture parameters need to be chosen based on the specific task at hand, e.g., quality control [248,291], functional correlation [18,213] or hunting for optimum process parameters [49,84,93] and process signatures [12,196,421] and defects [350]. Therefore, the choice of parameter or filter setting is case specific. There has also been some incremental progress in the use of feature-based [275,276] and multi-scale [198] characterization approaches and optimization of measurement methods [79,110,147,363].

Due to the creation of high temperature gradients during metal AM processes, residual stress is a significant source of deformations and reduced structural integrity of fabricated components. Modeling, prediction, and minimizing residual stress is therefore one of the top priorities for AM users [105]. However, there is no direct measurement method for residual stresses. They are inferred from measurements of elastic strain, speed of sound through the material or magnetic signature, which are all related to the stress [394]. Various techniques have been described to capture these measures [155,343,394] (see Fig. 5.3 for comparison of these techniques).

Other factors influencing structural integrity of additively manufactured components include the defects and porosity generated during AM processes. The types and characteristics of such defects have been studied extensively in literature [91,185,324]. However, their effects vary depending on the functional requirements of the AM parts.

The measurement methods rely on the critical sizes and distributions of such defects, which are the subject of ongoing research. Non-destructive inspection methods, including acoustic, ultrasonic, magnetic and XCT, for detecting various sizes of defects typically found in AM parts have been studied [100,279]. An overview of

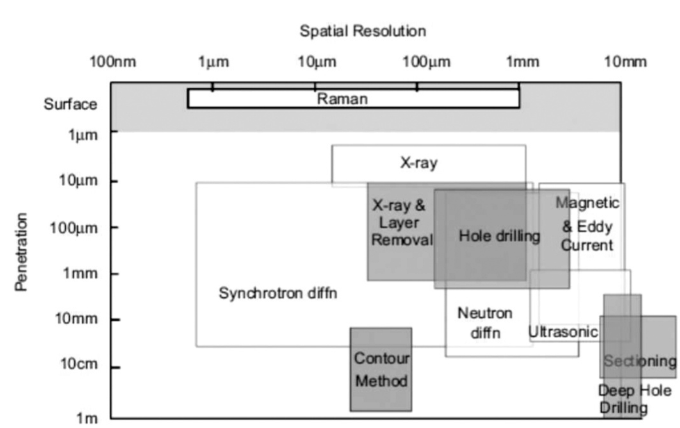

Fig. 5.3. Schematic indication of the approximate capabilities of the various techniques of residual stress assessment. The destructive techniques are shaded grey. [394].

porosity measurements is provided by Wits et al. [395]. Although more expensive compared to other methods, XCT is the most relied upon method to measure defects and porosity. Accuracy evaluation of porosity measurements by XCT using a calibrated object has been reported [148].

Kim et al. [186] investigated the effects of XCT acquisition parameters on the probability of detection (POD) of simulated defects.

The vision on future needs and expectations

In the area of traceability of XCT dimensional measurements, more robust uncertainty assessment techniques will be needed in the future. Recently, a unified approach to traceability of XCT dimensional measurements, proposing a framework for the model-based uncertainty assessment using a combination of Monte Carlo simulation and the instrument scale calibration, has been described [108].

In the area of AM surface metrology, as mentioned earlier, the choice of parameter or filter setting is case specific. For example, in heat transfer/cooling channel applications, the effect of surface topology such as the presence of inverted cusp structures (weld beads) and spatter particles are as important as the other parameters like hydraulic diameter [112,238]. Therefore, specification of topography to optimize heat transfer requires measurement bandwidths from micrometers to tens of millimeters (i.e., a dynamic range greater than 10^4). For most current metrology tools this implies either stitching or data fusion, resulting in large data sets with the associated impacts on modeling. On the other hand, there are some general features present on an AM surface and these can be used to develop general guidelines, which are being worked on by various stakeholder organizations. The prospect of measuring surface topography in-process is now becoming a reality [85,229,418] and there are commercial offerings based on fringe projection technology. An unsolved problem for AM is that the present surface characterization parameters are not suited to characterize re-entrant surface features (like re-entrant spatter or surface pores) that often occur in AM. Machine learning has a good potential to predict such surface texture parameters [284].

Non-destructive testing methods for defect detection suffer from high noise floor and complexity of signatures due to complex part geometries and interactions among various types of defects. Therefore, machine learning and AI tools for pattern recognition are being investigated to help identify various types of defects [121]. Such complexities also necessitate the model-assisted measurement approaches [187]. Inexpensive detection methods for industrial applications are being pursued utilizing recent advances in resonant acoustics methods [246].

Qualification and certification of AM parts

The present problems/challenges

Literature on mission critical metal AM applications indicate that exploitation of the full potential of AM requires robust quality control and qualification procedures with clear certification requirements [322,335]. However, there is a lack of consensus about how to achieve these conditions, resulting in the lack of industry standards for qualification and certification. Even the definitions of qualification and certification vary depending on the context and application. Utilization of the ISO online browsing platform revealed more than 150 definitions for each [169]. Due to their involvement in critical aerospace and medical applications, the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the Food and Drug Administration (FDA) in the U.S. are active in the efforts to drive the development of qualification and certification standards for additively manufactured parts. In the absence of such consensus-based industrial standards and the general lack of relevant industry data, these organizations have developed guidance and specifications for their specific applications.

State of the art and current developments

NASA has produced two documents to address the qualification of PBF-LB processes and the fabricated parts [267,266]. These documents provide a general framework for adapting NASA's existing design and safety standards for the safe implementation of AM parts. AM parts are assessed by their consequence of failure, structural robustness, and AM risk, which addresses part inspection feasibility and build process sensitivities. The required Part Production Plan (PPP) includes CAD models of the parts, material information, required witness test coupons and acceptance conditions, complete build part location and orientation in the AM machine workspace, list of all production steps, build logs and inspection reports. NASA generated two new standards identifying the minimum set of requirements for AM parts used for NASA crewed spaceflight systems [272] and identifying requirements for control of AM equipment, facilities, and personnel [273]. FAA requires compliance with existing federal regulations regardless of the manufacturing method used. At the request of FAA, the Aerospace Industries Association (AIA) recently developed a guidance document for certification of AM components [7]. This document addresses the unique aspects of certifying AM components for aerospace applications and provides methods of compliance with existing federal regulations for PBF and DED processes by considering current industry best practices. It identifies five focus areas: i) process development (including, feedstock material specification, machine acceptance, key process variables, process parameter set, support structures, part position and orientation, and post-processing), ii) supply chain qualification, iii) material properties (process specific allowables and design values) development (providing basis for static, fatigue, and damage tolerance analyses), iv) part design qualification (part specific allowables based on representative test specimens), and v) quality controls (including process quality controls, build quality plan, and post-process inspection methods). The FDA also issued guidance on technical considerations specific to devices produced by AM [104]. It provides recommendations specific to design, fabrication, and testing of AM medical devices. To address nuclear power plant industries' needs, ASME published a new document defining the criteria for additively manufactured pressure retaining metallic components [13].

The vision on future needs and expectations

A recent review on qualification and certification for metal AM identified three fundamental components as standards, rules, and regulations [59]. It provided the summary of activities for the development of rules and regulations by organizations in the U.S., Europe, and Asia providing services such as feasibility evaluation, training and consultancy, quality management system accreditation, testing and audit, and survey. As an outlook for future developments, this review paper proposed another framework for digital qualification and certification.

In the AM standards community, there are efforts to develop in-process and post-process inspection standards to support qualification of AM parts. Recently published standards include ASTM E3353 [16], ASTM F3490 [17], ASTM E3166 [15], ISO/ASTM 52948 [167].

All the above-mentioned documents require an expensive and time-consuming series of destructive and non-destructive tests on parts and test specimens to qualify the final AM products. To speed up such qualification efforts, model-assisted qualification utilizing multi-physics modeling to develop robust parameter-process-structure-properties-performance relationship chains will be among the highest priorities [262]. While utilizing such models, uncertainty quantification plays an important role in making qualification assessments [384].

Subtractive post-processing of AM parts

The present problems/challenges

As-built AM parts usually show an elevated surface finish, which can be due to different causes, such as the feedstock material characteristics, deposition parameters, partially fused powders, and balling effect. Nevertheless, surfaces characterized by tight geometrical tolerances and high surface finish are required for subsequent assembly as well as for characteristics like fatigue life, wear and corrosion resistance, which are primarily affected by the surface finish and have to be assured for the part service life. On this basis, subtractive post-processing operations are generally mandatory after AM of metal parts. In view of the near-net-shape approach associated with AM, these post-processing operations can be classified as finishing ones. The geometrical complexity of the surface to be finished usually impacts on the selection of the type of post-processing operation to be carried out. The very significant design freedom that AM technologies enable may, in fact, hinder the use of those finishing operations that make use of fixed tools, since hidden zones, enclosed features, very small corners or lattice structures may not be accessible by conventional tools. As an alternative, non-conventional machining processes can be used to finish intrinsic part features as well as internal chambers or channels.

For the case of conventional subtractive post-processing operations, the basic concern is about the machinability of AM metal alloys, which can be very different than that of wrought alloys of the same chemical composition. The non-homogeneous cooling conditions inherent to AM may induce microstructural features and, thus, mechanical characteristics that may lead to a very different machining response in terms of forces and power consumption, chip morphology, tool wear, and machined surface finish and integrity.

State-of-the-art and current developments

Conventional subtractive post-processing operations

Titanium alloys (Ti6Al4V in particular), cobalt alloys, tool steels, and titanium aluminides are the most investigated among the metal alloys fabricated through DED, PBF-LB and PBF-EB processes. Among the machining operations, turning is the most investigated; drilling and milling have also been extensively suited.

The machinability of Ti6Al4V fabricated through DED using wire feedstocks was evaluated [282] and showed that non-uniform cooling and porosity in the AM process had deleterious effects. The performances of Ti6Al4V fabricated through PBF-LB and PBF-EB were compared with those of the wrought alloy proving a substantial difference of behavior, which was ascribed to the different mechanical and thermal properties of the investigated alloys [325]. In particular, the microstructural anisotropy induced by the AM process was demonstrated to have a significant effect on machinability. As an example, in the case of end milling of PBF-LB Ti6Al4V, the tool life was found to decrease and surface integrity to improve [230] when machining horizontally manufactured samples as compared to vertically manufactured ones. This was identified to be a consequence of the different orientation angle of the microstructural features (see Fig. 6.1). Besides Ti6Al4V, the machinability of other AM titanium alloys for high-load aerospace applications has gained attention. For example, machining of PBF-LB produced titanium alloy Ti-5553 studied by [129] and that of PBF-EB produced gamma titanium aluminide studied by [303]. The CrCoMo biomedical alloy fabricated by PBF-LB showed a peculiar microstructure and crystallographic texture that significantly influenced the material response to milling [106]. It was shown that the fabrication of tool steel

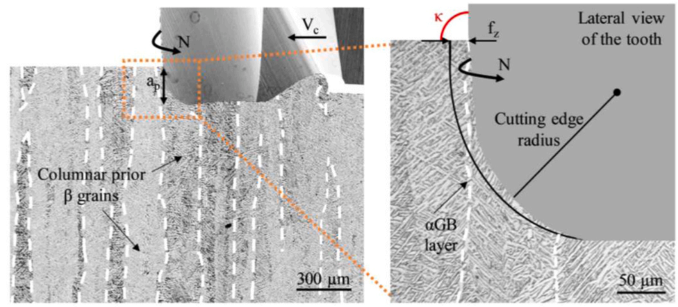

Fig. 6.1. Mechanics of cutting when end milling Ti6Al4V samples produced by PBF-LB [230].

inserts through AM allowed for an easy customization of dies and molds, which may be exploited for injection molding and die casting. In [290], the machinability of nickel alloy Inconel 625 fabricated by PBF-LB was found to vary in terms of peak milling force and chip morphology at varying building direction. PBF-LB produced maraging steels [111] and tool steels [41] were found to have improved machinability performance after heat treatment. The possibility to fabricate parts made of functionally-graded materials through AM poses new challenges in machining. For example, functionally-graded parts made of Ti6Al4V and WC, and fabricated via DED, were turned and demonstrated a material variation effect, also in terms of layer build strategy, on the machining response [283].

Grindability has also been found to be strictly correlated to the AM microstructure. The grinding and dressing parameters must also be adjusted to reflect the different microstructure of the part material compared to the one produced by the traditional route. A novel process named Shape Adaptive Grinding for polishing PBF-LB and PBF-EB AM Ti6Al4V parts was developed [32], and was demonstrated to be capable of finishing concave and convex curvatures with low surface roughness values (up to 10 nm) for a set of three different tools with different grain sizes.

When simulating machining operations carried out on AM metals, the modeling of the peculiar microstructural features characterizing the AM metal becomes necessary. As an example, the machined surface integrity of PBF-EB Ti6Al4V was numerically predicted [372] considering the thickness of the alpha lamellae characterizing the AM metal microstructure. Whereas, Segebade et al. [334] considered the PBF-LB AlSi10Mg anisotropy characteristics to predict chip morphology.

Non-conventional subtractive post-processing operations

Non-conventional subtractive post-processing operations are generally used to improve the AM surface finish, in some cases also giving raise to an overall surface integrity improvement.

Electro-polishing (EP) can be used to finish AM metals taking advantage of anodic levelling (macro-smoothening) and brightening (micro-smoothening) to get smooth and bright internal and external surfaces. The effects of EP on various AM alloys, e.g., titanium alloys [337,374], nickel-based alloys [20], Fe-based alloys [51] and CoCr alloys [80] have been recently investigated. A combination of over-potential and conventional EP processes was proposed to finish PBF-LB aluminum alloy lattice structures [51]. Despite its advantages, EP presents some challenges in the post-processing of AM parts. As a rough initial surface would impede a fast and effective EP process, a hybrid approach comprising an additional post-processing operation to reduce the as-built surface roughness to a certain extent is advisable [141,338].

Abrasive Fluid Polishing (AFP), using a combination of liquid impingement and abrasion from abrasive particles, is particularly suitable for polishing AM parts with complex internal structures such as lattice structures, internal channels, and thin-walled components used in aerospace and mold industries [[115], without risk of damage and contamination. The AFP main limitations (i.e., long polishing time and low processing efficiency) may be overcome through hybrid processes, as was proposed in [271], where a novel hydro-dynamic cavitation abrasion technique was developed to finish AM AlSi10Mg internal channels, yielding 80% higher material removal and 90% better surface finish than the case of pure cavitation and abrasion.

Blasting, based on erosion localization and intensification through a driving stream of abrasives against the part [247], is capable of lowering the roughness of outer surfaces by removing partially melted powder particles, layer marks, and improving the part mechanical properties [19] as well the part residual stress distribution [52], therefore leading to a general enhancement of the part surface integrity. To overcome some of the blasting drawbacks (i.e., noise issues, tapered geometry of the machined features, and impairment of the subsurface layer by micro-cracking when working a brittle material), the combination of blasting with other post-processing operations can effectively give a benefit.

A process chain combining sanding, polishing and burnishing was investigated in [404] for finishing PBF-LB 316 L parts, which made use of magnetic field-assisted finishing (MAF) (see Fig. 6.2). This process chain was proved to reduce the surface roughness and promote compressive residual stresses.

Laser polishing (LP) was studied in [354] to improve the surface finish and wettability of DED 316 L parts. Particular attention was paid to a correct laser power intensity in order not to increase the remelted layer thickness. LP was also used in [419] to post-process PBF-LB IN718 parts, reducing the surface roughness up to 98% and improving the mechanical and wear properties of the surface. Several researchers at KU Leuven [252,408] were able to reduce the surface roughness by a factor of ten using laser re-melting of the outer surface. Intermittent laser re-melting also achieved a porosity reduction of a factor of 20 in [408]. In [401], CW fiber laser and nanosecond pulsed laser polishing was used to finish Ti48Al2Cr2Nb samples fabricated through laser deposition. It was shown an enhancement of the part surface integrity, which, in turn, allowed an improved wear and corrosion resistance compared to the initial surface conditions when using CW laser polishing.

The combination of conventional and non-conventional subtractive operations for post-processing AM parts is also an active research field. As an example, the use of precision grinding followed by electro-polishing to enhance the surface integrity of PBF-EB Ti6Al4V parts was investigated in [131], stating that this combined approach made it possible to reduce the surface roughness to a value of 0.65 µm.

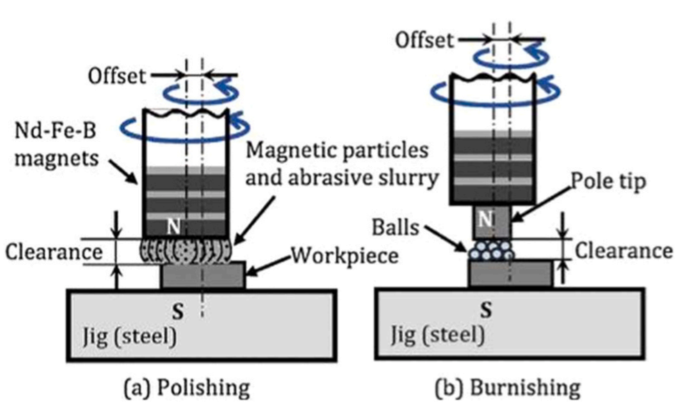

Fig. 6.2. Schematics of the magnetic field-assisted finishing processes [404].

The vision on future needs and expectations

Post-processing of AM parts poses challenges that both academia and industry are facing right now as a consequence of the different aspects that distinguish AM-based process chains from those based on more traditional fabrication processes. In this context, we feel that there are several aspects requiring special attention from the scientific community:

- Robust guidelines for the choice of the most appropriate subtractive post-processing operation must be developed accounting for the part geometrical features to be processed, desired characteristics, and processing costs. As an example, some techniques just improve the surface finish (e.g., chemical methods) while some others improve both the surface finish and surface integrity (e.g., conventional machining operations).
- The design of a metal part fabricated by AM requires a proper design and optimization of the post-processing steps, which are necessary to meet the product final requirements. In this sense, the concept of concurrent engineering is even more demanding than in case of conventionally-fabricated parts.
- Design for Additive Manufacturing must also into account post-processing operations, in order to rethink the AM-based process chain as a whole. For instance, the AM process design should consider no or minimal supports.
- New and functionally-graded metals fabricated through AM require an extensive characterization of their response to subtractive post-processing operations, the latter being strictly correlated to their peculiar microstructural features.
- One of the most challenging issues is to design and optimize the machining steps taking into account, on one side, the microstructural and mechanical properties induced by the AM process, and, on the other side, the part in-service characteristics.

Post-processing operations and hybrid additive/subtractive machines are being specifically developed for finishing AM parts, comprising the characteristics of different operations, which can either be conventional or unconventional or both. Of course, achieving an understanding of the mechanisms associated with hybrid processes is very challenging, which may limit their actual application in an industrial context.

Interoperability and cybersecurity

The present problems/challenges

Within Industry 4.0, connected cyber physical systems enable efficient cloud manufacturing through vertical and horizontal integration of these systems. Based on its highly digital nature, AM is seen as one of the production technologies in that vision. Interoperability for AM focuses on how to ensure reproduction of digital models at predefined quality levels, when they will be produced using different data formats, engineering tools and manufacturing hardware. Interoperability research also deals with the development of solutions that allow for the safe and reliable exchange of data among all entities in the AM value chain. Cybersecurity deals with protecting confidentiality, integrity, and availability of data and 3D models in a world where digital manufacturing, after the medical world, is the most targeted industry by cyberattacks [398]. These cyberattacks potentially target all digital entities in the AM life cycle and may hijack or damage hardware, corrupt data or result in intentional reduction of print quality. Counterfeiting of products is seen as a major challenge for cybersecurity, as this reduces profits while also leading to possible safety or security risks.

State of the art and current developments

Cybersecurity

To facilitate security of the digital thread, blockchain technology for AM is being developed. It allows for the establishment of mutual trust among all partners in a competitive environment, at low cost and without the need to include sources from outside the members of the digital thread [220,239]. Every participant of the digital thread has the ability to validate any step of the product development, from design changes to final product testing and qualification. For example, in the aerospace industry, the traceability of the production of parts is required to obtain certificates of airworthiness. Mandolla et al. [239] described the development of a blockchain based digital twin for metal-based AM. It was shown that the introduction of the blockchain concept could reduce the effort required for demonstrating the mandatory traceability, compliance, and authenticity. From that viewpoint, it could also play a major role in supporting the interoperability with and within the AM industry.

Counterfeiting

Counterfeited AM parts have a potential large impact on the safety of products, intellectual property rights of product developers and economics. The availability of cheap and high quality 3D surface scanning hardware however has enabled an almost effortless pathway for counterfeiting.

Current research related to counterfeiting is directed towards ways of ensuring that illegal reproduction of the design will result in modified parts (for example the inclusion of product labels or production errors) or by ensuring that products can be certified as original and legally produced. The modified parts are among others realized by creating unique, hard-to-copy (internal) features by implementing modifications at the process, material, and/or CAD-file level (see examples in Fig. 7.1). Wei et al. [387] developed a multi-metal PBF system where Cu10Sn powder was used to create an embedded quick response (QR) code in a 316 L part that could only be identified by thermal imaging. Chen et al. [53] produced a QR code by many small features dispersed over the volume of the part so they will not influence the mechanical behavior of the part and will only be created correctly with predefined segmentation and slicing settings.

In addition to embedding authentication codes, the design files themselves can be protected by adding design features that will only be printed correctly if the production process settings are also known (slicing settings, print orientation, layer thickness, etc.). Gupta et al. [134] introduced a zero thickness split feature in the STL file for a test specimen. The split feature reduces the print quality and increases the chance of failure of the printed artifact if it is not manufactured with the predefined processing settings and conditions. Eisenbarth et al. [92] looked at ways to vary process conditions for both PBF-LB and DED-LB. Within PBF-LB the volumetric energy density (see Section 3.1) was varied to create porous structures below the surface of the specimen. The laser power and scan speed for the DED-LB process were varied, among others, resulting in different penetration depths and, with that, differences in the magnetic permeability. In both cases Eddy current examination is used to visualize the coded patterns.

Some research focusses on capturing the fingerprint of the print setup or the printed part without deliberate modifications to the design or hardware setup. Adhikari et al. [3] assumes that the combination of the AM hardware, process settings and product design results in an unique error distribution on the part produced that can be used to authenticate that the part has been produced on a certain machine. Sandborn et al. [323] uses the concept that internal defects (pores etc.) alter the measured dynamic response, thus creating an unique fingerprint that may serve as a unclonable feature for determining part identity.

Interoperability

To enable interoperability, new data standards are being developed. For example, Application Protocol (AP) 242 Edition 2 [159] focuses on product information interoperability capabilities for, among others, product data management and 3D model based design. It enriches the product design data with information created during the manufacturing stage (build orientation, build location, minimal build volume, etc.). A standard published by the American Society of Mechanical Engineers [14] defines recommendations for product definitions for AM by including data and methods for controlling both product and manufacturing definition. It includes recommendations like tolerance zones for dimensional accuracy, part location and orientation, no-build zones around parts, fill patterns, support structures and location and orientation of test coupons. Milaat et al. [256] proposes to further extend the data standards with process specific parameters and settings. Examples for L-PBF include beam diameter, beam power or layer-to-layer scan strategy rotation.

The vision on future needs and expectations

Next to embedding features in the parts that are printed, research is looking at ways to fingerprint the hardware that is used to create the prints. Hardware imperfections show up as small distinguishable patterns in printed objects, thus potentially allowing for traceability of the production hardware [219]. Expert interviews [206] confirm the attractiveness of blockchain for AM. They identify four potential generic areas of blockchain-based improvement of AM quality: intellectual property (IP) rights management, lifecycle monitoring, process improvement, and data security. The current list of barriers for implementing blockchains is long and includes compatibility issues among blockchains, a lack of standardization for blockchain technology, and the configuration of the chosen blockchain technology itself. As a key enabling technology, it might play an important role, both in cybersecurity and in the support of interoperability.

AM-impact on KPIs across the product life cycle

The present problems/challenges

Three often-quoted reasons for AM are the creation of i) lightweight components, ii) complex 3D shapes (possibly with high level of feature/function integration), and iii) personalized components. These motivators suggest that AM provides functionality that is very difficult to achieve with conventional manufacturing processes. Moreover, these reasons indicate a strong focus on the use stage of the product life cycle. Of course, AM has impacts on the other life cycle stages as well. It is only by considering the totality of all the impacts, or Key Performance Indicators (KPIs), of AM across the entire life cycle of a product that an informed decision can be made about the efficacy of AM relative to other processes.

In terms of KPIs, measuring the performance of AM applications has largely emphasized production-related measures, e.g., costs, time, quality, and profitability. However, there is increasing recognition that all three pillars/dimensions of sustainability (environment, society, and economy) should be considered when making engineering decisions. KPIs from environmental and social perspectives such as energy consumption, material waste, greenhouse gas (GHG) emissions, and health and safety should also be assessed across the entire product life cycle. Kellens et al. [182] provided an overview of the benefits and weaknesses of additive manufacturing for these dimensions (see Fig. 8.1).

Looking at these KPIs, it is evident that challenges for AM exist. These include inadequate data situations, e.g., environmental impacts, and health and safety risks [182,231], as well as technological

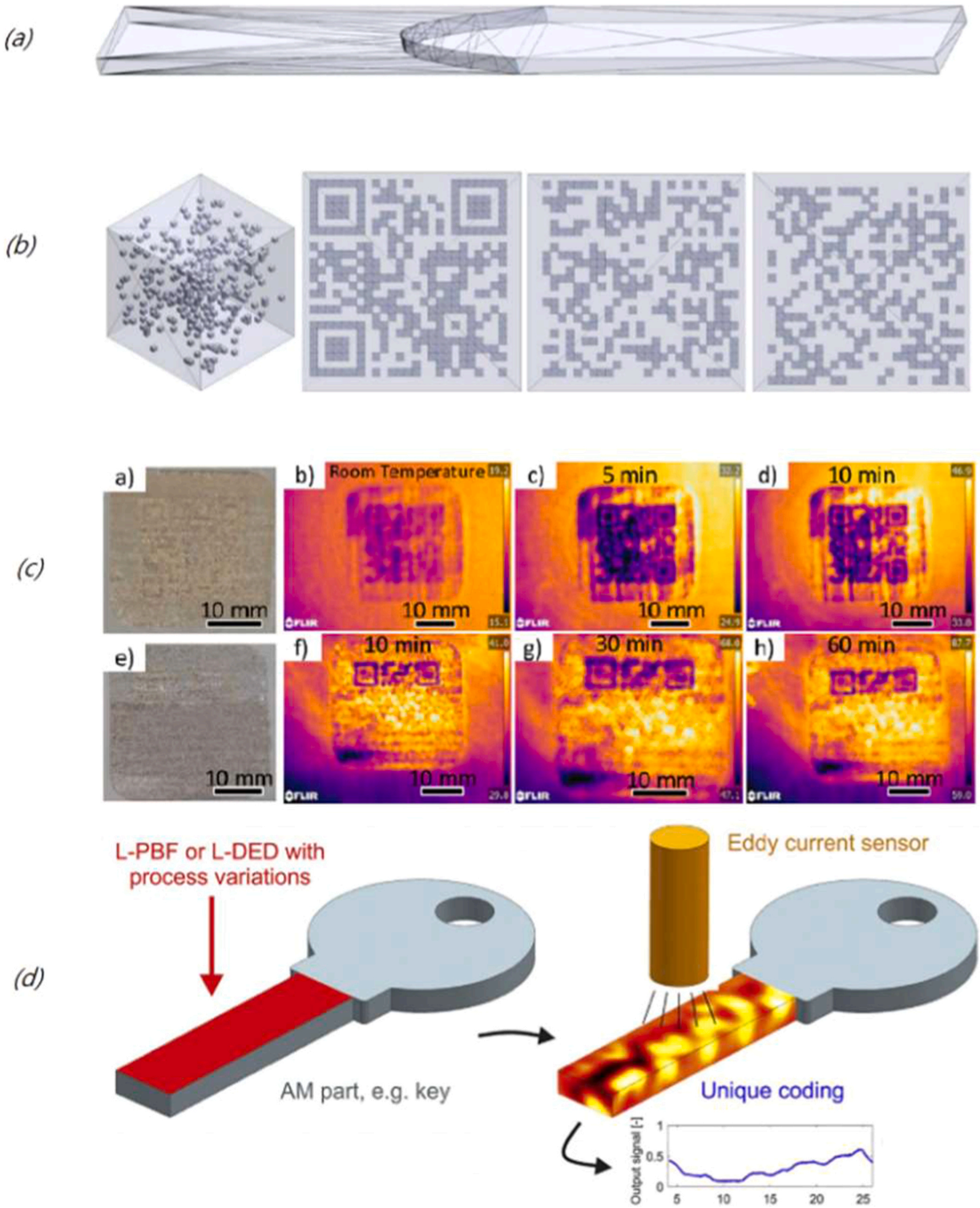

Fig. 7.1. Examples of anti-counterfeiting strategies based on control of local STL file or material properties. (a) [134] (b) [53]. (c) [387]. (d) [92].

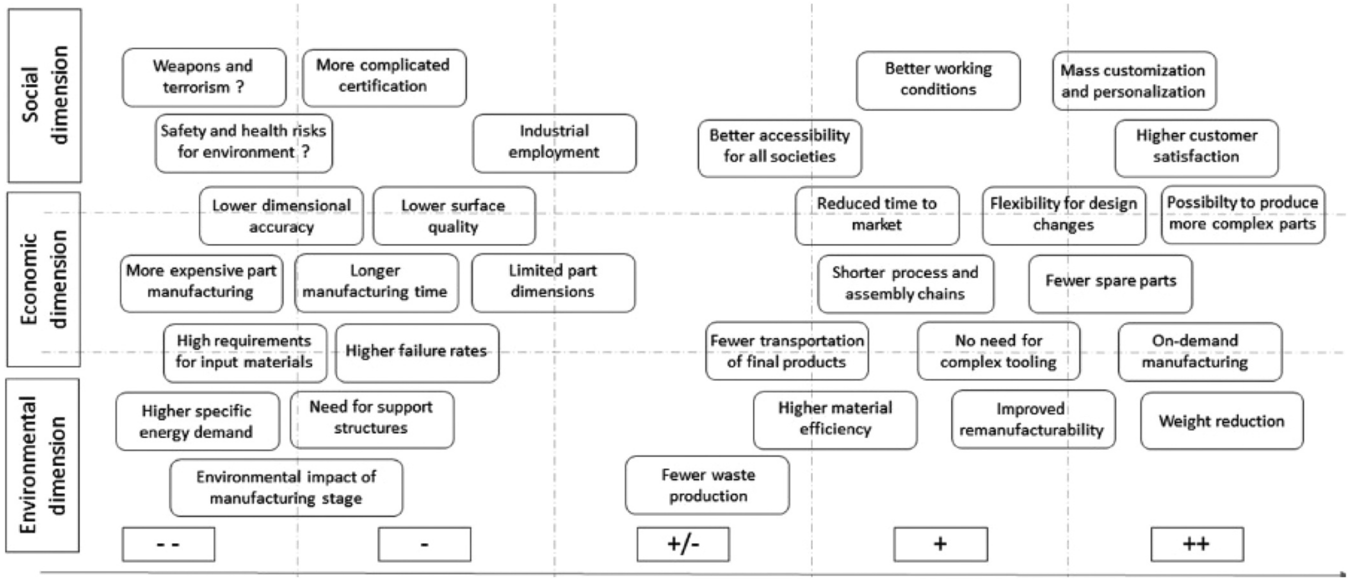

Fig. 8.1. Benefits (++) and weaknesses (−) of additive manufacturing processes compared to conventional manufacturing processes [182].

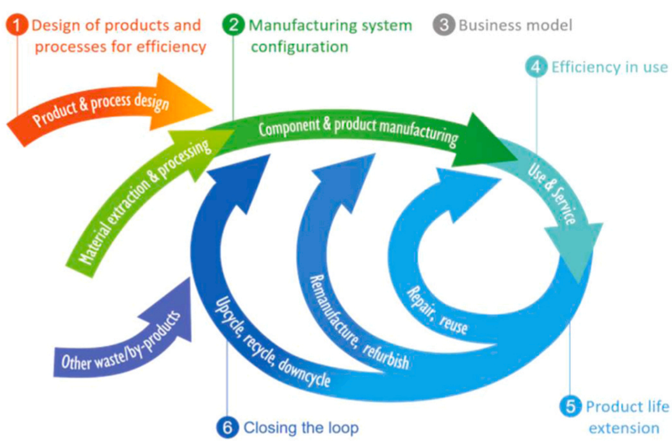

Fig. 8.2. Six areas for sustainability benefits across product life cycle using AM [83].

and economic uncertainties, such as low fatigue strengths and economic performance relative to conventional manufacturing [182]. These challenges are considered below.

State of the art and current developments

Despeisse et al. [83] proposed the framework of Fig. 8.2 to show the stages of the product life cycle (and the associated benefits to that stage) that could be impacted by AM. These six areas/benefits are:

1. Design of products and processes for efficiency: material waste reduction and improved product performance.
2. Manufacturing system configuration: improved flexibility and responsiveness for on-demand manufacturing, elimination of inventory, and reduced storage cost.
3. New business models: increased collaborations between manufacturer and consumer through the customization and personalization of the product.
4. Efficiency in use: improved energy efficiency in the use phase through the adoption of lightweight products;
5. Product life extension: more durable products through simpler assemblies (reduction in number of parts).
6. Closed-loop systems: enhanced recyclability through simpler supply chains and less material diversity.

It is to be noted that point (1) actually addresses two life cycle stages: manufacturing (less material waste during processing) and product use (better product performance). Moreover, points (4) and (5) also emphasize the use stage of the product.

In this section, we will summarize the benefits and challenges of AM for a variety of KPIs as reported in the literature. This discussion will be structured according to the product life cycle stages noted below:

- Product use: KPIs of AM products associated with the use stage of the product including lower operating costs and less environmental impacts.
- Manufacturing: KPIs for AM manufacturing processes including time, quality, cost, environmental impacts, and worker health.
- Closing the loop: KPIs for measuring the effectiveness of AM in fostering a circular economy across all stages of the product life cycle.

In addition to these three points, business related decisions and broader technology impacts will be discussed. In particular, we will examine how AM is changing the design process itself and supply chains. Social issues relating to AM-technologies will also be examined.

KPI-impact of AM on product design for use

The design of a product, the processes used to realize it, and the associated supporting systems (e.g., business and logistics) affect the performance of every stage in the life cycle of a product. It is well known that decisions made during product design largely determine the cost of a product as well as values for most other KPIs [153,205,370]. It is for this reason that Design for X (DFX) is promoted to ensure that all relevant stages and KPIs are considered in the design process [203].

In this section, we are particularly interested in the challenges and benefits associated with the use stage of the product life cycle when AM processes are being employed. The main KPIs that may be affected by the application of AM during product use are the **operating costs** and **environmental impacts** associated with the use stage (owing to the light weighting of AM parts/components) [320].

AM offers potential benefits during the product use stage such as i) improved functionality, ii) improved quality and durability, and iii) reduced product mass. AM can provide better functionality by offering a designer greater freedom in geometry and shapes that can better respond to the functional requirements of a product during use. For example, AM can provide customized or personalized functionality of products for medical devices and other medical applications, based on the individual patient requirements and data. AM can be used to produce products with various functionalities such as prosthetics and orthotics (hip joint and limb), and dentistry (crowns and dentures). These specific examples offer social sustainability benefits, e.g., improved quality of life and lower health care costs.

Improved quality and durability can extend product life and reduce maintenance and repair costs. According to Despeisse et al. [83], AM can produce higher quality products that are more durable during use. Longer product life and fewer needed product preservation activities may reduce environmental impact.

With conventional manufacturing, simple components are often combined to form an assembly. AM may allow the creation of a complex product that requires little assembly. With fewer material types, components and assembly interfaces, the product is likely to be more durable (i.e., have a longer product life). More durable, higher quality products are apt to have lower costs of ownership in terms of maintenance and repair [132] – this is positive in terms of economic sustainability.

AM allows a product to be designed providing the same function, with a smaller mass (light weighting). Most often, this is pursued for powered products, e.g., aircraft and automobiles. The aerospace industry has utilized AM in recent years, producing durable and lightweight structures (e.g., engine and turbine parts, hinges, and brackets). Lightweight parts require less power to be moved, which can result in substantial energy savings (enhancement in terms of environmental and economic performance) due to improved fuel economy and reduced material requirements. It is reported [154] that the mass of a 40,622 kg aircraft could be reduced by 1650–2840 kg through AM, producing a fuel savings of 6.4%. For additional information on KPIs regarding operating costs and environmental impacts, see also Section 2.

KPI-impact of AM on manufacturing

Unique process characteristics of AM technologies highly influence the manufacturing applications. These characteristics result in benefits, detriments, and risks, which can be structured by **time**, **quality**, **cost**, **environment,** and worker **health impact**.

The layer-by-layer principle of today's additive manufacturing technologies results in a processing **time** disadvantage for high product volumes if compared to casting or sintering technologies [182]. Nonetheless, the absence of tooling leads to an overall time to market advantage when the number of product variants is high [182]. Given the cycle time concern, current research is focused on the acceleration of the core additive process times through process parameter optimization, the use of multiple lasers, and automation of pre- and post-processing steps [366]. It is expected that pre- and post-process step automation will improve in the future, although processing time performance is inherently bound to the underlying physical principle and thus there are limits to performance improvement. Selecting the best AM technology as well as designing the right product and process chain offer the most potential for processing time improvement.

Manufacturing process stability and the achieved product **quality** depend on the specific AM technology and the specific AM machine, as also described in Section 4.3. Everton et al. [101] listed the most common defects of PBF-LB: gas and fusion pores, balling, unfused powder, and cracks. The process parameter selection for a specific product is complex, and has a substantial impact on the resulting defects and therefore the resulting product quality [101]. Today, experience-based process parameter optimization provides the most reliable results [366]. Automated technology and product-specific parameter optimization will be possible in the future. Methods like machine learning are likely to increase the performance of simulations (and actual processes) via parameter optimization.

A classical **cost** structure can be applied to evaluate AM technologies. Kopf et al. [193] gave an example for PBF-LB process chains: component cost was split into direct and indirect costs. Direct cost covered material cost, building board cost, and special direct cost. Indirect cost, consisted of machine, personnel, energy, and the cost of creating an inert atmosphere in the build chamber. The absence of tooling as well as the independence of the process time from complex geometrical product features result in the "complexity-for-free" slogan of additive manufacturing [366]. For additional information on KPIs regarding costs, see also Section 4.1.

An overview of the existing **environmental** impact analysis of several metal and non-metal AM technologies was given by Kellens et al. [182]. They showed that the quality and quantity of environmental-impact assessments for AM technologies is limited, but improving with time. Huang et al. [154] highlighted the cradle-to-gate advantage of AM in comparison to casting-based manufacturing in terms of energy consumption, energy intensity as well as the GHG emissions on the example of five aircraft component systems that are redesigned for AM. Overall, the cradle-to-gate impact for non-AM-specific designed parts through AM is higher than through conventional manufacturing, except for very small product volumes with high tooling effort needed for conventional manufacturing [182].

To enable the integrated evaluation of ecological and economic factors, multi-criteria decision-making methods have been a focus of researchers. Zaman et al. [410] proposed an Analytical Hierarchy Process (AHP) to evaluate several combinations of additive manufacturing processes and materials. The proposed criteria were structured by material class and split into function, cost and environment. For future environmental improvements of AM applications, the appropriate AM process and machine selection is crucial. The machine design, the build job configuration, and the process parameter settings each influence environmental performance, and can be modified to produce improvement [182].

Health and safety risks of AM due to harmful emissions and accidents are unclear, resulting in a possible lack of protection. Recent studies have stressed the uncertainty of health and safety aspects [182,231]. The health and safety risks depend on the specific AM process characteristics and the AM material. Due to a lack of sufficient studies for AM, Lunetto et al. [231] analyzed other industries working with similar materials and process characteristics. Several investigations highlighted possible health risks due to chronic metal powder exposure [231]. Moreover, explosions and fires, based on metal powder, have been reported [231]. To control such risks, further studies of cause-effect relationships are necessary, enabling the effective use of health and safety assessment tools. For example, Bours et al. [40] analyzed the potential exposures and hazards of AM processes and rated the danger of materials, taking toxicity tests and the powder particle size into account. This information was combined to analyze which kind of safety requirements need to be met for specific process-material combinations. Based on the current state of knowledge, to prevent health and safety issues, dust collection, air ventilation, protective gloves, glasses, and masks are suggested [182]. These protective measures are being applied in industrial AM [231].

KPI-impact of AM on closing the loop

In contrast to the traditional linear economy (take-make-use-dispose), a circular economy (CE) seeks to close material/ component

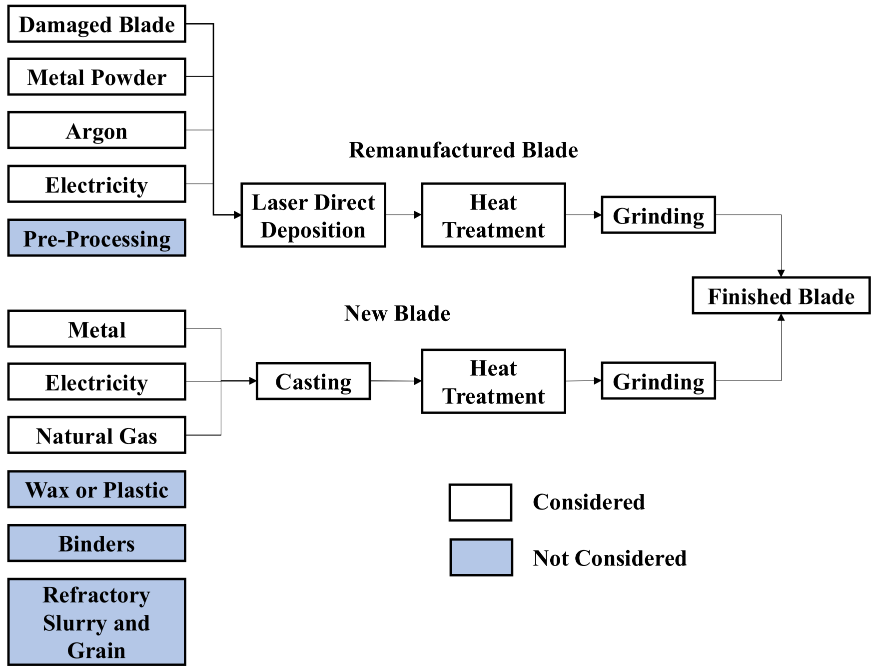

Fig. 8.3. Remanufacturing of turbine blades using laser direct deposition vs. new blade manufacturing [392].

loops (and also recover energy investments) by employing approaches such as maintenance, reuse, remanufacturing, and recycling. Product sustainability or circularity is increasingly a consideration in product design and development. The DED AM is well-suited to multiple applications in promoting a circular economy, especially in terms of **repair and remanufacturing**. For example, DED, and in some cases PBF-LB, can restore damaged parts to their original shape by gradually adding material layers. In addition, AM can create customized components/parts for remanufacturing. Efforts such as repair and remanufacturing that extend product life and avoid negative environmental consequences due to landfilling, can be viewed as being environmentally beneficial. Of course, the true impact of such strategies should be carefully examined with life cycle assessment methodologies. For example, Gutowski et al. [136] reported that remanufacturing might not always be the best environmental strategy.

Walachowicz et al. [382] analyzed the industrial repair process of gas turbine burners by comparing conventional repair and AM-based repair processes regarding energy consumption and resource efficiency. They demonstrated, based on Sankey diagrams, that the application of AM for repair has significant sustainability advantages when the whole product life cycle is considered. This concept was expanded in studies that considered repair and remanufacturing of sometime non-repairable components such as engine turbine blades [392]. In this study, it was shown that with relatively small defects (low volume, that is, approximately 10%), DED-LB is preferable to virgin manufacturing: at least a 45% reduction in carbon footprint and 36% reduction in total energy use is achievable via DED. A comparison of turbine blades is displayed in Fig. 8.3, exemplifying this scenario [392].

A primary drawback to AM when considering EoL is poorer strength fatigue of AM products. This may be attributable to a link between surface roughness and fatigue life [369]. This issue can be countered by optimizing print process parameters for smoother part texture and better material properties [54].

AM is often conducive to enabling material recycling at both the manufacturing and end-of-use (EoU) stages. After a printing process, the unused powder can be collected, sieved, and perhaps reused in subsequent builds. Moreover, by implementing an automatically closed-loop system, unused powder can be reintroduced into the printing process [407]. Furthermore, recycled materials such as plastic and metals from EoU products can serve as feedstocks for AM approaches [45].

With developing methods to better advance design for AM, there is potential to enhance the product life and close material loops (reduce usage of virgin material resources). Additionally, by reducing product lead-time and transportation, and enabling smaller factories positioned near customers, AM has the potential to shorten product supply chains and eliminate steps in product development. These changes serve to reduce the energy consumption and environmental impact of a product from cradle to gate. In addition, hybrid/combined processes (see Sections 4.2 and 6) offer the potential to reduce steps in the manufacturing of products. This also likely offers environmental benefits.

KPI-impact of AM on business models and broader impacts

The impact of AM is not limited to manufacturing and product design, but also impacts the supply chain, the business structure, and the ease of applying and abusing technology. Regarding **supply chain** management, the benefits of AM could result in on-demand, remote AM plants with reduced product lead time, logistic cost and transport time. However, recent findings [182] showed that there is no clear advantage of distributed AM over centralized, conventional manufacturing in terms of these KPIs.

Moreover, the performance of decentralized, remote AM depends on the specific AM process chain. Also, possible logistic advantages of shorter routes from raw material to manufacturing to customer, have only a small impact on the environmental performance of today's supply chain networks [9,177]. In the future, due to the high uncertainty in the global political landscape, centralized manufacturing seems advantageous. In contrast to this, regulatory approaches for increased sustainability and GHG taxation could result in more decentralized, remote manufacturing by increasing the importance of shorter logistic routes.

From a **business model** perspective, mass personalization is a unique selling point, especially for design-oriented business-to-customer (B2C) products. At present, the low volume of personalized products and the absence of a tooling cost enable AM to accelerate

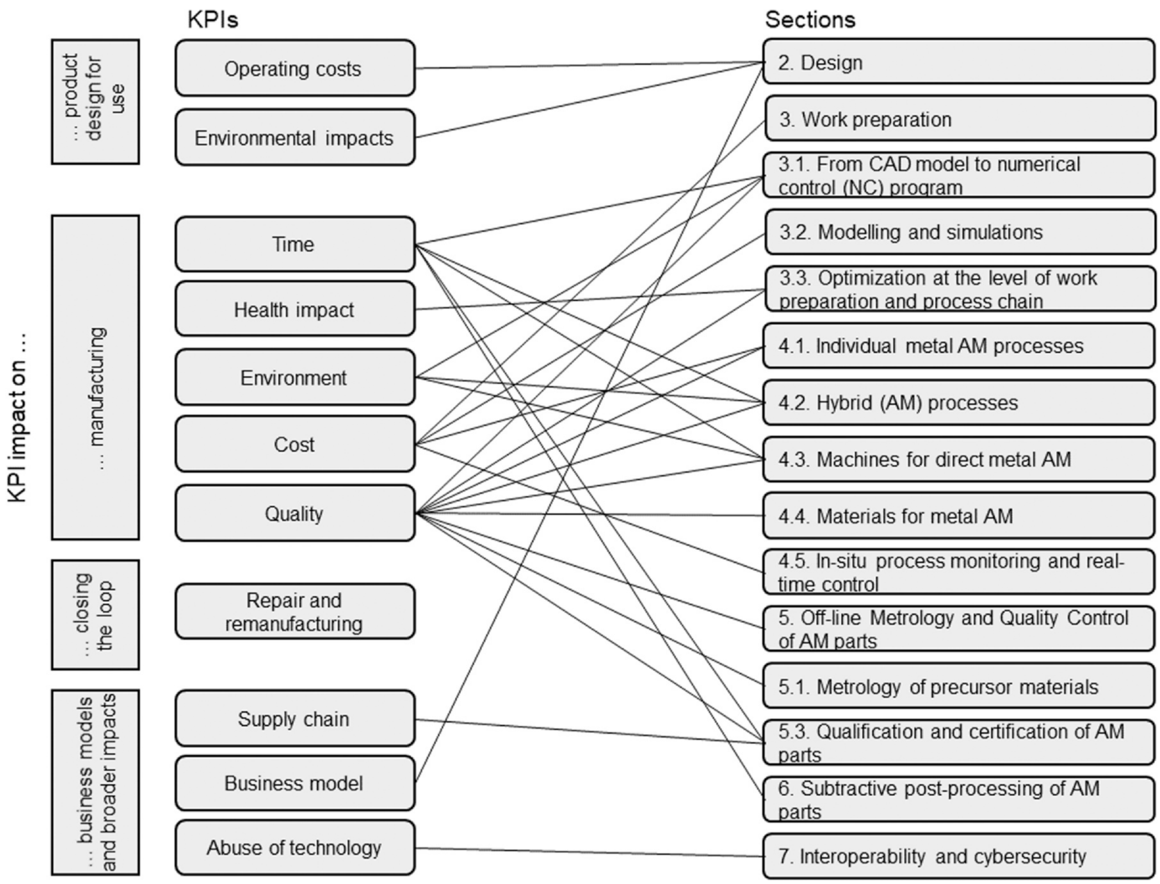

Fig. 8.4. KPIs across the product life cycle and mapping to other sections.

mass personalization [366], see Section 2. Despite this, the economic sustainability of mass personalization is unclear; however, potential benefits include reduced inventory and extended product life [191]. Moreover, applying AM for rapid prototyping during product design decreases the time to market for new products significantly [366]. It remains to be seen if mass personalization, in combination with decentralized manufacturing, can replace today's mass production and reduce the overall environmental footprint. Additionally, additive manufacturing is enabling positive social benefits such as customized crowns in dentistry and customized limbs in prosthetics. Of course, there is always the danger of **abuse of technology**, e.g., creating weapons or sabotage tools. This is already happening in the form of downloadable print files for weapons and shootings with 3D printed weapons [362,364]. There is early research, also driven by digitization, to protect or stop the manufacturing of certain products based on blockchain technology or to integrate physical design embedded security features, as also described in Section 7 [38,99]. Overall, the decreasing technological barriers through AM needs to be balanced by additional new security or protective barriers. This is an ongoing race.

The preceding section shows that there is a whole range of KPIs to be considered in additive manufacturing along the product life cycle. Fig. 8.4 therefore shows a visual representation of the KPIs discussed here. In addition, the figure contains cross-references to other sections for further information on the individual KPIs.

The vision on future needs and expectations

Based on the foregoing discussion on KPI-impacts of AM across the product life cycle, it is evident that there are significant advantages of AM in terms of i) product function improvements (e.g., weight reduction), ii) environmental impact through life extension, reuse, and remanufacturing, and iii) affordable personalization. Despite this, in certain life cycle stages, there is a negative impact of AM (or no clear benefit). This translates into the following research needs:

- Regarding product design for use, research should be conducted in the fields of physical and digital design. User engagement is needed in the product design phase that can help secure timely feedback. Development and standardization of new materials to meet usage needs (improved quality and reduced product weight) is also required.
- A down-side of AM is the long build time, which makes AM a poor fit to deliver high product volumes. In addition, concerns regarding AM process quality and negative environmental/ safety impacts are challenges that should be addressed in future process and machine improvements. Decision support tools are also needed for users to select the most efficient AM technology (considering multiple KPIs) and to optimize the pre- and post-process chain.
- In an era where circular economy and the greenhouse gas impacts of raw material production are increasing concerns, the role of AM technologies at product EoL in closing material loops is important. Certainly, greater attention should be directed at developing AM processes in support of value recovery from EoL products (remanufacturing and repair). In addition, product design in an AM-oriented world should also reflect appropriate consideration of DfX (design for remanufacturing, design for recycling, design for disassembly, etc.).
- With regards to the business impact, the advantages of decentralized AM factories close to customers are not clear. The efficacy

of decentralized facilities will ultimately be demonstrated by their market appearance and associated successful business performance. Holistic perspectives on the role of AM in terms of both economy/productivity and the environment have yet to be achieved, and are likely to vary dramatically from case to case. Moreover, the overall net social impact of AM has to be understood.

By combining economic, social, and environmental factors over the product life cycle, a holistic evaluation of an AM application is possible. Decreasing the effort and thereby increasing the use of holistic evaluation approaches including all life cycle stages is a major challenge for widening and efficient application of AM.

Challenges in training and education

The present problems/challenges

AM is relatively new as a manufacturing technology, especially for metal parts. Training and education in this field implies changing the way of thinking about many aspects of designing and manufacturing parts. But, at the same time, it is important to rely on conventional knowledge and practices of material science, process planning, post-processing and control, heat treatments, etc. So, the main issue is to elaborate competence units that allow combining conventional contents and to add sufficient knowledge to let the AM actors decide how and why to choose and to combine AM technologies with the different other steps of manufacturing. At a more tactical and strategic point of view, AM is also becoming a new way of manufacturing/re-manufacturing/repairing parts, products and systems in order to optimize their lifecycle. So, economic and management issues are also important issues that have to be learned by the AM actors, in addition, but mostly in comparison, with other more conventional value-chains. Many challenges, such as minimizing scrap, minimizing inventories, minimizing footprint, and manufacturing "first time right", have to be addressed by trainees.

State of the art and current developments

Fortunately, many initiatives, public and private, have been proposed during the last thirty years. At the beginning, training was quite exclusively based on manufacturing unique or very small batches of parts. Learning by doing is the best way to learn how to use a technology and to see the limits of its applications. More than ten years ago, groups from ASTM and ISO started to elaborate standards and many publications have shared good practices as well as different guides. More recently, the European Commission has proposed several Erasmus+ programs on AM, especially the Sector Skills for Additive Manufacturing (SAM) project with a goal of building up a European observatory of competences and employment in the field of AM. To achieve this goal, the consortium has proposed a global methodology to accelerate the construction and the delivery of teaching and training content all over Europe. This approach is based on a certification of training centers in each European country in order to create an efficient network in direct relationship with the most skilled practitioners of the field. Many other European projects relating to AM have a work package dedicated to education and training. In addition, some partners contribute to several of these projects, which helps in elaborating a global set of coherent competence units' contents in the field. Other countries have proposed initiatives, like USA with US AM Forward.

The vision on future needs and expectations

The main issue to be solved is managing to provide the right competencies to the market even if many evolutions are expected in the different fields detailed in this paper, from design to post-treatments. Standardization of practices and robustness of technologies will help in stabilizing core knowledge and good practices that will be transferable from one machine to another. One challenge is to have more knowledge shared in open access concerning the best design practices, the best manufacturing strategy and the best process selection, the best combinations of machine parameters, the best knowledge about material capabilities, etc. Several additional challenges relate to metal AM in particular. In this field of application, main levels of competences will have to be acquired:

- For designers, by ensuring a large spectrum of knowledge in order to get a systemic vision of manufacturability issues related to the parts/products while taking also into account the product usage properties.
- For machine operators, by integrating environmental and safety issues as well as managing materials life cycle, quality control, and some first level of maintenance.
- For quality managers, by adopting a global vision in order to fit the different requirements and to find the best means of control, qualification, and certification.
- For commercial and marketing actors, by understanding all potential developments and economical best practices. In fact, for all practitioners in the company, to let them know more about actual and future limits of AM technologies.
- For R&D people machine learning and data science will become an indispensable tool for further development at all levels (development of processes, hardware/machines, software, machine/process control, materials, quality assurance, safety, post-processing, etc.). Those actors should be educated with those new technologies.

Summary and future trends

The aim of this paper is to propose **a vision on metal additive manufacturing**, based on actual challenges, state of the art and future trends for each section that corresponds to one brick of the AM-based value chain, as described in Fig. 1.4. The main originality of the paper relates to the links that exist between the different bricks/steps/stages of this value chain (see Fig. 1.4), showing that the future progress could not be achieved without a real systemic vision, as demonstrated in the different sections of this paper.

This is why **part design** is not possible without a detailed knowledge of the possibilities of the AM technologies. Some of the main challenges at design stage are the following: minimizing support structures, minimizing the volume of material, minimizing the manufacturing time, validating the final properties of the material and of the part according to the manufacturing strategies, validating the manufacturing strategies (AM and finishing ones) as well as the various inspection strategies (including post-process part inspection). Based on such considerations, it is then expected to optimize economic conditions with an accurate costing evaluation.

Work preparation is important because this is the step of the process that would fix the future characteristics of the manufactured parts. All parameters have to be chosen accordingly to the expectations/requirements related to the part and that have been taken into account when designing the part. The key issue is how to fix operational parameters according to the final characteristics of the parts. A real integration between design and work preparation would be of real benefit. All information concerning real time sensing of the process would have to be connected with the models used to prepare the design of the part and the manufacturing process of a batch of parts. This information would also help in improving the simulation models, which are very complicated to elaborate, mostly because of the multi-scale and multi-physic issues that have to be understood and modelled, based on data collected and machine learning applications. A global optimization at work preparation stage could help in improving the efficiency of AM processes and also more widely, the entire AM-based value chain.

However, what is really expected, especially for metal AM, is that AM-based value chains become efficient and reliable **production systems**, with respect to industrial standards. This goal could be targeted firstly if individual AM processes fit the industrial requirements in terms of the standard KPIs. Much recent progress has been reported that focus on increasing the efficiency of manufacturing, decreasing the cost, improving the machine control (e.g., new beam shaping functions), extending machine quality control systems, and extending the physical principles of AM technologies. While AM is advantageous relative to conventional manufacturing processes in that it does not need any tooling (e.g., complex and costly tools such as molds or dies, or complex involute-shaped hobbing cutters or grinding wheels) to manufacture parts, AM of tools is attracting industrial interest in terms of tooling lead time, cost, and quality [48]. Many new AM technologies could provide interesting AM-based value chains coupled to conventional industrial production facilities requiring, for example, casting or injection molding. In such case, the main benefit is to provide capabilities to control energy/thermal flow within the tools with optimized conformal cooling channels and also to facilitate the rapid production change.

While AM has so far often been used as an isolated manufacturing system, more attention should go to the integration of AM in a manufacturing process chain that combines AM with other (conventional) manufacturing processes like metal machining, forming, and heat treatment. The challenge and tendency are to integrate those processes in a so-called hybrid production machine, where several processes occur within the same machine. **Hybrid AM** should be more than inserting an AM head (e.g., laser cladding unit) within a milling machine. Substantial research should be devoted to adapting cutting conditions for machining AM materials. This is even more stringent when combining AM with forming processes. Hybrid processing will be most profitable if the various processes being combined (additive, subtractive, roughing, finishing, surface treatment, texturing, heat treatments, etc.) are based on the same technology. Laser processing offers unique possibilities to do so as lasers can be used for additive as well as subtractive manufacturing, for forming (laser forming), for polishing or texturing, for thermal treatments (such as annealing and hardening), etc.

However, in the center of these evolutions, there are still the individual AM machines. One fundamental question is: “is it possible to get a constant quality of the parts produced with metal AM machines?”. Reproducibility/repeatability is still an issue and a crucial one with respect to the great expectations in the field of spare parts and for production-on-demand. As soon as companies have switched to and invested in AM-based value chains, this question will have to be answered in a robust manner. But, as described in this paper, the variety of metal AM technologies opens several ways of approaching this problem. Certain technologies are focusing on high material deposition rate but rather low geometrical and dimensional quality, mostly for large dimension products. At the same time, other ones are focusing more on precision with smaller parts. In any case and independently of the process, closed-loop control is expected to be introduced across the industry and widely integrated into the machines.

As investigation of this global system continues, the control of the material transformation is absolutely crucial. During the development of AM, even now, the most important challenge for AM technologies has been to produce parts with, at the end of the deposition/transformation process, the same material and similar properties as compared to materials obtained with conventional manufacturing technologies, like casting, forging, and machining, with respect to the technical and, more specially, economical performance. There also may be huge potential in materials designed for AM. The important challenge is in demonstrating that the AM material meets the needs of the application, following whatever quality/regulatory requirements may exist (not necessarily demonstrating equivalency). However, the cost of material manufacturing must be considered in addition to the material life-cycle. Specific bulk/powder materials/alloys are to be designed for AM (even if in-situ alloying is used to modify the material/alloy during the AM process) to take into account the right balance between cost and performances. Yet the question will be to provide modeling and simulation tools to people in charge of process design and preparation, coupled with part design. This is a real challenge when considering the combination of AM and other technologies in a hybrid way all along the AM-based value chain, and when considering the integration of post-process treatments in these modeling and simulation tools.

In order to provide accurate and representative models, new knowledge has to be captured by exploring the processes using **in-situ process monitoring** in order to achieve a completely integrated system, from design to final part production. Different solutions for observation of the physical transformation of the material have been proposed but have yet to be industrialized and generalized. An interesting challenge is to provide a complete **on-line control** of the material transformation in real time, based on specific requirements. These issues are complicated and are complex multi-physic and multi-scale problems, addressing different KPIs at the same time.

Off-line metrology and quality control present numerous challenges. Current XCT and non-destructive testing solutions have to be adapted to the characteristics of AM parts: detection of (minimal) internal and external defects, adaptation to the (maximum) size of AM parts, appropriate thresholding or edge detection, specific roughness characteristics of AM parts, etc. Coupling the physical defects to the process parameters and to the control of these parameters is of significant importance to enable a real efficient closed-loop control system. Thus, off-line metrology and quality control techniques (in particular XCT) will help in learning more in detail about these relationships among defects and process parameters for a given material and for a given set of requirements. A common database/information framework to access these relationships between defects and process parameters would allow for the improvement of the capabilities of the different actors in order to globally increase the level of skills and good practices of the companies and also let consumers/end-users be more confident in AM part performance. This goal is very difficult to achieve because of industrial competition and because of intellectual property. A royalty system should be unacted in order to compensate those who share their knowledge. In addition, in a coherent systemic approach, there is a need for standards related to metrology and quality control for AM, in particular for XCT measurement and roughness measurement, but also for CMM measurement and material analysis (e.g., settings for fatigue testing of metallic AM parts). Ultimately, what is of collective interest is to develop and open up the market and the applications of AM-based value chains, with **qualification and certification** of AM parts, tools and processes. This would need to take into account all stages of this value chain, in particular **subtractive post-processing** of AM parts and finishing machining operations, where much progress is needed and expected in order to adapt design and machining conditions, in particular for new and functionally-graded materials.

One very important issue is confidentiality. Even if switching from physical logistics to digital logistics, **interoperability and cybersecurity** have to be assured from start to end. In addition, blockchain technologies have to be more widely integrated in order to certify that the right process has been realized and also to avoid additional illegal reproductions. Progress is expected to improve interoperability all along the AM-based value chain, because at present, many individual systems are not up-to-date, need format conversions, which may result in a lack or loss of information. With a global systemic vision of such a value chain, it is exceedingly than important to provide new solutions in order to promote a global integrative approach from design to delivery, including all the different stages, even if subcontracted.

Finally, a global control of any AM-based value chain should rely on a clear definition and application of KPIs that could/should be traceable. This is expected in order to assess the **AM-impact on KPIs across the product life cycle**, and in particular to achieve a real understanding of sustainability performance. Considering all stages, including the one related to part usage, many possibilities offered by AM-based value chains should be exploited in order to really fit many requirements. These requirements concern all aspects, from economical ones to environmental ones. Different technical and information frameworks have been proposed showing the benefit of AM-based value chains compared to traditional ones. Adopting and controlling KPIs is one of the key issues of the generalization of usage of these value chains, including certain potential B2C solutions and manufacturing centers, exploiting the possibilities of personalization of the products offered by AM. At a global level, AM allows a real "just need" approach: by taking into account the "just need" requirements of the future users (design for use), by designing the "just need" product with lightweight approaches, by controlling the global process of production by a "just need" production-on-demand, by using the "just need" material and energy, by addressing "just need" post-processing and control solutions, etc. End of life is to be considered from the very beginning in terms of recyclability, by integrating possibilities of disassembly, of remanufacturing, and of material recycling, with a global vision of circular economy, with decentralized production centres located close to the place of usage of the products. Health and safety risks are obviously addressed and specific KPIs are also considered. In short, the main challenge is to be able to emphasize the capabilities of AM-based value chains to take into account and to control specific aspects of the whole life cycle for a product.

Obviously, all these issues have to be resolved by the different actors acting along the value chain. There is also a great social challenge with respect to the adoption of AM as a real production technology, as a potential way of advancing manufacturing towards the new paradigm, namely Manufacturing III, which, as a manufacturing advancement law, will be inevitably developed in the foreseeable future. These advancements will need new skills for the 21st century workforce. When speaking of employment, **training and education** are to be developed with respect to good practices based on certifications. Initiatives at all levels, international, national, and regional are now in place in order to be ready to provide new opportunities for employment for experienced people but also for students who would like to extend their knowledge for positions within AM-based value chains (in design engineering, materials engineering, mechanical engineering, software engineering, automation engineering, manufacturing engineering, maintenance, quality control, production management, marketing and commerce, etc.).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] 3MF Consortium, ⟨https://3mf.io/⟩ (last accessed on 8 Nov, 2022).
[2] Acharya, R., Sharon, J.A., Staroselsky, A., 2017, Prediction of Microstructure in Laser Powder Bed Fusion Process. Acta Materialia, 124:360–371. https://doi.org/10.1016/j.actamat.2016.11.018.
[3] Adhikari, R.R., ElSayed, K.A., Akleman, E., Panchal, J.H., Krishnamurthy, V., 2022, SplitCode: Voronoi-based Error Exaggeration for Authentication of Manufactured Parts. ISSN 0278-6125 Journal of Manufacturing Systems, Volume 65/2022: 605–621. https://doi.org/10.1016/j.jmsy.2022.10.005.
[4] Aggarwal, A., Chouhan, A., Patel, S., Yadav, D.K., Kumar, A., Vinod, A.K., Prashanth, K.G., Gurao, N.P., 2020, Role of Impinging Powder Particles on Melt Pool Hydrodynamics, Thermal Behaviour And Microstructure In Laser-assisted DED Process: A Particle-scale DEM – CFD – CA Approach. International Journal of Heat and Mass Transfer, 158:119989. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119989.
[5] Agrawal, R., Anantachaisilp, F., Tirano, J., Ramirez, H.Z., Marquez, Z., Luhrs, C., 2019, Paste-based 3D Printing of Metallic Materials: Effect of Binders and Precursor Sizes. Materials Research Express, 6/10:106561. Aug 21.
[6] Ahmed, N., Barsoum, I., Haidemenopoulos, G., Al-Rub, R.A., 2022, Process Parameter Selection and Optimization of Laser Powder Bed Fusion for 316l Stainless Steel: A Review. Journal of Manufacturing Processes, 2022/75: 415–434. https://doi.org/10.1016/j.jmapro.2021.12.064.
[7] AIA Additive Manufacturing Working Group, 2020, Recommended guidance for certification of AM component, ⟨https://www.aia-aerospace.org/wp-content/uploads/2020/02/AIA-Additive-Manufacturing-Best-Practices-Report-Final-Feb2020.pdf⟩, last accessed Aug 16, 2021.
[8] Ansys, ⟨https://www.ansys.com/products/additive#tab1-3⟩. 2023.
[9] Apple Inc, 2020, Product environmental report iPhone 12. ⟨https://www.apple.com/environment/pdf/products/iphone/iPhone_12_PER_Oct2020.pdf⟩ (accessed 16 February 2022).
[10] Arndt, A., Hackbusch, H., Anderl, R., 2015, An Algorithm-based Method for Process-specific Three-dimensional Nesting for Additive Manufacturing Processes. 2015 Solid Freeform Fabrication Symposium⟨https://repositories.lib.utexas.edu/bitstream/handle/2152/89423/2015-109-Arndt.pdf?sequence=2&isAllowed=y⟩.
[11] Arnold, C., Böhm, J., Körner, C., 2019, In Operando Monitoring by Analysis of Backscattered Electrons During Electron Beam Melting. Advanced Engineering Materials, 1901102.
[12] Artzt, K., Mishurova, T., Bauer, P.P., Gussone, J., Barriobero-Vila, P., Evsevleev, S., Bruno, G., Requena, G., Haubrich, J., 2020, Pandora's Box–influence of Contour Parameters on Roughness and Subsurface Residual Stresses in Laser Powder Bed Fusion of Ti-6Al-4V. Materials, 28/13(15): 3348.
[13] ASME PTB-13, 2021, Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing. The American Society of Mechanical Engineers,, New York, N.Y. USA⟨https://www.asme.org/codes-standards/find-codes-standards/ptb-13-criteria-pressure-retaining-metallic-components-using-additive-manufacturing/2021/drm-enabled-pdf⟩.
[14] ASME Y14.46, 2022, Product Definition for Additive Manufacturing. The American Society of Mechanical Engineers, New York, N.Y. USA.
[15] ASTM E3166, 2020, Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build. ASTM International,, West Conshohocken, PA.
[16] ASTM E3353, 2022, Standard Guide for In-Process Monitoring Using Optical and Thermal Methods for Laser Powder Bed Fusion. ASTM International,, West Conshohocken, PA.

[17] ASTM F3490, 2021, Standard Practice for Additive Manufacturing — General Principles — Overview of Data Pedigree. ASTM International,, West Conshohocken, PA.
[18] Attarzadeh, F., Fotovvati, B., Fitzmire, M., Asadi, E., 2020, Surface Roughness and Densification Correlation for Direct Metal Laser Sintering. The International Journal of Advanced Manufacturing Technology, 107:2833–2842.
[19] Bagehorn, S., Wehr, J., Maier, H.J., 2017, Application of Mechanical Surface Finishing Processes for Roughness Reduction and Fatigue Improvement of Additively Manufactured Ti-6Al-4V Parts. International Journal of Fatigue, 102:135–142. https://doi.org/10.1016/j.ijfatigue.2017.05.008.
[20] Baicheng, Z., Xiaohua, L., Jiaming, B., Junfeng, G., Pan, W., Chen-nan, S., Muiling, N., Guojun, Q., Jun, W., 2017, Study of Selective Laser Melting (SLM) Inconel 718 Part Surface Improvement By Electrochemical Polishing. Materials & Design, 116:531–537. https://doi.org/10.1016/j.matdes.2016.11.103.
[21] Bambach, M., 2016, Recent Trends in Metal Forming: From Process Simulation And Microstructure Control in Classical Forming Processes to Hybrid Combinations Between Forming and Additive Manufacturing. Journal of Machine Engineering, 16/2: 5–17.
[22] Bambach M., 2016a, Process and plant for combined additive and forming production. Patent DPMA No. 102016111047B3 (DE).
[23] Bambach M., Sviridov A., Weisheit A., 2017a, Stiffness management of sheet metal parts using laser metal deposition, in: AIP Conference Proceedings. Proceedings of The International Conference of Global Network for Innovative Technology and AWAN Intern. Conf. in Civil Engineering (IGNITE-AICCE'17). doi: 10.1063/1.5008094.
[24] Bambach, M., Sviridov, A., Weisheit, A., Schleifenbaum, J., 2017, Case Studies on Local Reinforcement of Sheet Metal Components by Laser Additive Manufacturing. Metals, 7/4: 113. https://doi.org/10.3390/met7040113.
[25] Bambach, M., Sizova, I., Silze, F., Schnick, M., 2018, Hot Workability and Microstructure Evolution of the Nickel-based Superalloy Inconel 718 Produced by Laser Metal Deposition. Journal of Alloys and Compounds, 740:278–287. https://doi.org/10.1016/j.jallcom.2018.01.029.
[26] Bambach, M.D., Bambach, M., Sviridov, A., Weiss, S., 2017, New Process Chains Involving Additive Manufacturing and Metal Forming – A Chance for Saving Energy? Procedia Engineering, 207/54: 1176–1181. https://doi.org/10.1016/j.proeng.2017.10.1049.
[27] Bandyopadhyay, A., Heer, B., 2018, Additive Manufacturing of Multi-material Structures. Materials Science and Engineering: R: Reports, 129:1–16. https://doi.org/10.1016/j.mser.2018.04.001.
[28] Banh, T.T., Luu, N.G., Lee, D., 2021, A Non-homogeneous Multi-material Topology Optimization Approach for Functionally Graded Structures With Cracks. Composite Structures, Volume 273:114230. https://doi.org/10.1016/j.compstruct.2021.114230.
[29] Barrett, C., Carradero, C., Harris, E., Rogers, K., MacDonald, E., Conner, B., 2019, Statistical Analysis of Spatter Velocity With High-speed Stereovision in Laser Powder Bed Fusion. Progress in Additive Manufacturing, 4/4: 423–430.
[30] Bayat, M., Dong, W., Thorborg, J., Hattel, J. H, A.C., 2021, A Review of Multi-scale and Multi-physics Simulations of Metal Additive Manufacturing Processes With Focus on Modeling Strategies. Additive Manufacturing, 47:102278. https://doi.org/10.1016/j.addma.2021.102278.
[31] Beakawi Al-Hashemi, H., Baghabra Al-Amoudi, O., 2018, A Review on the Angle of Repose of Granular Materials. Powder Technology, 330:397–417. https://doi.org/10.1016/j.powtec.2018.02.003.
[32] Beaucamp, A.T., Namba, Y., Charlton, P., Jain, S., Graziano, A.A., 2015, Finishing of Additively Manufactured Titanium Alloy by Shape Adaptive Grinding (SAG). Surface Topography: Metrology and Properties, 3:0224001. https://doi.org/10.1088/2051-672X/3/2/024001.
[33] Belay, G.Y., Kinds, Y., Goossens, L., et al., 2022, Dynamic Optical Beam Shaping System to Generate Gaussian and Top-hat Laser Beams of Various Sizes With Circular and Square Footprint for Additive Manufacturing applications. LANE Conference, Procedia CIRP, Vol. 111:75–80. https://doi.org/10.1016/j.procir.2022.08.134.
[34] Bernard, A., Fischer, A., 2002, New Trends in Rapid Product Development. CIRP Annals, 51/2/2002:635–652.
[35] Berumen, S., Bechmann, F., Lindner, S., Kruth, J.-P., Craeghs, T., 2010, Quality Control of Laser- and Powder Bed-based Additive Manufacturing (AM) Technologies. Phys Procedia, 5:617–622.
[36] Binder M., Anstaett C., Horn M., Herzer F., Schlick G., Seidel C., Schilp J., Reinhart G., 2018, Potentials and challenges of multi-material processing by laser-based powder bed fusion. Solid Free. Fabr. 2018 Proc. 29th Annu. Int. Solid Free. Fabr. Symp. - An Addit. Manuf. Conf. SFF 2018, 376–387.
[37] Bong, K.D., Witherell, P., Lipman, R., Feng, S.C., 2015, Streamlining the Additive Manufacturing Digital Spectrum: A Systems Approach. Additive Manufacturing, 5/2015: 20–30.
[38] Bossuet, L., Torres, L., 2017, Foundations of Hardware IP Protection. Springer, Cham, Switzerland: 240.
[39] Bourell, D., Kruth, J.-P., Leu, M., Levy, G., Rosen, D., Beese, A.M., Clare, A., 2017, Materials for Additive Manufacturing. CIRP Annals, 66/2: 659–681. https://doi.org/10.1016/j.cirp.2017.05.009.
[40] Bours, J., Adzima, B., Gladwin, S., Cabral, J., Mau, S., 2017, Addressing Hazardous Implications of Additive Manufacturing: Complementing Life Cycle Assessment With a Framework For Evaluating Direct Human Health and Environmental Impacts. Journal of Industrial Ecology, 21:25–36. https://doi.org/10.1111/jiec.12587.
[41] Breidenstein, B., Brenne, F., Wu, L., Niendorf, T., Denkena, B., 2018, Effect of Post-process Machining on Surface Properties of Additively Manufactured H13 Tool Steel. Journal of Heat Treatment and Materials, 73/4: 173–186. https://doi.org/10.3139/105.110359.
[42] Brundle, C.R., 1992, X-ray Photoelectron Spectroscopy. Brundle CR, Evan CAJr, Wilson S, (Eds.) Encyclopedia of Materials Characterization. Butterworth-Heinemann Press, Boston: 282–299.
[43] Brunton, S.L., Kutz, J.-N., 2022, 2022 Brunton SL, Kutz JN, (Eds.) Data-Driven Science and Engineering, Machine Learning, Dynamical Systems and Control. second ed. Cambridge.
[44] Butzhammer L., Dubjella P., Huber F., Schaub A., Aumüller M., Baum A., Petrunenko O., Merklein M., Schmidt M., 2017, Experimental investigation of a process chain combining sheet metal bending and laser beam melting of Ti-6Al-4V, in: Wissenschaftliche Gesellschaft Lasertechnik e.V. (Ed.), Proceedings of the Lasers in Manufacturing LIM, Munich.
[45] Cacace, S., Furlan, V., Sorci, R., Semeraro, Q., Boccadoro, M., 2020, Using Recycled Material to Produce Gas-atomized Metal Powders for Additive Manufacturing Processes. ISSN 0959-6526, doi Journal of Cleaner Production, Volume 268/2020:122218. https://doi.org/10.1016/j.jclepro.2020.122218.
[46] Calta, N., Martin, A., Hammons, J., Nielsen, M., Roehling, T., Fezzaa, K., Lee, J., 2020, Pressure Dependence of the Laser-metal Interaction Under Laser Powder Bed Fusion Conditions Probed By in Situ X-ray Imaging. Additive Manufacturing, 32:101084.
[47] Canellidis, V., Giannatsis, J., Dedoussis, V., 2013, Efficient Parts Nesting Schemes for Improving Stereolithography Utilization. Computer-Aided Design, 45:875–886. https://doi.org/10.1016/j.cad.2012.12.002.
[48] Cao, J., Brinksmeier, E., Fu, M.W., Gao, R.X., Liang, B., Merklein, M., Schmidt, M., Yanagimoto, J., 2019, Manufacturing of Advanced Smart Tooling for Metal Forming. CIRP Annals, Vol. 68/2: 605–628. https://doi.org/10.1016/j.cirp.2019.05.001.
[49] Carolo, L.C.B., Cooper, R.E., 2022, A Review on the Influence Of Process Variables on the Surface Roughness of Ti-6Al-4V by Electron Beam Powder Bed Fusion. Additive Manufacturing, 59/A. https://doi.org/10.1016/j.addma.2022.103103.
[50] Chadwick, A.F., Voorhees, P.W., 2022, Recursive Grain Remapping Scheme for Phase-field Models of Additive Manufacturing. International Journal for Numerical Methods in Engineering. https://doi.org/10.1002/nme.6966.
[51] Chang, S., Liu, A., Ong, C.Y.A., Zhang, L., Huang, X., Tan, Y.H., Zhao, L., Li, L., Ding, J., 2019, Highly Effective Smoothening of 3D-printed Metal Structures via Overpotential Electrochemical Polishing. Materials Research Letters, 7:282–289. https://doi.org/10.1080/21663831.2019.1601645.
[52] Chen, F., Miao, X., Tang, Y., Yin, S., 2017, A Review on Recent Advances in Machining Methods Based on Abrasive Jet Polishing (AJP). The International Journal of Advanced Manufacturing Technology, 90:785–799. https://doi.org/10.1007/s00170-016-9405-7.
[53] Chen, F., Luo, Y., Tsoutsos, N.G., Maniatakos, M., Shahin, K., Gupta, N., 2018, Embedding Tracking Codes in Additive Manufactured Parts for Product Authentication. Advanced Engineering, 2019/21/4: 1800495. https://doi.org/10.1002/adem.201800495.
[54] Chen, H., Zhao, Y., 2016, Process Parameters Optimization for Improving Surface Quality And Manufacturing Accuracy of Binder Jetting Additive Manufacturing Process. Rapid Prototyping Journal, 22:527–538. https://doi.org/10.1108/RPJ-11-2014-0149.
[55] Chen, H., Wei, Q., Zhang, Y., Chen, F., Shi, Y., Yan, W., 2019, Powder-spreading Mechanisms in Powder-bed-based Additive Manufacturing: Experiments and Computational Modeling. Acta Materialia, 179:158–171. https://doi.org/10.1016/j.actamat.2019.08.030.
[56] Chen, H., Chen, Y., Liu, Y., Wei, Q., Shi, Y., Yan, W., 2020, Packing Quality of Powder Layer During Counter-rolling-type Powder Spreading Process in Additive Manufacturing. International Journal of Machine Tools and Manufacture, 153:103553. https://doi.org/10.1016/j.ijmachtools.2020.103553.
[57] Chen, L., Lau, T.Y., Tang, K., 2020, Manufacturability Analysis and Process Planning for Additive and Subtractive Hybrid Manufacturing of Quasi-Rotational Parts With Columnar Features. Computer-Aided Design, Volume 118:102759. https://doi.org/10.1016/j.cad.2019.102759.
[58] Chen, Q., Liang, X., Hayduke, D., Liu, J., Cheng, L., Oskin, J., Whitmore, R., To, A.C., 2019, An Inherent Strain Based Multiscale Modeling Framework for Simulating Part-scale Residual Deformation for Direct Metal Laser Sintering. Additive Manufacturing, 28:406–418. https://doi.org/10.1016/j.addma.2019.05.021.
[59] Chen, Z., Han, C., Gao, M., Kandukuri, S.Y., Zhou, K., 2022, A Review on Qualification and Certification for Metal Additive Manufacturing. Virtual and Physical Prototyping, 17/2: 382–405. https://doi.org/10.1080/17452759.2021.2018938.
[60] Chen, Z., Sang, X., Xu, W., Dycus, J.H., LeBeau, J.M., D'Alfonso, A.J., Allen, L.J., Findlay, S.D., 2016, Quantitative Atomic Resolution Elemental Mapping Via Absolute-scale Energy Dispersive X-ray Spectroscopy. Ultramicroscopy, 168:7–16. https://doi.org/10.1016/j.ultramic.2016.05.008.
[61] Cheng, B., Lane, B., Whiting, J., Chou, K.A., 2018, Combined Experimental-numerical Method to Evaluate Powder Thermal Properties in Laser Powder Bed Fusion. Journal of Manufacturing Science and Engineering, 1/140(11):111008.
[62] Cheng, L., To, A., 2019, Part-scale Build Orientation Optimization For Minimizing Residual Stress and Support Volume for Metal Additive Manufacturing: Theory and Experimental Validation. Computer-Aided Design, Volume 113:1–23. https://doi.org/10.1016/j.cad.2019.03.004.
[63] Chergui, A., Hadj-Hamou, K., Vignat, F., 2018, Production Scheduling and Nesting in Additive Manufacturing. Computers & Industrial Engineering, 126:292–301. https://doi.org/10.1016/j.cie.2018.09.048.

[64] Chivel, Y., 2016, New Approach to Multi-material Processing in Selective Laser Melting. Physics Procedia, 83:891–898. https://doi.org/10.1016/j.phpro.2016.08.093.
[65] Cho, H.W., Shin, S.J., Seo, G.J., Kim, D.B., Lee, D.H., 2022, Real-time Anomaly Detection Using Convolutional Neural Network in Wire Arc Additive Manufacturing: Molybdenum Material. Journal of Materials Processing Technology:117495. https://doi.org/10.1016/j.jmatprotec.2022.117495.
[66] Clayton, J., Millington-Smith, D., Armstrong, B., 2015, The Application of Powder Rheology in Additive Manufacturing. JOM, 67/3:544–548. https://doi.org/10.1007/s11837-015-1293-z.
[67] Clijsters, S., Craeghs, T., Buls, S., Kempen, K., Kruth, J.-P., 2014, In Situ Quality Control of the Selective Laser Melting Process Using A High-speed, Real-time Melt Pool Monitoring System. The International Journal of Advanced Manufacturing Technology, 75/5: 1089–1101.
[68] Colosimo, B.M., Grossi, E., Caltanissetta, F., Grasso, M., 2020, Penelope: A Novel Prototype for In Situ Defect Removal in LPBF. JOM Journal, Vol. 72:1332–1339. https://doi.org/10.1007/s11837-019-03964-0.
[69] Cook, P.S., Murphy, A.B., 2020, Simulation of Melt Pool Behaviour During Additive Manufacturing: Underlying Physics and Progress. Additive Manufacturing, 31:100909. https://doi.org/10.1016/j.addma.2019.100909.
[70] Cooper, K., Steele, P., Cheng, B., Chou, K., 2018, Contact-Free Support Structures for Part Overhangs in Powder-Bed Metal Additive Manufacturing. 2018 Inventions, 3/1: 2. https://doi.org/10.3390/inventions3010002.
[71] Cortina, M., Arrizubieta, J.I., Ruiz, J.E., Ukar, E., Lamikiz, A., 2018, Latest Developments in Industrial Hybrid Machine Tools that Combine Additive and Subtractive Operations. Materials, 11.2583/12. https://doi.org/10.3390/ma11122583.
[72] Craeghs T., Kruth J.-P., 2010b, Developing a Quality Inspection Method for Selective Laser Melting of Metals with NI Hardware and Software, National instruments case studies, ⟨http://www.ni.com⟩.
[73] Craeghs, T., Bechmann, F., Berumen, S., Kruth, J.-P., 2010, Feedback Control of Layerwise Laser Melting Using Optical Sensors. Physics Procedia, 5:505–514.
[74] Cunningham, R., Zhao, C., Parab, N., Kantzos, C., Pauza, J., Fezzaa, K., Sun, T., Rollett, A.D., 2019, Keyhold Threshold and Morphology in Laser Melting Revealed By Ultrahig-speed X-ray Imaging. Science, 363/6429: 849–852. https://doi.org/10.1126/science.aav4687.
[75] Dadbakhsh, S., Hao, L., Sewell, N., 2012, Effect of Selective Laser Melting Layout on the Quality of Stainless Steel Parts. Rapid Prototyping Journal, 18/3: 241–249. https://doi.org/10.1108/13552541211218216.
[76] Dadbakhsh, S., Mertens, R., Hao, L., van Humbeeck, J., Kruth, J.-P., 2019, Selective Laser Melting to Manufacture "In Situ" Metal Matrix Composites: A Review. Advanced Engineering, 21/3: 1801244. https://doi.org/10.1002/adem.201801244.
[77] Dadbakhsh, S., Mertens, R., Vanmeensel, K., Vleugels, J., van Humbeeck, J., Kruth, J.-P., 2018, In situ alloying and reinforcing of Al6061 during selective laser melting. Procedia CIRP, 74:39–43. https://doi.org/10.1016/j.procir.2018.08.009.
[78] Davies S., 2020, AMT launches two de-powdering systems for 3D printed parts with Leering Hengelo. TCT magazine., Published online on 23rd April 2020, ⟨https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/amt-de-powdering-systems-3d-printed-parts-leering/⟩.
[79] De Pastre, M.A., Thompson, A., Quinsat, Y., García, J.A., Senin, N., Leach, R., 2020, Polymer powder bed fusion surface texture measurement. Measurement Science and Technology, 31/31(5):055002.
[80] Demir, A.G., Previtali, B., 2017, Additive manufacturing of cardiovascular CoCr stents by selective laser melting. Materials & Design, 119:338–350. https://doi.org/10.1016/j.matdes.2017.01.091.
[81] Depond, P., Guss, G., Ly, S., Calta, N., Deane, D., Khairallah, S., Matthews, M., 2018, In Situ Measurements of Layer Roughness During Laser Powder Bed Fusion Additive Manufacturing Using Low Coherence Scanning Interferometry. Materials and Design, 154/2018: 347–359.
[82] Desai, P.S., Mehta, A., Dougherty, P.S.M., Higgs, F.C., 2019, A Rheometry Based Calibration of A First-order DEM Model to Generate Virtual Avatars of metal Additive Manufacturing (AM) Powders. Powder Technology, 342:441–456. https://doi.org/10.1016/j.powtec.2018.09.047.
[83] Despeisse, M., Yang, M., Evans, S., Ford, S., Minshall, T., 2017, Sustainable Value Roadmapping Framework for Additive Manufacturing. Procedia CIRP, 61:594–599. https://doi.org/10.1016/j.procir.2016.11.186.
[84] Detwiler, S., Watring, D., Spear, A., Raeymaekears, A., 2022, Relating the Surface Topography of As-built Inconel 718 Surfaces to Laser Powder Bed Fusion Process Parameters Using Multivariate Regression Analysis. Precision Engineering, 74:303–315. https://doi.org/10.1016/j.precisioneng.2021.12.003.
[85] Dickins, A., Widjanarko, T., Sims-Waterhouse, D., Thompson, A., Lawes, S., Leach, R., 2020, Multi-view Fringe Projection System for Surface Topography Measurement During Metal Powder Bed Fusion. Journal of the Optical Society of America A, Vol. 37/No. 9: B93–105.
[86] Didier, P., Le Coz, G., Robin, G., Lohmuller, P., Piotrowski, B., Moufki, A., Laheurte, P., 2021, Consideration of SLM additive manufacturing supports on the stability of flexible structures in finish milling. Journal of Material Processes, Volume 62:213–220. https://doi.org/10.1016/j.jmapro.2020.12.027.
[87] Dong, G., Wong, J.C., Lestandi, L., Mikula, J., Vastola, G., Jhon, M.H., Dao, M.H., Kizhakkinan, U., Ford, C.S., Rosen, D.W., 2022, A Part-scale, Feature-based Surrogate Model for Residual Stresses in The Laser Powder Bed Fusion Process. Journal of Materials Processing Technology:117541. https://doi.org/10.1016/j.jmatprotec.2022.117541.
[88] Doris, 2015, Concept Laser "AM Factory of Tomorrow" Opens Up Potential with Modular Machine Configurations. 3PRINTR.com. ⟨https://www.3printr.com/concept-lasersconfigurations-1832207/⟩. (Accessed July 11, 2022).
[89] Du, Y., Mukherjee, T., DebRoy, T., 2021, Physics-informed Machine Learning and Mechanistic Modeling of Additive Manufacturing to Reduce Defects. Applied Materials Today, 24:101123.
[90] Duda, T., Raghavan, L.V., 2018, 3D Metal Printing Technology: The Need to Re-invent Design Practice. AI & Society, 33:241–252. https://doi.org/10.1007/s00146-018-0809-9.
[91] Echeta, I., Feng, X., Dutton, B., Leach, R., Piano, S., 2020, Review of Defects in Lattice Structures Manufactured By Powder Bed Fusion. The International Journal of Advanced Manufacturing Technology, 106:2649–2668. https://doi.org/10.1007/s00170-019-04753-4.
[92] Eisenbarth, D., Stoll, P., Klahn, C., Heinis, T., Meboldt, M., Wegener, K., 2020, Unique Coding For Authentication and Anti-counterfeiting By Controlled And Random Process Variation in L-PBF and L-DED. ISSN 2214-8604, doi Additive Manufacturing, Volume 35/2020:101298. https://doi.org/10.1016/j.addma.2020.101298.
[93] Elambasseril, J., Rogers, J., Wallbrink, C., Munk, D., 2022, Laser Powder Bed Fusion Additive Manufacturing (LPBF-AM): The Influence Of Design Features and LPBF Variables on Surface Topography and Effect on Fatigue Properties. Critical Reviews in Solid State and Materials Sciences, 48/1:132–168. https://doi.org/10.1080/10408436.2022.2041396.
[94] Elangeswaran, C., Gurung, K., Koch, R., Cutolo, A., van Hooreweder, B., 2020, Post-treatment Selection For Tailored Fatigue Performance OF 18NI300 Maraging Steel Manufactured By Laser Powder Bed Fusion. Fatigue & Fracture of Engineering Materials & Structures, 43/10: 2359–2375. https://doi.org/10.1111/ffe.13304.
[95] EOS Solutions GmbH, 2022, NextGenAM – the Future, Here Today, Industrial 3D Printing Fully Automated. ⟨https://www.eos.info/en/innovations/digital-manufacturing-production/next-gen-am-industry-40⟩. (Accessed July 12, 2022).
[96] Eschner, E., Staudt, T., Schmidt, M., 2020, Correlation of Spatter Behavior and Process Zone Formation in Powder Bed Fusion of Metals. CIRP Annals, 69:209–212. https://doi.org/10.1016/j.cirp.2020.04.092.
[97] Eschner, N., Weiser, L., Häfner, B., Lanza, G., 2020, Classification of specimen density in Laser Powder Bed Fusion (L-PBF) using in-process structure-borne acoustic process emissions. Additive Manufacturing, 34:101324.
[98] ESI, ⟨https://myesi.esi-group.com/products/additive-manufacturing⟩.
[99] Esmaeilian, B., Deka, A., Behdad, S., 2019, A Blockchain Platform for Protecting Intellectual Property: Implications for Additive Manufacturing. ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference Proceedings. https://doi.org/10.1115/DETC2019-98293.
[100] Everton, S., Dickens, P., Tuck, C., Dutton, B., 2018, Using Laser Ultrasound to Detect Subsurface Defects in Metal Laser Powder Bed Fusion Components. JOM, 70/3:378–383. https://doi.org/10.1007/s11837-017-2661-7.
[101] Everton, S., Hirsch, M., Stravroulakis, P., Leach, R., Clare, A., 2016, Review of In-situ Process Monitoring and In-situ Metrology for Metal Additive Manufacturing. Materials & Design, 95:431–445. https://doi.org/10.1016/j.matdes.2016.01.099.
[102] Fan, Z., Wang, H., Huang, Z., Liao, H., Fan, J., Lu, J., Liu, C., Li, B., 2020, A Lagrangian Meshfree Mesoscale Simulation of Powder Bed Fusion Additive Manufacturing of Metals. International Journal for Numerical Methods in Engineering, vol. 122/2: 483–514. https://doi.org/10.1002/nme.6546.
[103] Fang, F.Z., Zhang, X., Gao, W., Guo, Y., Byrne, G., Hansen, H.N., 2017, Nanomanufacturing- Perspective and Applications. CIRP Annals-Manufacturing Technology, 66/2: 683–705.
[104] FDA, 2017, U.S. food and drug administration, technical considerations for additive manufactured medical devices guidance for industry and food and drug administration staff, ⟨https://www.fda.gov/regulatory-information/search-fda-guidance-documents/technical-considerations-additive-manufactured-medical-devices⟩.
[105] Fergani, O., Berto, F., Welo, T., Liang, S.Y., 2017, Analytical Modelling of Residual Stress in Additive Manufacturing. Fatigue & Fracture of Engineering Materials & Structures, 40:971–978. https://doi.org/10.1111/ffe.12560.
[106] Fernandez-Zelaia, P., Nguyen, V., Zhang, H., Kumar, A., Melkote, S.N., 2019, The Effect of Material Anisotropy on Secondary Processing of Additively Manufactured CoCrMo. Additive Manufacturing, 29:100764. https://doi.org/10.1016/j.addma.2019.06.015.
[107] Ferrar, B., Mullen, L., Jones, E., Stamp, R., Sutcliffe, C.J., 2012, Gas Flow Effects on Selective Laser Melting (SLM) Manufacturing Performance. Journal of Materials Processing Technology, 212/2: 355–364. https://doi.org/10.1016/j.jmatprotec.2011.09.020.
[108] Ferrucci, M., Ametova, E., 2021, Charting the Course Towards Dimensional Measurement Traceability by X-ray Computed Tomography. Measurement Science and Technology, 32/092001: 26. https://doi.org/10.1088/1361-6501/abf058.
[109] Fleming, T., Nestor, S., Allen, T., Boukhaled, M., Smith, N., Fraser, J., 2020, Tracking and Controlling the Morphology Evolution of 3D Powder-bed Fusion in Situ Using Inline Coherent Imaging. Additive Manufacturing, 32:100978.
[110] Flys, O., Berglund, J., Rosen, B.G., 2020, Using Confocal Fusion for Measurement of metal AM Surface Texture. Surface Topography: Metrology and Properties, 8:024003.
[111] Fortunato, A., Lulaj, A., Melkote, S., Liverani, E., Ascari, A., Umbrello, D., 2018, Milling of Maraging Steel Components Produced by Selective Laser Melting.

International Journal of Advanced Manufacturing Technology, 94:1895–1902. https://doi.org/10.1007/s00170-017-0922-9.
[112] Fox, J., Evans, C., Mandloi, K., 2021, Characterization of Laser Powder Bed Fusion Surfaces for Heat Transfer Applications. CIRP Annals – Manufacturing Technology, 70/1:467–470. https://doi.org/10.1016/j.cirp.2021.04.032.
[113] Freemelt, K.D., Witherell, P., Lipman, R., Feng, S.C., 2015, Streamlining the Additive Manufacturing Digital Spectrum: A Systems Approach. Additive Manufacturing, 5/2015: 20–30.
[114] Furumoto, T., Ueda, T., Alkahari, M., Hosokawa, A., 2013, Investigation of Laser Consolidation Process for Metal Powder By Two-color Pyrometer and High-speed Video Camera. CIRP Annals, 62:223–226.
[115] Furumoto, T., Ueda, T., Amino, T., Kusunoki, D., Hosokawa, A., Tanaka, R., 2012, Finishing Performance of Cooling Channel With Face Protuberance Inside The Molding Die. Journal of Materials Processing Technology, 212:2154–2160. https://doi.org/10.1016/j.jmatprotec.2012.05.016.
[116] Gan, Z., Li, H., Wolff, S.J., Bennett, J.L., Hyatt, G., Wagner, G.J., Cao, J., Liu, W.K., 2019, Data-driven Microstructure and Microhardness Design in Additive Manufacturing Using A Self-organizing Map. Engineering, 5/4: 730–735. https://doi.org/10.1016/j.eng.2019.03.014.
[117] GE Additive, 2008, New manufacturing milestone: 30,000 additive fuel nozzles, 〈https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles〉, published Oct. 2018, Accessed April 2023.
[118] Ghorbanpour, S., Ershadul Alam Md, Ferreri, N.C., Kumar, A., McWilliams, B.A., Vogel, S.C., Bicknell, J., Beyerlein, I.J., Knezevic, M., 2020, Experimental Characterization and Crystal Plasticity Modeling of Anisotropy, Tension-compression Asymmetry, and Texture Evolution of Additively Manufactured Inconel 718 at Room and elevated temperatures. International Journal of Plasticity, Vol. 125:63–79. https://doi.org/10.1016/j.ijplas.2019.09.002.
[119] Gibson, I., Rosen, D.W., Stucker, B., 2015, Additive manufacturing technologies: 3Dprinting, rapid prototyping, and direct digital manufacturing. 2nd ed.., Springer-Verlag New York,, New York.
[120] Glaessgen E.H., Levine L.E., Witherell P.W., Donmez M.A., Gorelik M., Ashmore N.A., Barto R.R., Battaile C.C., Millwater H.R., Nanni G.J., Rollett A.D., Schwalbach C.J., and Venkatesh V., 2021, NASA/NIST/FAA Technical Interchange Meeting on Computational Materials Approaches for Qualification by Analysis for Aerospace Applications (No. NASA/TM-20210015175).
[121] Gobert, C., Reutzel, E.W., Petrich, J., Nassar, A.R., Phoha, S., 2018, Application of Supervised Machine Learning for Defect Detection During Metallic Powder Bed Fusion Additive Manufacturing Using High Resolution Imaging. Additive Manufacturing, 1/21: 517–528.
[122] Godfrey D.G., Baughman B.G., McNair M., Lastre H.A., Guthrie D., Schnepf J., Kielbus R., Dolan J., Harms E., Figueroa M., 2019, Devices and methods for evaluating the spreadability of powders utilized in additive manufacturing. European Patent Application EP 3 569 331 A1, Application no. 19173963.0.
[123] Gonzalez-Gutierrez, J., Cano, S., Schuschnigg, S., Kukla, C., Sapkota, J., Holzer, C., 2018, Additive Manufacturing of Metallic and Ceramic Components By The Material Extrusion of Highly-filled Polymers: A Review and Future Perspectives. Materials, 11:840. https://doi.org/10.3390/ma11050840.
[124] Goossens, K., 2014, Interpretatie en validatie van het optisch kwaliteitscontrole systeem voor Selectief Laser Smelten, MS thesis 2013-2014. KU Leuven.
[125] Goossens, L., Van Hooreweder, B., 2021, A Virtual Sensing Approach for Monitoring Melt-pool Dimensions Using High Speed Coaxial Imaging During Laser Powder Bed Fusion of Metals. Additive Manufacturing, Vol. 40:101923.
[126] Grasso, M., Colosimo, B.M., 2017, Process Defects And in-situ Monitoring Methods in Metal Powder Red Fusion: A Review. Measurement Science & Technology, 28:044005. https://doi.org/10.1088/1361-6501/aa5c4f.
[127] Grasso, M., Demir, A.G., Previtali, B., Colosimo, B.M., 2018, In Situ Monitoring of Selective Laser Melting of Zinc Powder Via Infrared Imaging of the Process Plume. Robotics and Computer-Integrated Manufacturing, 49:229–239.
[128] Grasso, M., Remani, A., Dickins, A., Colosimo, B.M., Leach, R., 2021, In-situ Measurement and Monitoring Methods for Metal Powder Bed Fusion – An Updated Review. id.112001 Measurement Science and Technology, Volume 32/ Issue 11: 46. https://doi.org/10.1088/1361-6501/ac0b6b.
[129] Grove, T., Denkena, B., Maib, O., Krodel, A., Schwab, H., Kuhn, U., 2018, Cutting Mechanism and Surface Integrity In Milling of Ti-5553 Processed By Selective Laser Melting. Journal of Mechanical Science and Technology, 32/10: 4883–4892. https://doi.org/10.1007/s12206-018-0936-8.
[130] Guo C., Lin F., Ge W.J., Zhang J., 2014, Development of Novel EBSM System for High-Tech Material Additive Manufacturing Research (researchgate.net), 2014 International Solid Freeform Fabrication Symposium (SFF), 298–308, 〈https://www.researchgate.net/publication/277562180〉.
[131] Guo, J., Goh, N.H., Wang, P., Huang, R., Lee, X., Wang, B., Nai, S.M.L., Wei, J., 2020, Investigation on Surface Integrity of Electron Beam Melted Ti6Al4V by Precision Grinding and Polishing. Chinese Journal of Aeronautics, in Press. https://doi.org/10.1016/j.cja.2020.08.014.
[132] Guo, N., Leu, M., 2013, Additive Manufacturing: Technology, Applications and Research Needs. Front Mech Eng, 8:215–243. https://doi.org/10.1007/s11465-013-0248-8.
[133] Guo, Q., Zhao, C., Qu, M., Xiong, L., Escano, L., Hojjatzadeh, S.M.H., Parab, N.D., Fezzaa, K., Everhart, W., Sun, T., Chen, L., 2019, In-situ Characterization and Quantification of Melt Pool Variation Under Constant Input Energy Density In Laser Powder Bed Fusion Additive Manufacturing Process. Additive Manufacturing, 28:600–609.
[134] Gupta N., Chen F., Tsoutsos N., Maniatakos, M., 2017, INVITED: ObfusCADe: Obfuscating additive manufacturing CAD models against counterfeiting, 54th ACM/EDAC/IEEE Design Automation Conference. (DAC), 2017, pp. 1–6, doi: 10.1145/3061639.3079847.
[135] Gutknecht, K., Haferkamp, L., Cloots, M., Wegener, K., 2020, Determining Process Stability of Laser Powder Bed Fusion Using Pyrometry. Procedia CIRP, 95:127–132. https://doi.org/10.1016/j.procir.2020.01.147.
[136] Gutowski, T., Sahni, S., Boustani, A., Graves, S., 2011, Remanufacturing and Energy Savings. Environmental Science & Technology, 45:4540–4547. https://doi.org/10.1021/es102598b.
[137] Häfele, T., Schneberger, J.-H., Kaspar, J., Vielhaber, M., Griebsch, J., 2019, Hybrid Additive Manufacturing – Process Chain Correlations and Impacts. Procedia CIRP, 84/1: 328–334. https://doi.org/10.1016/j.procir.2019.04.220.
[138] Hagedorn-Hansen, D., Bezuidenhout, M., Dimitrov, D., Oosthuizen, T., 2017, The Effects of Selective Laser Melting Scan Strategies on Deviation of Hybrid parts. SAJIE, 28/3. https://doi.org/10.7166/28-3-1862.
[139] Han, C., Fang, Q., Shi, Y., Tor, S.B., Chua, C.K., Zhou, K., 2020, Recent Advances on High-Entropy Alloys for 3D Printing (wiley.com). Advanced Materials, 32:1903855. https://doi.org/10.1002/adma.201903855.
[140] Han, C., Babicheva, R., Dong Qiu Chua, J., Ramamurty, U., Tor, S.B., Sun, C.-N., Zhou, K., 2020, Microstructure and Mechanical Properties of (TiB+TiC)/Ti Composites Fabricated In Situ Via Selective Laser Melting of Ti and B4C Powders. Additive Manufacturing, 36:101466. https://doi.org/10.1016/j.addma.2020.101466.
[141] Han, W., Fang, F.Z., 2019, Fundamental Aspects And Recent Developments In Electropolishing. International Journal of Machine Tools and Manufacture, 139:1–23. https://doi.org/10.1016/j.ijmachtools.2019.01.001.
[142] Hare, C., Zafar, U., Ghadiri, M., Freeman, T., Clayton, J., Murtagh, M.J., 2015, Analysis of the Dynamics of the FT4 Powder Rheometer. Powder Technology, 1/285: 123–127.
[143] Hartig F., Krystek M., 2009, Correct treatment of systematic errors for the evaluation of measurement uncertainty. 9th International symposium on measurement technology and intelligent instruments, Saint Petersburg (Russia), pp. 1–016-1–019.
[144] Havrilla, D.L., Feuchtenbeiner, S., Speker, N., Haug, P., Hesse, T., 2018, BrightLine weld-spatter reduced high speed welding with disk lasers. Kaierle S, Heinemann SW, (Eds.) High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VII. SPIE: 11.
[145] He, F., Yuan, L., Mu, H., Ros, M., Ding, D., Pan, Z., Li, H., 2023, Research and Application of Artificial Intelligence Techniques For Wire Arc Additive Manufacturing: A State-of-the-art Review. ISSN 0736-5845 Robotics and Computer-Integrated Manufacturing, Volume 82:102525. https://doi.org/10.1016/j.rcim.2023.102525.
[146] He, Y., Hassanpour, A., Bayly, A., 2020, Linking Particle Properties to Layer Characteristics: Discrete Element Modelling of Cohesive Fine Powder Spreading in Additive Manufacturing. Additive Manufacturing, 36. https://doi.org/10.1016/j.addma.2020.101685.
[147] Heinl, M., Greiner, S., Wudy, K., Pobel, C., Rasch, M., Huber, F., Papke, T., Merklein, M., Schmidt, M., Körner, C., Drummer, D., 2020, Measuring Procedures for Surface Evaluation of Additively Manufactured Powder Bed-based Polymer and Metal Parts. Measurement Science and Technology, 17/31(9): 0952022.
[148] Hermanek, P., Carmignato, S., 2017, Porosity Measurements by X-ray Computed Tomography: Accuracy Evaluation Using a Calibrated Object. Precision Engineering, 49:377–387. https://doi.org/10.1016/j.precisioneng.2017.03.007.
[149] Herzog F., Bechmann F., Berumen S., Craeghs T., Kruth J.-P., 2010, Procedure for mapping process behavior in selective laser power processing, Patent, DPMA No. 20 2010 010 771.7 (DE).
[150] Hirtler, M., Jedynak, A., Sydow, B., Sviridov, A., Bambach, M., 2018, Investigation of Microstructure and Hardness of A Rib Geometry Produced By Metal Forming and Wire-arc Additive Manufacturing. MATEC Web Confernece, 190:2005. https://doi.org/10.1051/matecconf/201819002005.
[151] Hitzler, L., Hirsch, J., Heine, B., Merkel, M., Hall, W., Öchsner, A., 2017, On the Anisotropic Mechanical Properties of Selective Laser-melted Stainless Steel. Materials (Basel, Switzerland), 10/10. https://doi.org/10.3390/ma10101136.
[152] Hölker R., Khalifa N.B., Tekkaya A.E., 2014, Method and device for the combined production of components by means of incremental sheet metal forming and additive processes in one setting. Patent DPMA No. 10 2014014202A1 (DE).
[153] Huang, G., 1996, Design for X: Concurrent Engineering Imperatives. Springer Netherlands, Dordrecht.
[154] Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., Masanet, E., 2016, Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components. Journal of Cleaner Production, 135:1559–1570. https://doi.org/10.1016/j.jclepro.2015.04.109.
[155] Huang, X., Liu, A., Xie, H., 2013, Recent Progress in Residual Stress Measurement Techniques. Acta Mechanica Solida Sinica, 26/6:570–583.
[156] Huang, Y., Khamesee, M.B., Toyserkani, E., 2019, A New Physics-based Model for Laser Directed Energy Deposition (Powder-fed Additive Manufacturing): From Single-track To Multi-track and Multi-layer. Optics & Laser Technology, 109:584–599. https://doi.org/10.1016/j.optlastec.2018.08.015.
[157] Huber, F., Papke, T., Kerkien, M., Tost, F., Geyer, G., Merklein, M., Schmidt, M., 2019, Customized Exposure Strategies For Manufacturing Hybrid Parts by Combining Laser Beam Melting and Sheet Metal Forming. Journal of Laser Applications, 31/2: 22318. https://doi.org/10.2351/1.5096115.
[158] Hulme-Smith, C.N., Hari, V., Mellin, P., 2021, Spreadability Testing of Powder for Additive Manufacturing. Bergisch Huettenmaenn Monatsh, 166:9–13. https://doi.org/10.1007/s00501-020-01069-9.

[159] ISO 10303-242, 2020, Industrial Automation Systems and Integration — Product Data Representation and Exchange — Part 242: Application protocol: Managed Model-based 3D Engineering. International Organization for Standardization, Geneva, Switzerland.
[160] ISO 13320, 2020, Particle Size Analysis – Laser Diffraction Methods. International Organization for Standardization,, Geneva, Switzerland.
[161] ISO 13322-2, 2006, Particle Size Analysis – Image Analysis Methods- Part 2: Dynamic Image Analysis Methods. International Organization for Standardization, Geneva, Switzerland.
[162] ISO 15530-3, 2011, Geometrical product specifications (GPS) — coordinate measuring machines (CMM): technique for determining the uncertainty of measurement — Part 3: Use of calibrated workpieces or measurement standards. International Organization for Standardization, Geneva, Switzerland.
[163] ISO 4490, 2018, Metallic Powders — Determination of Flow Rate By Means of A Calibrated Funnel (Hall flowmeter). International Organization for Standardization,, Geneva, Switzerland.
[164] ISO 8130-1, 2019, Coating Powders – Part 1: Determination of Particle Size Distribution By Sieving. International Organization for Standardization,, Geneva, Switzerland.
[165] ISO/ASTM 52900, 2021, Additive Manufacturing – General Principles – Fundamentals and Vocabulary. International Organization for Standardization,, Geneva, Switzerland.
[166] ISO/ASTM 52941, 2020, (en) Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application, ISO/TC 261 Additive Manufacturing. International Organization for Standardization, Geneva, Switzerland.
[167] ISO/ASTM 52948,Additive manufacturing of metals – Non-destructive testing and evaluation – Defect classification in PBF parts, International Organization for Standardization, Geneva, Switzerland.
[168] ISO/IEC Guide 98-3, 2008, Uncertainty of Measurement — Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995). International Organization for Standardization, Geneva, Switzerland.
[169] ISO-OPB Online Browsing Platform, ⟨www.iso.org/obp⟩, last accessed Aug 16, 2021.
[170] Jacob, A., Windhuber, K., Ranke, D., Lanza, G., 2018, Planning, Evaluation and Optimization of Product Design and Manufacturing Technology Chains For New Product and Production Technologies On the Example of Additive Manufacturing. Procedia CIRP, 70:108–113. https://doi.org/10.1016/j.procir.2018.02.049.
[171] Jafari, D., Vaneker, T., Gibson, I., 2021, Wire and Arc Additive Manufacturing: Opportunities and Challenges to Control The Quality and Accuracy of Manufactured Parts. ISSN 0264-1275, doi: Materials & Design, Volume 202:109471. https://doi.org/10.1016/j.matdes.2021.109471.
[172] Jafari, D., Wits, W., Vaneker, T., Demir, A.G., Previtali, B., Geurts, B., Gibson, I., 2020, Pulsed Mode Selective Laser Melting of Porous Structures: Structural and Thermophysical Characterization. Additive Manufacturing, Volume 35. https://doi.org/10.1016/j.addma.2020.101263.
[173] Jaiswal, P., Rai, R., 2019, A Geometric Reasoning Approach for Additive Manufacturing Print Quality Assessment and Automated Model Correction. Computer-Aided Design, Volume 109:1–11. https://doi.org/10.1016/j.cad.2018.12.001.
[174] Jiang, J., Xu, X., Stringer, J., 2018, Support Structures for Additive Manufacturing: A Review. Journal of Manufacturing and Material Processing. https://doi.org/10.3390/jmmp2040064.
[175] Jin, W., Li, F., 2010, Study on Laser Diffraction Measurement Uncertainty Comparing Traditional and Statistical Method with Virtual Instrument. 2010 International Conference On Computer Design and Applications, V3:468–471. https://doi.org/10.1109/ICCDA.2010.5541325.
[176] Jin, Z., Zhang, Z., Demir, K., Gu, G., 2020, Machine Learning for Advanced Additive Manufacturing. 4 November 2020 Matter, Volume 3/Issue 5: 1541–1556. https://doi.org/10.1016/j.matt.2020.08.023.
[177] Jørgen Hanssen, O., 1998, Environmental Impacts of Product Systems in A Life Cycle Perspective. Journal of Cleaner Production, 6:299–311. https://doi.org/10.1016/S0959-6526(98)00031-6.
[178] Josten, M., 2018, GKN Powder Metallurgy: Moving metal Additive Manufacturing towards mass production with HP. Metal Additive Manufacturing, 129–134.
[179] Kalentics, N., Boillat, E., Peyre, P., Gorny, C., Kenel, C., Leinenbach, C., Jhabvala, J., Logé, R.E., 2017, 3D Laser shock peening – a new method for the 3D control of residual stresses in Selective Laser Melting. Materials & Design, 130/2: 350–356. https://doi.org/10.1016/j.matdes.2017.05.083.
[180] Karnati S., Matta N., Sparks T., Liou F., 2013, Vision-based process monitoring for laser metal deposition processes, 24th SFF Symp., Austin, TX.
[181] Kayacan, M.Y., Özsoy, K., Duman, B., Yilmaz, N., Kayacan, M.C., 2019, A Study on Elimination of Failures Resulting From Layering and Internal Stresses in Powder Bed Fusion (PBF) Additive Manufacturing. Materials and Manufacturing Processes, 34/13: 1467–1475. https://doi.org/10.1080/10426914.2019.1655151.
[182] Kellens, K., Baumers, M., Gutowski, T., Flanagan, W., Lifset, R., Duflou, J., 2017, Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. Journal of Industrial Ecology, 21:49–68. https://doi.org/10.1111/jiec.12629.
[183] Keller, T., Lindwall, G., Ghosh, S., Ma, L., Lane, B.M., Zhang, F., Kattner, U.R., Lass, E.A., Heigel, J.C., Idell, Y., Williams, M.E., Allen, A.J., Guyer, J.E., Levine, L.E., 2017, Application of Finite Element, Phase-field, and CALPHAD-Based Methods to Additive Manufacturing of Ni-based Superalloys. Acta Materialia, 139:244–253. https://doi.org/10.1016/j.actamat.2017.05.003.
[184] Khanafer, K., Al-Masri, A., Aithal, S., Deiab, I., 2019, Multiphysics Modeling and Simulation of Laser Additive Manufacturing Process. Int J Interact Des Manuf, 13/2: 537–544. https://doi.org/10.1007/s12008-018-0520-6.
[185] Kim, F., Moylan, S., 2018, Literature Review of Metal Additive Manufacturing Defects. NIST Advanced Manufacturing Series, 100–116. https://doi.org/10.6028/NIST.AMS.100-16.
[186] Kim, F.H., Pintar, A.L., Moylan, S.P., Garboczi, E.J., 2019, The Influence of X-Ray Computed Tomography Acquisition Parameters on Image Quality and Probability of Detection of Additive Manufacturing Defects. Journal of Manufacturing Science and Engineering, 1/141(11):111002.
[187] Kim, F.H., Pintar, A., Obaton, A.F., Fox, J., Tarr, J., Donmez, A., 2021, Merging Experiments and Computer Simulations in X-ray Computed Tomography Probability of Detection Analysis of Additive Manufacturing Flaws. NDT & E International, 1/119:102416.
[188] Kim, J.Y., Garcia, D., Zhu, Y., Higdon, D.M., Hang, Z.Y., 2022, A Bayesian Learning Framework For Fast Prediction and Uncertainty Quantification of Additively Manufactured Multi-material Components. Journal of Materials Processing Technology, 303:117528. https://doi.org/10.1016/j.jmatprotec.2022.117528.
[189] Kirschenmann, L., Pechhold, W., 2002, Piezoelectric Rotary Vibrator (PRV) – A New Oscillating Rheometer for Linear Viscoelasticity. Rheol Acta, 41:362–368. https://doi.org/10.1007/s00397-002-0229-z.
[190] Klobcar, D., Baloš, S., Bašic, M., Djuric, A., Lindic, M., Šcetinec, A., 2020, WAAM and Other Unconventional Metal Additive Manufacturing Technologies. Adv Technol Mater, 45/2: 1–9. https://doi.org/10.24867/ATM-2020-2-001.
[191] Kohtala, C., 2015, Addressing Sustainability in Research On Distributed Production: An Integrated Literature Review. Journal of Cleaner Production, 106:654–668. https://doi.org/10.1016/j.jclepro.2014.09.039.
[192] Kolb, T., Huber, F., Akbulut, B., Donocik, C., Urban, N., Maurer, D., Franke, J., 2016, Laser Beam Melting of NdFeB for the production of rare-earth magnets. 6th International Electric Drives Production Conference (EDPC), 2016:34–40. https://doi.org/10.1109/EDPC.2016.7851311.
[193] Kopf R., Lingen A., Lanza G., 2016, Developing the process chain of selective laser melting towards a cost efficient series production. 6th International Conference on Additive Technologies iCAT 2016.
[194] Kopf, R., Gottwald, J., Jacob, A., Brandt, M., Lanza, G., 2018, Cost-oriented Planning of Equipment For Selective Laser Melting (SLM) in Production Lines. CIRP Annals, 67:471–474. https://doi.org/10.1016/j.cirp.2018.04.032.
[195] Kouprianoff, D., Luwes, N., Newby, E., Yadroitsava, I., Yadroitsev, I., 2017, On-line Monitoring of Laser Powder Bed Fusion By Acoustic Emission: Acoustic Emission For Inspection of Single Tracks Under Different Powder Layer Thickness. Pattern Recognition Association of South Africa and Robotics and Mechatronics (PRASA-RobMech), 2017. IEEE: 203–207.
[196] Kozior, T., Bochnia, J., Zmarzły, P., Gogolewski, D., Mathia, T.G., 2020, Waviness of freeform surface characterizations from austenitic stainless steel (316L) manufactured by 3D printing-selective laser melting (SLM) technology. Materials, 30/13(19): 4372.
[197] Krauss H., Eschey C., Zaeh M., 2012, Thermography for monitoring the selective laser melting process, 23rd SFF Symp.; Austin.
[198] Krishna, A.V., Flys, O., Reddy, V.V., Berglund, J., Rosén, B.G., 2020, Areal Surface Topography Representation of As-built and Post-processed Samples Produced By Powder Bed Fusion Using Laser Beam Melting. Surface Topography: Metrology and Properties, 18/8(2):024012.
[199] Krückemeier, S., Anderl, R., 2022, Concept for Digital Twin Based Virtual Part Inspection for Additive Manufacturing. Procedia CIRP, 107:458–462.
[200] Kruth, J.-P., 1991, Material Incress Manufacturing by Rapid Prototyping Techniques. CIRP Annals, 40/2/1991:603–614.
[201] Kruth J.-P., Mercelis P., 2006, Procedure and Apparatus for in-situ Monitoring and Feedback Control of Selective Laser Powder Processing. Patent GB-0612204.8, U.S. Application 12/308,032.
[202] Kruth, J.-P., Leu, M., Nakagawa, T., 1998, Progress in Additive Manufacturing and Rapid Prototyping. CIRP Annals, 47/2/1998:525–540.
[203] Kumke, M., Watschke, H., Hartogh, P., Bavendiek, A.-K., Vietor, T., 2018, Methods and tools for identifying and leveraging additive manufacturing design potentials. International Journal on Interactive Design and Manufacturing, 12:481–493. https://doi.org/10.1007/s12008-017-0399-7.
[204] Kunovjanek, M., Knofius, N., Reiner, G., 2022, Additive Manufacturing and Supply Chains – A Systematic Review. Production Planning & Control, Vol. 33/13/1231–1251: 2022. https://doi.org/10.1080/09537287.2020.1857874.
[205] Kuo, T.-C., Huang, S., Zhang, H.-C., 2001, Design for Manufacture and Design for 'X': Concepts, Applications, and Perspectives. Computers & Industrial Engineering, 41:241–260. https://doi.org/10.1016/S0360-8352(01)00045-6.
[206] Kurpjuweit, S., Schmidt, G., Klockner, M., Wagner, S., 2021, Blockchain in Additive Manufacturing and Its Impact on Supply Chains. Journal of Business Logistics, Volume42–1:46–70. https://doi.org/10.1111/jbl.12231.
[207] Lan, L., Jin, X., Gao, S., He, B., Rong, Y., 2020, Microstructural Evolution And Stress State Related To Mechanical Properties Of Electron Beam Melted Ti-6Al-4V Alloy Modified By Laser Shock Peening. Journal of Materials Science & Technology, Volume 50:153–161. https://doi.org/10.1016/j.jmst.2019.11.039.
[208] Lane, B., Moylan, S., Whitenton, E.P., Ma, L., 2016, Thermographic Measurements of the Commercial Laser Powder Bed Fusion Process at NIST. Rapid Prototyping Journal, 22:778–787. https://doi.org/10.1108/RPJ-11-2015-0161.
[209] Langelaar, M., 2018, Combined Optimization of Part Topology, Support Structure Layout and Build Orientation for Additive Manufacturing. Structural

and Multidisciplinary Optimization, 57:1985–2004. https://doi.org/10.1007/s00158-017-1877-z.
[210] Laserline GmbH. LDMblue: blue diode laser. ⟨https://www.laserline.com/en-int/ldm-blue-diode-laser/⟩ (Accessed 26 June 2022).
[211] Lauwers, B., Klocke, F., Klink, A., Tekkaya, A.E., Neugebauer, R., Mcintosh, D., 2014, Hybrid Processes in Manufacturing. CIRP Annals, 63/2: 561–583. https://doi.org/10.1016/j.cirp.2014.05.003.
[212] Leach, R., Bourell, D., Carmignato, S., Donmez, A., Senin, N., Dewulf, W., 2019, Geometrical Metrology for Metal Additive Manufacturing. CIRP Annals, 68/2:677–700. https://doi.org/10.1016/j.cirp.2019.05.004.
[213] Lee, S., Pegues, J.W., Shamsaei, N., 2020, Fatigue Behavior and modeling for Additive Manufactured 304L Stainless Steel: The Effect of Surface Roughness. International Journal of Fatigue, 141:105856.
[214] Leutenecker-Twelsiek, B., Klahn, C., Meboldt, M., 2016, Considering Part Orientation in Design for Additive Manufacturing. 26th CIRP Design Conference, Procedia CIRP, 50/2016: 408–413. https://doi.org/10.1016/j.procir.2016.05.016.
[215] Levy, A., Miriyev, A., Sridharan, N., Han, T., Tuval, E., Babu, S.S., Dapino, M.J., Frage, N., 2018, Ultrasonic Additive Manufacturing of Steel: Method, Post-processing Treatments and Properties. Journal of Materials Processing Technology, 256:183–189. https://doi.org/10.1016/j.jmatprotec.2018.02.001.
[216] Levy, G., Schindel, R., Kruth, J.-P., 2003, Rapid Manufacturing and Rapid Tooling With Layer Manufacturing (LM) Technologies, State of The Art and Future Perspectives. CIRP Annals, 52/2/2003:589–609.
[217] Lhuissier, P., Bataillon, X., Maestre, C., Sijobert, J., Cabrol, E., Bertrand, P., Boller, E., Rack, A., Blandin, J.-J., Salvo, L., Martin, G., 2020, In SItu 3D X-ray Microtomography of Laser-based Powder-bed Fusion (LPBF) - A Feasibility Study. Additive Manufacturing:101271. https://doi.org/10.1016/j.addma.2020.101271.
[218] Li, M., Wilkinson, D., Patchigolla, K., 2005, Comparison of Particle Size Distributions Measured Using Different Techniques. Particulate Science and Technology, 23/3:265–284. https://doi.org/10.1080/02726350590955912.
[219] Li Z., Rathore A.S., Song C., Wei S. Wang Y. Xu W., 2018, PrinTracker: Fingerprinting 3D printers using commodity scanners. CCS'18, October 15–19, 2018, Toronto, ON, Canada, doi: 10.1145/3243734.3243735.
[220] Li, Z., Zhong, R.Y., Tian, Z.G., Dai, H., Barenji, A.V., Huang, G.Q., 2021, Industrial Blockchain: A State-of-the-art Survey. Robotics and Computer-Integrated Manufacturing, Volume 70/2021:102124. https://doi.org/10.1016/j.rcim.2021.102124.
[221] Liao, S., Xue, T., Jeong, J., Webster, S., Ehmann, K., Cao, J., 2023, Hybrid Thermal Modeling of Additive Manufacturing Processes Using Physics-informed Neural Networks For Temperature Prediction and Parameter Identification, To Appear. Computational Mechanics.
[222] Lim, J., You, C., Dayyani, I., 2020, Multi-objective Topology Optimization and Structural Analysis of Periodic Spaceframe Structures. Materials & Design, Volume 190:108552. https://doi.org/10.1016/j.matdes.2020.108552.
[223] Lin, X., Wang, Q., Fuh, J.Y.H., Zhu, K., 2022, Motion Feature Based Melt Pool Monitoring for Selective Laser Melting Process. Journal of Materials Processing Technology, 303:117523. https://doi.org/10.1016/j.jmatprotec.2022.117523.
[224] Liu, C., Le Roux, L., Ji, Z., Kerfriden, P., Lacan, F., Bigot, S., 2020, Machine Learning-enabled Feedback Loops for Metal Powder Bed Fusion Additive Manufacturing. Procedia Computer Science, 176:2586–2595.
[225] Liu, H., Li, Y., Li, D., 2016, Research on Rheological Properties and Extrusion Behavior of Aqueous Alumina Paste in Paste-extrusion-based SFF Processes. The International Journal of Advanced Manufacturing Technology, 83:2039–2047. https://doi.org/10.1007/s00170-015-7720-z.
[226] Liu, K., 2009, Some Factors Affecting Sieving Performance and Efficiency. Powder Technology, 193:208–213. https://doi.org/10.1016/j.powtec.2009.03.027.
[227] Liu, S., Shin, Y.C., 2019, Additive Manufacturing of Ti6Al4V alloy: A Review. Materials & Design, 164:107552. https://doi.org/10.1016/j.matdes.2018.107552.
[228] Liu, W., Chen, L., Mai, G., Song, L., 2020, Toolpath Planning for Additive Manufacturing Using Sliced Model Decomposition and Metaheuristic Algorithms. Advances in Engineering Software, 149/2020:102906. https://doi.org/10.1016/j.advengsoft.2020.102906.
[229] Liu, Y., Blunt, L., Zhang, Z., Rahman, H.A., Gao, F., Jiang, X., 2020, In-situ Areal Inspection of Powder Bed For Electron Beam Fusion System Based on Fringe Projection Profilometry. Additive Manufacturing, 31:100940.
[230] Lizzul, L., Sorgato, M., Bertolini, R., Ghiotti, A., Bruschi, S., 2020, Influence of Additive Manufacturing-induced Anisotropy on Tool Wear in End Milling of Ti6Al4V. Tribology International, 146:106200. https://doi.org/10.1016/j.triboint.2020.106200.
[231] Lunetto, V., Catalano, A., Priarone, P., Settineri, L., 2019, Comments About the Human Health Risks Related to Additive Manufacturing. Dao D, Howlett RJ, Setchi R, Vlacic L, (Eds.) Sustainable Design and Manufacturing 2018,, vol. 130. Springer International Publishing, Cham: 95–104.
[232] Ma, W., But, W., He, P., 2004, NURBS-based Adaptive Slicing for Efficient Rapid Prototyping. 2004 Computer-Aided Design, Volume 36/Issue 13: 1309–1325. https://doi.org/10.1016/j.cad.2004.02.001.
[233] Ma, Z., Merkus, H.G., de Smet, J.G., Heffels, C., Scarlett, B., 2000, New Developments in Particle Characterization By Laser Diffraction: Size and Shape. Powder Technology 21, 111/1–2: 66–78. https://doi.org/10.1016/S0032-5910(00)00242-4.
[234] Macosko, C.W., 1994, Rheology: Principles, Measurements, and Applications. Wiley-VCH. ISBN 0-471-18575-2.
[235] Maidin, S., Pei, E., Campbell, R.I., 2012, Development of a Design Feature Database to Support Design for Additive Manufacturing. July 2012 Assembly Automation.https://doi.org/10.1108/01445151211244375.
[236] Majumdar, D., Bazin, T., Ribeiro, E.M.C., Frithj, J., Birbilis, N., 2019, Understanding the Effects of PBF Process Parameter Interplay on Ti-6Al-4V Surface Properties. PLoS One, 14/8:e0221198. https://doi.org/10.1371/journal.pone.0221198.
[237] Manco, P., Macchiaroli, R., Maresca, P., Fera, M., 2019, The Additive Manufacturing Operations Management Maturity: a Closed or an Open Issue? Procedia Manufacturing, 41. 908-105.
[238] Mandloi K., Evans C., Fox J., Cherukuri H., Miller J., Allen A., Deisenroth D., Donmez A. 2021, Toward specification of complex additive manufactured metal surfaces for optimum heat transfer. Proc. Jt. Spec. Interest Group Meet. Euspen ASPE, St. Gallen, Switzerland. Sep 23.
[239] Mandolla, C., Petruzzelli, A.M., Percoco, G., Urbinati, A., 2019, Building a Digital Twin for Additive Manufacturing Through the Exploitation Of Blockchain: A Case Analysis of the Aircraft Industry. 2019 Computers in Industry, Volume 109:134–152. https://doi.org/10.1016/j.compind.2019.04.011.
[240] Mani, M., Lane, B., Donmez, A., Feng, S., Moylan, S., 2017, A Review on Measurement Science Needs For Real-time Control of Additive Manufacturing Metal Powder Bed Fusion Processes. International Journal of Production Research, 55:1400–1418.
[241] Matsuyama, T., Yamamoto, H., 2005, Particle Shape and Laser Diffraction: A Discussion of the Particle Shape Problem. Journal of Dispersion Science and Technology, 25/4. https://doi.org/10.1081/DIS-200025692.
[242] Matthews, M.J., Roehling, T.T., Khairallah, S.A., Tumkur, T.U., Guss, G., Shi, R., Roeh Ling, J.D., Smith, W.L., Vrancken, B.K., Ganeriwala, R.K., McKeown, J.T., 2020, Controlling Melt Pool Shape, Microstructure and Residual Stress in Additively Manufactured Metals Using Modified Laser Beam Profiles. Procedia CIRP, 94:200–204. https://doi.org/10.1016/j.procir.2020.09.038.
[243] Mayerhofer, M., Schwentenweinz, M., Lepuschitz, W., 2019, Manufacturability Analysis for Add. Manuf. 24th IEEE Intern Conference on Emerging Technologies and Factory Automation, 2019:1252–1255. https://doi.org/10.1109/ETFA.2019.8868965.
[244] McConaha, M., Venugopal, V., Anand, S., 2020, Integration of Machine Tool Accessibility of Support Structures With Topology Optimization for Additive Manufacturing. Procedia Manufacturing, Volume 48/2020: 634–642. https://doi.org/10.1016/j.promfg.2020.05.092.
[245] McGregor, D.J., Tawfick, S., King, W.P., 2019, Automated Metrology and Geometric Analysis of Additively Manufactured Lattice Structures. Additive Manufacturing, 28:535–545. https://doi.org/10.1016/j.addma.2019.05.026.
[246] McGuigan, S., Arguelles, A.P., Obaton, A.F., Donmez, A.M., Riviere, J., Shokouhi, P., 2021, Resonant Ultrasound Spectroscopy for Quality Control of Geometrically Complex Additively Manufactured Components. Additive Manufacturing, 1/39:101808.
[247] Melentiev, R., Fang, F.Z., 2018, Recent Advances and Challenges of Abrasive Jet Machining. CIRP Journal of Manufacturing Science and Technology, 22:1–20. https://doi.org/10.1016/j.cirpj.2018.06.001.
[248] Melia, M.A., Duran, J., Koepke, J., Saiz, D., Jared, B.H., Schindelolz, E.J., 2020, How Build Angle and Post-processing Impact Roughness and Corrosion of Additively Manufactured 316L Stainless Steel. Materials Degradation, 4:1–11.
[249] Mercelis P., Kruth J.-P., Van Vaerenbergh J., 2007. Feedback control of selective laser melting. Proc. 15th Intern. Symposium on Electro-Machining, (ISEM-XV). Pittsburgh, USA, ISBN-0979497701: 421–426).
[250] Merklein, M., Junker, D., Schaub, A., Neubauer, F., 2016, Hybrid Additive Manufacturing Technologies – An Analysis Regarding Potentials and Applications. Physics Procedia, 83:549–559. https://doi.org/10.1016/j.phpro.2016.08.057.
[251] METAL A.M., 2020. SLM solutions launches 12-laser metal additive manufacturing machine, ⟨https://www.metal-am.com/slm-solutions-launches-12-laser-metal-additive-manufacturing-machine/⟩ (Accessed July 11, 2022).
[252] Metelkova, J., Ordnung, D., Kinds, Y., van Hooreweder, B., 2021, Novel Strategy for Quality Improvement of Up-facing Inclined Surfaces of LPBF Parts by Combining Laser-induced Shock Waves and in Situ Laser Remelting. Journal of Materials Processing Technology, 290:116981. https://doi.org/10.1016/j.jmatprotec.2020.116981.
[253] Metelkova, J., Ordnung, D., Kinds, Y., Witvrouw, A., Van Hooreweder, B., 2020, Improving the Quality of Up-facing Inclined Surfaces in Laser Powder Bed Fusion of Metals Using A Dual Laser Setup. Procedia CIRP, Vol. 94:266–269. https://doi.org/10.1016/j.procir.2020.09.050.
[254] Metelkova, J., de Formanoir, C., Haitjema, H., Witvrouw, A., Pfleging, W., Van Hooreweder, B., 2019, Elevated Edges of Metal Parts Produced by Laser Powder Bed Fusion: Characterization and Post-process Correction. Proc. ASPE-euspen.
[255] Michl, D., Sydow, B., Bambach, M., 2020, Ring Rolling of Pre-forms Made by Wire-arc Additive Manufacturing. Procedia Manufacturing, 47:342–348. https://doi.org/10.1016/j.promfg.2020.04.275.
[256] Milaat, F.A., Witherell, P., Hardwick, M., Yeung, H., Ferrero, V., Monnier, L., Brown, M., 2022, STEP-NC Process Planning for Powder Bed Fusion Additive Manufacturing. Journal of Computing and Information Science in Engineering, 22/6:060904.
[257] Mireles J., Terrazas C., Medina F., Wicker R., 2013. Automatic feedback control in electron beammelting using infrared thermography, 24th Solid Freeform Fabrication (SFF) Symp.; Austin, TX.
[258] Mitchell, J.A., Ivanoff, T.A., Dagel, D., Madison, J.D., Jared, B., 2020, Linking Pyrometry to Porosity in Additively Manufactured Metals. Additive Manufacturing, 31:100946.

[259] Mitterlehner, M., Danninger, H., Gierl-Mayer, C., Gschiel, H., 2021, Investigation of the Influence of Powder Moisture on the Spreadability Using the Spreading Tester. Bergisch Huettenmaenn Monatsh, 166:14–22. https://doi.org/10.1007/s00501-020-01067-x.
[260] Moges, T., Yang, Z., Jones, K., Feng, S., Witherell, P., Lu, Y., 2021, Hybrid Modeling Approach for Melt-pool Prediction in Laser Powder Bed Fusion Additive Manufacturing. Journal of Computing and Information Science in Engineering, 21:5.
[261] Montero-Sistiaga, M.L., Mertens, R., Vrancken, B., Wang, X., van Hooreweder, B., Kruth, J.-P., van Humbeeck, J., 2016, Changing the Alloy Composition of Al7075 for Better Processability by Selective Laser Melting. Journal of Materials Processing Technology, 238/2: 437–445. https://doi.org/10.1016/j.jmatprotec.2016.08.003.
[262] Motaman, S.A., Kies, F., Köhnen, P., Létang, M., Lin, M., Molotnikov, A., Haase, C., 2020, Optimal Design for Metal Additive Manufacturing: An Integrated Computational Materials Engineering (ICME) Approach. Jom, 72/3: 1092–1104.
[263] Mozaffar, M., Liao, S., Lin, H., Ehmann, K., Cao, J., 2021, Geometry-agnostic Data-driven Thermal Modeling of Additive Manufacturing Processes Using Graph Neural Networks. Additive Manufacturing:102449. https://doi.org/10.1016/j.addma.2021.102449.
[264] Mozaffar, M., Ndip-Agbor, E., Lin, S., Wagner, G.J., Ehmann, K., Cao, J., 2019, Acceleration Strategies for Explicit Finite Element Analysis of Metal Powder-based Additive Manufacturing Processes Using Graphical Processing Units. Computational Mechanics, 64/3: 879–894. https://doi.org/10.1007/s00466-019-01685-4.
[265] Mozaffar, M., Liao, S.H., Xie, X.Y., Saha, S., Park, C., Cao, J., Liu, W.K., Gan, Z., 2022, "Mechanistic Artificial Intelligence (Mechanistic-ai) For Modeling, Design, and Control of Advanced Manufacturing Processes: Current State and Perspectives. J Materials Processing Technology, (Vol. 302). https://doi.org/10.1016/j.jmatprotec.2021.117485.
[266] MSFC-SPEC-3717, Specification for control and qualification of laser powder bed fusion metallurgical processes, October 2017. ⟨https://www.nasa.gov/sites/default/files/atoms/files/msfcspec3717baseline.pdf⟩.
[267] MSFC-STC-3716, Standard for additively manufactured spaceflight hardware by laser powder bed fusion in metals, October. 2017. ⟨https://standards.nasa.gov/sites/default/files/standards/MSFC/Baseline/0/msfc-std-3716.pdf⟩.
[268] Mukherjee, T., Zhang, W., DebRoy, T., 2017, An Improved Prediction of Residual Stresses and Distortion in Additive Manufacturing. Computational Materials Science, 126:360–372. https://doi.org/10.1016/j.commatsci.2016.10.003.
[269] Murtezaoglu, Y., Plakhotnik, D., Stautner, M., Vaneker, T., van Houten, F., 2018, Geometry-based Process Planning for Multi-axis Support-free Additive Manufacturing. Procedia CIRP, 78:73–78. https://doi.org/10.1016/j.procir.2018.08.175.
[270] NAE workshop 2019, National Academies of Sciences, Engineering, and Medicine 2019. Data-driven modeling for additive manufacturing of metals: proceedings of a workshop. Washington, DC: The National Academies Press, doi:10.17226/25481.
[271] Nagalingam, A.P., Yuvaraj, H.K., Yeo, S.H., 2020, Synergistic Effects in Hydrodynamic Cavitation Abrasive Finishing for Internal Surface-finish Enhancement of Additive-manufactured Components. Additive Manufacturing, 33:101110. https://doi.org/10.1016/j.addma.2020.101110.
[272] NASA-STD-6030, 2021, Additive Manufacturing for Spaceflight Systems, ⟨https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021–04-21_nasa-std-6030-approveddocx.pdf⟩.
[273] NASA-STD-6033, 2021, Additive Manufacturing Requirements for Equipment and Facility Control, ⟨https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/2021–04-21_nasa-std-6033_-_approveddocx.pdf⟩.
[274] Ness, K.L., Paul, A., Sun, L., Zhang, Z., 2022, Towards a Generic Physics-based Machine Learning Model for Geometry Invariant Thermal History Prediction in Additive Manufacturing. Journal of Materials Processing Technology, 302:117472. https://doi.org/10.1016/j.jmatprotec.2021.117472.
[275] Newton, L., Senin, N., Smith, B., Chatzivagiannis, E., Leach, R., 2019, Comparison and Validation of Surface Topography Segmentation Methods for Feature-based Characterisation of Metal Powder Bed Fusion Surfaces. Surface Topography: Metrology and Properties, 7/7(4):045020.
[276] Newton, L., Senin, N., Chatzivagiannis, E., Smith, B., Leach, R., 2020, Feature-based Characterisation of Ti6Al4V Electron Beam Powder Bed Fusion Surfaces Fabricated at Different Surface Orientations. Additive Manufacturing.
[277] Nie, Z., Jung, S., Kara, L.B., Whitefoot, K.S., 2019, Optimization of Part Consolidation for Minimum Production Costs and Time Using Additive Manufacturing. Journal of Mechanical Design. https://doi.org/10.1115/1.4045106.
[278] Ning, J., Wang, W., Ning, X., Sievers, D.E., Garmestani, H., Liang, S.Y., 2020, Analytical Thermal Modeling of Powder Bed Metal Additive Manufacturing Considering Powder Size Variation and Packing. Materials, 13/8: 1988. https://doi.org/10.3390/ma13081988.
[279] Obaton, A.-F., Butsch, B., McDonough, S., Carcreff, E., Laroche, N., Gaillard, Y., Tarr, J., Bouvet, P., Cruz, R., Donmetz, A., 2020, Evaluation of Nondestructive volumetric testing methods for additively manufactured parts. Shamsaei N, Daniewicz S, Hrabe N, Beretta S, Waller J, Seifi M, (Eds.) Structural Integrity of Additive Manufactured Parts ASTM International, West Conshohocken, PA: 51–91. https://doi.org/10.1520/STP162020180099.
[280] Oh, Y., Zhou, C., Behdad, S., 2018, Part Decomposition and Assembly-based (Re) Design For Additive Manufacturing: A Review. Additive Manufacturing, Volume 22:230–242. https://doi.org/10.1016/j.addma.2018.04.018.
[281] Oropeza, D., Roberts, R., Hart, A., 2021, A Modular Testbed For Mechanized Spreading of Powder Layers for Additive Manufacturing. Journal of Scientific Instruments, 92:015114. https://doi.org/10.1063/5.0031191.
[282] Oyelola, O., Crawforth, P., M'Saoubi, R., Clare, A.T., 2016, Machining of Additively Manufactured Parts: Implications for Surface Integrity. Procedia CIRP, 45:119–122. https://doi.org/10.1016/j.procir.2016.02.066.
[283] Oyelola, O., Crawfroth, P., M'Saoubi, R., Clare, A.T., 2018, Machining of Functionally Graded Ti6Al4V/WC Produced By Directed Energy Deposition. Additive Manufacturing, 24:20–29. https://doi.org/10.1016/j.addma.2018.09.007.
[284] Ozel, T., Altay, A., Kaftanoglu, B., Senin, N., 2020, Focus Variation Measurement and Prediction of Surface Texture Parameters Using Machine Learning in Laser Powder Bed Fusion. Journal of Manufacturing Science & Engineering, 142/1. https://doi.org/10.1115/1.4045415.
[285] Pal, D., Patil, N., Zeng, K., Stucker, B., 2014, An Integrated Approach to Additive Manufacturing Simulations Using Physics Based, Coupled Multiscale Process Modeling. Journal of Manufacturing Science and Engineering, 136/6: 285. https://doi.org/10.1115/1.4028580.
[286] Pandiyan, V., Drissi-Daoudi, R., Shevchik, S., Masinelli, G., Le-Quang, T., Logé, R., Wasmer, K., 2022, Deep Transfer Learning of Additive Manufacturing Mechanisms Across Materials in Metal-based Laser Powder Bed Fusion Process. Journal of Materials Processing Technology, 303:117531. https://doi.org/10.1016/j.jmatprotec.2022.117531.
[287] Papke, T., Merklein, M., 2020, Processing of 316L Hybrid Parts Consisting of Sheet Metal and Additively Manufactured Element by Powder Bed Fusion Using a Laser Beam. Procedia CIRP, 94:35–40. https://doi.org/10.1016/j.procir.2020.09.008.
[288] Papke, T., Junker, D., Schmidt, M., Kolb, T., Merklein, M., 2018, Bulk Metal Forming of Additively Manufactured Elements. MATEC Web Conf, 190:3002. https://doi.org/10.1051/matecconf/201819003002.
[289] Parker, W.J., Jenkins, R.J., Butler, C.P., Abbott, G.L., 1961, Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity. Journal of Applied Physics, 32/9:1679–1684. https://doi.org/10.1063/1.1728417.
[290] Patel, K., Fei, J., Liu, G., Ozel, T., 2019, Milling Investigations and Yield Strength Calculations for Nickel Alloy Inconel 625 Manufactured With Laser Powder Bed Fusion Process. Production Engineering, 13:693–702. https://doi.org/10.1007/s11740-019-00922-2.
[291] Patel, S., Rogalsky, A., Vlasea, M., 2020, Towards Understanding Side-skin Surface Characteristics in Laser Powder Bed Fusion. Journal of Materials Research, 35:2055–2064.
[292] Paulson, N., Gould, B., Wolff, S., Stan, M., Greco, A., 2020, Correlations Between Thermal History and Keyhole Porosity in Laser Powder Bed Fusion. Additive Manufacturing:101213.
[293] Pavlov, M., Doubenskaia, M., Smurov, I., 2010, Pyrometric Analysis of Thermal Processes in SLM Technology. Physics Procedia, 5:523–531.
[294] Pelzer, L., Hopman, C., 2021, Additive Manufacturing of Non-planar Layers with Variable Layer Height. Additive Manufacturing, 37:10169. https://doi.org/10.1016/j.addma.2020.101697.
[295] Peng, X., Kong, L., Chen, Y., et al., 2020, Design of a Multi-sensor Monitoring System for Additive Manufacturing Process. Nanomanufacturing and Metrology, 3:142–150. https://doi.org/10.1007/s41871-020-00062-7.
[296] Petrik, J., Sydow, B., Bambach, M., 2022, Beyond Parabolic Weld Bead Models: AI-based 3D Reconstruction of Weld Beads Under Transient Conditions in Wire-arc Additive Manufacturing. Journal of Materials Processing Technology, 302:117457. https://doi.org/10.1016/j.jmatprotec.2021.117457.
[297] Phua, A., Davies, C.H.J., Delaney, G.W., 2022, A Digital Twin Hierarchy for Metal Additive Manufacturing. ISSN 0166-3615, doi: Computers in Industry, Volume 140:103667. https://doi.org/10.1016/j.compind.2022.103667.
[298] Piili, H., Happonen, A., Väistö, T., Venkataramanan, V., Partanen, J., Salminen, A., 2015, Cost Estimation of Laser Additive Manufacturing of Stainless Steel. Physics Procedia, 78:388–396. https://doi.org/10.1016/j.phpro.2015.11.053.
[299] du Plessis, A., Sperling, P., Beerlink, A., Tshabalala, L., Hoosain, S., Mathe, N., le Roux, S.G., 2018, Standard Method for microCT-based Additive Manufacturing Quality Control 1: Porosity Analysis. MethodsX, Volume 5/2018: 1102–1110. https://doi.org/10.1016/j.mex.2018.09.005.
[300] Pobel, C.R., Gotterbarm, M.R., Samfaß, V., Osmanlic, F., Koerner, C., 2016, Innovative processing strategies for selective electron beam melting. Drstvenšek I, Drummer D, Schmidt M, (Eds.) in: Proceedings of 6th International Conference on Additive Technologies. Interesansa - zavod, Ljubljana.
[301] Pobel, C.R., Arnold, C., Osmanlic, F., Fu, Z., Körner, C., 2019, Immediate Development of Processing Windows for Selective Electron Beam Melting Using Layerwise Monitoring via Backscattered Electron Detection. Materials Letters, 249:70–72. https://doi.org/10.1016/j.matlet.2019.03.048.
[302] Pragana, J.P.M., Cristino, V.A.M., Bragança, I.M.F., Silva, C.M.A., Martins, P.A.F., 2020, Integration of Forming Operations on Hybrid Additive Manufacturing Systems Based on Fusion Welding. International Journal of Precision Engineering and Manufacturing, 7/3: 595–607. https://doi.org/10.1007/s40684-019-00152-y.
[303] Priarone, P.C., Rizzuti, S., Settineri, L., Vergnano, G., 2012, Effects of Cutting Angle, Edge Preparation, and Nano-structured Coating on Milling Performance of a Gamma Titanium Aluminide. Journal of Materials Processing Technology, 212:2619–2628. https://doi.org/10.1016/j.jmatprotec.2012.07.021.
[304] Pujana, J., Madarieta, M., Garmendia, I., Leunda, J., 2018, Additive Manufacturing of Metal Components Using Concentric-wire Laser Metal Deposition. DYNA, 93/1: 675–680. https://doi.org/10.6036/8819.

[305] Qi, X., Chen, G.F., Li, Y., Cheng, X., Li, C., 2019, Applying Neural-Network-Based Machine Learning to Additive Manufacturing: Current Applications, Challenges, and Future Perspectives. Engineering, 5:721–729.
[306] Qin, Y., Qi, Q., Scott, P.J., 2019, Determination of Optimal Build Orientation for Additive Manufacturing Using Muirhead Mean and Prioritised Average Operators. Journal of Intelligent Manufacturing, 30:3015–3034. https://doi.org/10.1007/s10845-019-01497-6.
[307] Qin, Y., Qi, Q., Scott, P.J., Jiang, X., 2019, Status, Comparison, and Future of the Representations of Additive Manufacturing Data. Computer-Aided Design, Volume 111:44–64. https://doi.org/10.1016/j.cad.2019.02.004.
[308] Ramakrishnan, R., Griebel, B., Volk, W., Günther, D., Günther, J., 2014, 3D Printing of Inorganic Sand Moulds for Casting Applications. Advanced Materials Research, 1018:441–449. https://doi.org/10.4028/www.scientific.net/AMR.1018.441.
[309] Rane, K., Strano, M., 2019, A Comprehensive Review of Extrusion-based Additive Manufacturing Processes for Rapid Production of Metallic and Ceramic Parts. Advances in Manufacturing, 7:155–173. https://doi.org/10.1007/s40436-019-00253-6.
[310] Ranjan, R., Chen, Z., Ayas, C., Langelaar, M., Van Keulen, F., 2023, Overheating Control in Additive Manufacturing Using a 3D Topology Optimization Method and Experimental Validation. Additive Manufacturing, Volume 61. https://doi.org/10.1016/j.addma.2022.103339.
[311] Raoelison, R.N., Verdy, C., Liao, H., 2017, Cold Gas Dynamic Spray Additive Manufacturing Today: Deposit Possibilities, Technological Solutions and Viable Applications. Materials & Design, 2017/133: 266–287. https://doi.org/10.1016/j.matdes.2017.07.067.
[312] Raplee, J., Plotkowski, A., Kirka, M., Dinwiddie, R., Okello, A., Dehoff, R., Babu, S., 2017, Thermographic Microstructure Monitoring in Electron Beam Additive Manufacturing. Scientific Reports, 7:43554.
[313] Rasch, M., Bartels, D., Sun, S., Schmidt, M., 2022, AlSi10Mg in Powder Bed Fusion with Laser Beam: An Old and Boring Material. Materials, 15:16. https://doi.org/10.3390/ma15165651.
[314] Rasch, M., Roider, C., Kohl, S., Strauß, J., Maurer, N., Nagulin, K.Y., Schmidt, M., 2019, Shaped Laser Beam Profiles for Heat Conduction Welding of Aluminium-copper Alloys. Optics and Lasers in Engineering, 115:179–189. https://doi.org/10.1016/j.optlaseng.2018.11.025.
[315] Rasch, M., Heberle, J., Dechet, M.A., Bartels, D., Gotterbarm, M.R., Klein, L., Gorunov, A., Schmidt, J., Körner, C., Peukert, W., Schmidt, M., 2019, Grain Structure Evolution of Al–Cu Alloys in Powder Bed Fusion With Laser Beam for Excellent Mechanical Properties. Materials, 13:82. https://doi.org/10.3390/ma13010082.
[316] Reichler, A.-K., Redeker, J., Gabriel, F., Falke, F., Vietor, T., Dröder, K., 2020, Combined Design and Process Planning for Incremental Manufacturing. Procedia CIRP, 93:927–932. https://doi.org/10.1016/j.procir.2020.03.061.
[317] Reichwein, J., Rudolph, K., Geis, J., Kirchner, E., 2021, Adapting Product Architecture to Additive Manufacturing Through Consolidation and Separation. Procedia CIRP, Volume 100:79–84. https://doi.org/10.1016/j.procir.2021.05.013.
[318] RENA Technologies, 2020. Automatic post-processing of 3D-printed metal parts, ⟨https://www.rena.com/en/products/additive-manufacturing/finishing-modules⟩.
[319] Rieder, H., Spies, M., Bamberg, J., Henkel, B., 2016, On- and Offline Ultrasonic Inspection of Additively Manufactured Components. 19th World Conference on Non-Destructive Testing, 13–17.
[320] Rosen, D., 2014, Research Supporting Principles for Design For Additive Manufacturing. Virtual and Physical Prototyping, 9:225–232. https://doi.org/10.1080/17452759.2014.951530.
[321] Rosenthal, S., Platt, S., Hölker-Jäger, R., Gies, S., Kleszczynski, S., Tekkaya, A.E., Witt, G., 2019, Forming Properties of Additively Manufactured Monolithic Hastelloy X sheets. Materials Science and Engineering: A, 753:300–316. https://doi.org/10.1016/j.msea.2019.03.035.
[322] Russell, R., Wells, D., Waller, J., Poorganji, B., Ott, E., Nakagawa, T., Sandoval, H., Shamsaie, N., Seifi, M., 2019, Qualification and certification of metal additive manufactured hardware for aerospace applications. Additive Manufacturing for the Aerospace Industry. 2019 Elsevier Inc,: 33–66. https://doi.org/10.1016/B978-0-12-814062-8.00003-0.
[323] Sandborn, M., Olea, C., White, J., Williams, C., Tarazaga, P.A., Sturm, L., Albakri, M., Tenney, C., 2021, Towards Secure Cyber-physical Information Association for Parts. ISSN 0278-6125, doi Journal of Manufacturing Systems, Volume 59/2021: 27–41. https://doi.org/10.1016/j.jmsy.2021.01.003.
[324] Sanei, N., Fatemi, A., Phan, N., 2019, Defect Characteristics and Analysis of Their Variability in Metal L-PBF Additive Manufacturing. Materials & Design, 182:108091. https://doi.org/10.1016/j.matdes.2019.108091.
[325] Sartori, S., Moro, L., Ghiotti, A., Bruschi, S., 2017, On the Tool Wear Mechanisms in Dry and Cryogenic Turning Additive Manufactured Titanium Alloys. Tribology International, 105:264–273. https://doi.org/10.1016/j.triboint.2016.09.034.
[326] Scetinec, A., Klobcar, D., Bracun, D., 2021, In-process Path Replanning and Online Layer Height Control Through Deposition Arc Current for Gas Metal Arc Based Additive Manufacturing. Journal of Manufacturing Processes, 64:1169–1179. https://doi.org/10.1016/j.jmapro.2021.02.038.
[327] Schaub, A., Juechter, V., Singer, R.F., Merklein, M., 2014, Characterization of Hybrid Components Consisting of SEBM Additive Structures and Sheet Metal Of Alloy Ti-6Al-4V. KEM, 611–612:609–614. https://doi.org/10.4028/www.scientific.net/KEM.611-612.609.
[328] Schaub, A., Ahuja, B., Karg, M., Schmidt, M., Merklein, M., 2014, Fabrication and Characterization of Laser Beam Melted Ti-6Al-4V Geometries on Sheet Metal. DDMC Fraunhofer Direct Digital Manufacturing Conference, 1–5.
[329] Schaub, A., Ahuja, B., Butzhammer, L., Osterziel, J., Schmidt, M., Merklein, M., 2016, Additive Manufacturing of Functional Elements on Sheet Metal. Physics Procedia, 83:797–807. https://doi.org/10.1016/j.phpro.2016.08.082.
[330] Schmidt, M., Merklein, M., Bourell, D., Dimitrov, D., Hausotte, T., Wegener, K., Overmeyer, L., Vollertsen, F., Levy, G., 2017, Laser Based Additive Manufacturing in Industry and Academia. CIRP Annals, 66:561–583. https://doi.org/10.1016/j.cirp.2017.05.011.
[331] Schneberger, J., Kaspar, J., Vielhaber, M., 2020, Post-processing and Testing-oriented Design for Additive Manufacturing – A General Framework for the Development of Hybrid AM Parts. Procedia CIRP, Volume 90:91–96. https://doi.org/10.1016/j.procir.2020.01.059.
[332] Schuh, G., Kreysa, J., Orilski, S., 2009, Roadmap "Hybride Produktion". ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 104:385–391.
[333] Sealy, M.P., Madireddy, G., Williams, R.E., Rao, P., Toursangsaraki, M., 2018, Hybrid Processes in Additive Manufacturing. Journal of Manufacturing Science and Engineering, 140/6: 79. https://doi.org/10.1115/1.4038644.
[334] Segebade, E., Gerstenmeyer, M., Dietrich, S., Zanger, F., Schulze, V., 2019, Influence of Anisotropy of Additively Manufacturing Alsi10mg Parts on Chip Formation During Orthogonal Cutting. Procedia CIRP, 82:113–118. https://doi.org/10.1016/j.procir.2019.04.043.
[335] Seifi, M., Salem, A., Beuth, J., Harrysson, O., Lewandowski, J.J., 2016, Overview of Materials Qualification Needs for Metal Additive Manufacturing. Jom, 68/3: 747–764.
[336] Seifi, M., Gorelik, M., Waller, J., Hrabe, N., Shamsaei, N., Daniewicz, S., Lewandowski, J.J., 2017, Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification. JOM, 69/3: 439–455.
[337] Shen, M., Fang, F.Z., 2023, Advances in Polishing of Internal Structures on Parts Made By Laser-based Powder Bed Fusion. Frontiers of Mechanical Engineering, 18/1: 8. https://doi.org/10.1007/s11465-022-0724-0.
[338] Shen, M., Kang, C., Fang, F.Z., 2022, Material Removal Characteristics of Various Surface Features on Selective Laser Melted 316l Stainless Steel During Electropolishing. Journal of Manufacturing Processes, 79:639–653. https://doi.org/10.1016/j.jmapro.2022.04.072.
[339] Sheng, X., Lu, X., Zhang, J., Lu, Y., 2020, An Analytical Solution to Temperature Field Distribution in A Thick Rod Subjected to Periodic-motion Heat Sources And Application In Ball Screws. Engineering Optimization, 1–20. https://doi.org/10.1080/0305215X.2020.1849172.
[340] Sher D., 2019. 10 top hybrid manufacturing companies. ⟨https://www.3dprintingmedia.network/the-top-ten-hybrid-manufacturing-companies/⟩. Accessed 22.02.22.
[341] Shi, X., Gu, D., Li, Y., Dai, D., Ge, Q., Sun, Y., Chen, H., 2021, Thermal Behavior And Fluid Dynamics Within Molten Pool During Laser Inside Additive Manufacturing of 316l Stainless Steel Coating on Inner Surface of Steel Tube. (art. no.). Optics and Laser Technology, 138:106917. https://doi.org/10.1016/j.optlastec.2021.106917.
[342] Shi, Y., Zhang, Y., Baek, S., De Backer, W., Harik, R., 2017, Manufacturability Analysis for Additive Manufacturing Using A Novel Feature Recognition Technique. computer-Aided Design & Applications, 14(a). doi: 10.1080/16864360.2018.1462574.
[343] Simson, T., Emmel, A., Dwars, A., Böhm, J., 2017, Residual Stress Measurements on AISI 316L Samples Manufactured by Selective Laser Melting. Additive Manufacturing, 17:183–189. https://doi.org/10.1016/j.addma.2017.07.007.
[344] Simuleon, 2023 ⟨https://info.simuleon.com/blog/using-abaqus-to-simulate-additive-manufacturing-printing-an-optimized-hip-implant⟩.
[345] Sing, L., Kuo, C.N., Shih, C.T., Ho, C.C., Chua, C.K., 2021, Perspectives of Using Machine Learning in Laser Powder Bed Fusion for Metal Additive Manufacturing. Virtual and Physical Prototyping, Volume 16/Issue 3. https://doi.org/10.1080/17452759.2021.1944229.
[346] Sizova, I., Bambach, M., 2018, Hot Workability and Microstructure Evolution of Pre-forms for Forgings Produced by Additive Manufacturing. Journal of Materials Processing Technology, 256:154–159.
[347] Slotwinski, J.A., Garboczi, E.J., Stutzman, P.E., Ferraris, C.F., Watson, S.S., Peltz, M.A., 2014, Characterization of Metal Powders Used for Additive Manufacturing. J Res Natl Inst Stand Technol, 119:460–493. https://doi.org/10.6028/jres.119.018.
[348] Smith, J., Xiong, W., Cao, J., Liu, W.K., 2016, Thermodynamically Consistent Microstructure Prediction of Additively Manufactured Materials. Comput Mech, 57/3: 359–370. https://doi.org/10.1007/s00466-015-1243-1.
[349] Snoeys, R., Dauw, D., Kruth, J.-P., 1983, Survey of Adaptive Control in Electro-discharge Machining. Journal of Manufacturing Systems, 2/2:147–164.
[350] Snow, Z., Nassar, A., Reutzel, E.W., 2020, Review of the Formation and Impact of Flaws in Powder Bed Fusion Additive Manufacturing. Additive Manufacturing, 36:101457.
[351] Snow, Z., Reutzel, E.W., Petrich, J., 2022, Correlating In-situ Sensor Data to Defect Locations and Part Quality for Additively Manufactured Parts Using Machine Learning. Journal of Materials Processing Technology, 302:117476. https://doi.org/10.1016/j.jmatprotec.2021.117476.
[352] Solukon, 2021. Solukon equips depowdering system SFM-AT200 with new frequency excitation. ⟨https://www.solukon.de/en/news/solukon-equips-depowdering-system-sfm-at200-with-new-frequency-excitation/⟩. (Accessed July 13, 2022).
[353] Sourceforge, 2022. Compare the top 3D printing software of 2022. Sourceforge. ⟨https://sourceforge.net/software/3d-printing/⟩.(Accessed July 12, 2022).

[354] Souza, A.M., Ferreira, R., Baragan, G., Nunez, J.G., Mariani, F.E., Jannone da Silva, E., Coelho, R.T., 2021, Effects of Laser Polishing on Surface Characteristics and Wettability of Directed Energy-deposited 316L Stainless Steel. Journal of Materials Engineering and Performance, 30:6742–6765. https://doi.org/10.1007/s11665-021-05991-y.
[355] Spierings, A.B., Dawson, K., Heeling, T., Uggowitzer, P.J., Schäublin, R., Palm, F., Wegener, K., 2017, Microstructural Features of Sc- and Zr-modified Al-Mg Alloys Processed by Selective Laser Melting. Materials & Design, 115:52–63. https://doi.org/10.1016/j.matdes.2016.11.040.
[356] Stevenson K., 2020. Hirtenberger's Automated Metal 3D Print Post Processing System, published online on 20th February 2020, ⟨https://www.fabbaloo.com/2020/02/hirtenbergers-automated-metal-3d-print-post-processing-system⟩.
[357] Stichel, T., Brandl, T., Hauser, T., Geißler, B., Roth, S., 2018, Electrophotographic Multi-material Powder Deposition for Additive Manufacturing. Procedia CIRP, 74:249–253. https://doi.org/10.1016/j.procir.2018.08.104.
[358] Stoll, T., Trautnitz, P., Schmiedeke, S., Franke, J., Travitzky, N., 2020, Process Development for Laser Powder Bed Fusion of Pure Copper. Proc SPIE 11271, Laser 3D Manufacturing VII, 112710:1–14. https://doi.org/10.1117/12.2563870.
[359] Strantza, M., Vrancken, B., Prime, M.B., Truman, C.E., Rombouts, M., Brown, D.W., Guillaume, P., van Hemelrijck, D., 2019, Directional and Oscillating Residual Stress on the Mesoscale in Additively Manufactured Ti-6Al-4V. Acta Materialia, 168/4: 299–308. https://doi.org/10.1016/j.actamat.2019.01.050.
[360] Syed-Khaja, A., Schwarz, D., Franke, J., 2015, Advanced Substrate and Packaging Concepts for Compact System Integration With Additive Manufacturing Technologies for High Temperature Applications. IEEE CPMT Symposium Japan (ICSJ), 156–159. https://doi.org/10.1109/ICSJ.2015.7357402.
[361] Syed-Khaja, A., Freire, A.P., Kaestle, C., Franke, J., 2017, Feasibility Investigations on Selective Laser Melting for the Development of Microchannel Cooling in Power Electronics. IEEE 67th Electronic Components and Technology Conference (ECTC), 1491–1496. https://doi.org/10.1109/ECTC.2017.232.
[362] Talbot, T., Skaggs, A., 2020, Regulating 3D-Printed Guns PostHeller: Why Two Steps Are Better Than One. The Journal of Law, Medicine & Ethics: a Journal of the American Society of Law, Medicine & Ethics, 48:98–104. https://doi.org/10.1177/1073110520979407.
[363] Tato W., Blunt L., Llavori I., Aginagalde A., Townsend A., Zabala A., 2020. Surface integrity of additive manufacturing parts: a comparison between optical topography measuring techniques. Proc. CIRP, 87, 403–408.
[364] The Independent, 2019. Use of 3D printed guns in German synagogue shooting must act as warning to security services, experts say., published online by Lizzie Dearden on 11th October 2019, ⟨https://www.independent.co.uk/news/world/europe/3d-gun-print-germany-synagogue-shooting-stephan-balliet-neo-nazi-a9152746.html⟩.
[365] Thomas, D., 2009, The Development of Design Rules For Selective Laser Melting. PhD Thesis. University of Wales Institute,⟨http://hdl.handle.net/10369/913⟩.
[366] Thompson, M., Moroni, G., Vaneker, T., Fadel, G., Campbell, R., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., Martina, F., 2016, Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints. CIRP Annals, 65:737–760. https://doi.org/10.1016/j.cirp.2016.05.004.
[367] Tofail, S.A.M., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., Charitidis, C., 2018, Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities. Materials Today, 21/1: 22–37. https://doi.org/10.1016/j.mattod.2017.07.001.
[368] TRUMPF SE + Co. KG. Disk Laser. TruDisk with green wavelength. Green laser light for welding copper, ⟨https://www.trumpf.com/en_INT/products/laser/disk-lasers/trudisk-with-green-wavelength/⟩. (Accessed July 11, 2022).
[369] Uhlmann, E., Fleck, C., Gerlitzky, G., Faltin, F., 2017, Dynamical Fatigue Behavior of Additive Manufactured Products for a Fundamental Life Cycle Approach. Procedia CIRP, 61:588–593. https://doi.org/10.1016/j.procir.2016.11.138.
[370] Ullman, D., 1997, The mechanical design process. second ed. McGraw-Hill, Boston, Mass.
[371] Ullsperger, T., Liu, D., Yürekli, B., tthäus, G., Schade, L., Seyfarth, B., Kohl, H., Ramm, R., Rettenmayr, M., Nolte, S., 2021, Ultra-short Pulsed Laser Powder Bed Fusion of Al-Si Alloys: Impact of Pulse Duration and Energy in Comparison to Continuous Wave Excitation. Additive Manufacturing, 46/1:102085. https://doi.org/10.1016/j.addma.2021.102085.
[372] Umbrello, D., Imbrogno, S., Bordin, A., Bruschi, S., 2017, 3D Finite Element Modelling of Surface Modification in Dry and Cryogenic Machining of EBM Ti6Al4V Alloy. CIRP Journal – Manufacturing Science and Technology, 18:92–100. https://doi.org/10.1016/j.cirpj.2016.10.004.
[373] Ünsal I., Hama-Saleh R., Sviridov A., Bambach M., Weisheit A., Schleifenbaum J. H., 2018. Mechanical properties of sheet metal components with local reinforcement produced by additive manufacturing, in:. Proceedings of the 21st International Esaform Conference On Material Forming: Esaform, Palermo, Italy. 23–25 April 2018. Author(s), p. 160028.
[374] Urlea, V., Brailovski, V., 2017, Electropolishing and Electropolishing-related Allowances For Powder Bed Selectively Laser-melted Ti-6Al-4V Alloy Components. Journal of Materials Processing Technology, 242:1–11. https://doi.org/10.1016/j.jmatprotec.2016.11.014.
[375] Vaezi, M., Chianrabutra, S., Mellor, B., Yang, S., 2013, Multiple Material Additive Manufacturing – Part 1: A Review. Virtual and Physical Prototyping, 8/1: 19–50. https://doi.org/10.1080/17452759.2013.778175.
[376] Valcun, 2023, The Game Changer in Aluminum Additive Manufacturing for sustainable serial production, ⟨https://www.valcun.be⟩ (accessed April 2023).
[377] Vaneker, T., Bernard, A., Moroni, G., Gibson, I., Zhang, Y., 2020, Design for Additive Manufacturing: Framework and Methodology. ISSN 0007-8506, doi CIRP Annals, Volume 69/Issue 2: 578–599. https://doi.org/10.1016/j.cirp.2020.05.006.
[378] Vasileska, E., Demir, A., Colosimo, B., 2019, Layer-wise Control of Selective Laser Melting by Means of Inline Melt Pool Area Measurements. Proc ICALEO.
[379] Villarraga H., et al., 2015. Dimensional metrology of complex inner geometries built by additive manufacturing. Proc. - ASPE 2015 Spring Top. Meet. Achiev. Precis. Toler. Addit. Manuf. 60, 164–169.
[380] Villarraga-Gomez, H., Lee, C., Smith, S., 2018, Dimensional Metrology with X-ray CT: A Comparison with CMM Measurements on Internal Features and Compliant Structures. Precision Engineering, 51:291–307. https://doi.org/10.1016/j.precisioneng.2017.08.021.
[381] Vrancken, B., Ganeriwala, R.K., Matthews, M.J., 2020, Analysis of Laser-induced Microcracking in Tungsten Under Additive Manufacturing Conditions: Experiment and simulation. Acta Materialia, 194:464–472. https://doi.org/10.1016/j.actamat.2020.04.060.
[382] Walachowicz, F., Bernsdorf, I., Papenfuss, U., Zeller, C., Graichen, A., Navrotsky, V., Rajvanshi, N., Kiener, C., 2017, Comparative Energy, Resource and Recycling Lifecycle Analysis of the Industrial Repair Process of Gas Turbine Burners Using Conventional Machining and Additive Manufacturing. Journal of Industrial Ecology, 21:203–215. https://doi.org/10.1111/jiec.12637.
[383] Wang, D., Liu, L., Deng, G., Deng, G., Deng, C., Bai, Y., et al., 2022, Recent Progress on Additive Manufacturing of Multi-material Structures With Laser Powder Bed Fusion. Virtual and Physical Prototyping, Vol. 17/2: 329–365. https://doi.org/10.1080/17452759.2022.2028343.
[384] Wang, X., Xiong, W., 2020, Uncertainty Quantification and Composition Optimization for Alloy Additive Manufacturing Through a CALPHAD-based ICME Framework. npj Computational Materials, 6:188. https://doi.org/10.1038/s41524-020-00454-9.
[385] Warrier, N., Kate, K.H., 2018, Fused Filament Fabrication 3D Printing With Low-melt Alloys. Progress in Additive Manufacturing, 3:51–63. https://doi.org/10.1007/s40964-018-0050-6.
[386] Wei, C., Li, L., Zhang, X., Chueh, Y.-H., 2018, 3D Printing of Multiple Metallic Materials Via Modified Selective Laser Melting. CIRP Annals, 67/1: 245–248. https://doi.org/10.1016/j.cirp.2018.04.096.
[387] Wei, C., Sun, Z., Huang, Y., Li, L., 2018, Embedding Anti-counterfeiting Features in Metallic Components Via Multiple Material Additive Manufacturing. ISSN 2214-8604, doi Additive Manufacturing, Volume 24/2018: 1–12. https://doi.org/10.1016/j.addma.2018.09.003.
[388] Wei, C., Zhang, Z., Cheng, D., Sun, Z., Zhu, M., Li, L., 2020, An Overview of Laser-based Multiple Metallic Material Additive Manufacturing: From Macro- to Micro-scales. International Journal of Extreme Manufacturing, 3:012003. https://doi.org/10.1088/2631-7990/abce04.
[389] Wei, L.C., Ehrlich, L.E., Powell-Palm, M.J., Montgomery, C., Beuth, J., Malen, J.A., 2018, Thermal Conductivity of Metal Powders for Powder Bed Additive Manufacturing. Additive Manufacturing, 1/21: 201–208.
[390] Whiting, J.G., Tondare, V.N., Scott, J.H., Phan, T.Q., Donmez, M.A., 2019, Uncertainty of Particle Size Measurements Using Dynamic Image Analysis. CIRP Annals, 1/68(1): 531–534.
[391] Whiting, J.G., Garboczi, E.J., Tondare, V.N., Scott, J.H., Donmez, M.A., Moylan, S.P., 2022, A Comparison of Particle Size Distribution and Morphology Data Acquired Using Lab-based and Commercially Available Techniques: Application to Stainless Steel Powder. Powder Technology, 1/396: 648–662.
[392] Wilson, J., Piya, C., Shin, Y., Zhao, F., Ramani, K., 2014, Remanufacturing of Turbine Blades by Laser Direct Deposition With its Energy and Environmental Impact Analysis. Journal of Cleaner Production, 80:170–178. https://doi.org/10.1016/j.jclepro.2014.05.084.
[393] Witherell P., 2021. Digital Twins for Part Acceptance in Advanced Manufacturing Applications with Regulatory Considerations. The 46th MPA Seminar, Stuttgart, DE October 2021.
[394] Withers, P.J., Turski, M., Edwards, L., Bouchard, P.J., Buttle, D.J., 2008, Recent Advances in Residual Stress Measurement. International Journal of Pressure Vessels and Piping, 1/85(3): 118–127.
[395] Wits, W.W., Carmignato, S., Zanini, F., Vaneker, T.H., 2016, Porosity Testing Methods for the Quality Assessment of Selective Laser Melted Parts. CIRP Annals, 1/65(1): 201–204.
[396] Wohlers Associates Wohlers Report 2019; Wohlers Associates, Inc., 2019; ISBN 978-0-9113332-5-7.
[397] Wong, H., Neary, D., Jones, E., Fox, P., Sutcliffe, C., 2019, Pilot Capability Evaluation of a Feedback Electronic Imaging System Prototype for In-process Monitoring in Electron Beam Additive Manufacturing. The International Journal of Advanced Manufacturing Technology, 100:707–720.
[398] Wu, D., Ren, A., Zhand, W., Fan, F., Liu, P., Fu, X., Terpenny, J., 2018, Cybersecurity for Digital Manufacturing. Journal of Manufacturing Systems, 48:3–12. https://doi.org/10.1016/j.jmsy.2018.03.006.
[399] Xerox, 2023, Introducing the Xerox® ElemX™ Liquid Metal Printer - YouTube, ⟨https://www.youtube.com/watch?v=Bpj6uUspCJA⟩ (accessed April 2023).
[400] Xiao, X., Joshi, S., 2020, Process Planning for Five-axis Support Free Additive Manufacturing. Additive Manufacturing, 36:101569. https://doi.org/10.1016/j.addma.2020.101569.
[401] Xu, Z., Ouyang, W., Liu, Y., Jiao, J., Liu, Y., Zhang, W., 2021, Effects of Laser Polishing on Surface Morphology and Mechanical Properties of Additive Manufactured TiAl Components. Journal of Manufacturing Processes, 65:51–59. https://doi.org/10.1016/j.jmapro.2021.03.014.
[402] Xue, T., Gan, Z., Liao, S., Cao, J., 2022, Physics-embedded Graph Network for Accelerating Phase-field Simulation of Microstructure Evolution in Additive

Manufacturing. npj Computational Mechanics, 8:201. https://doi.org/10.1038/s41524-022-00890-9.
[403] Yablokova, G., Speirs, M., Van Humbeeck, J., Kruth, J.-P., Schrooten, J., Cloots, R., Boschini, F., Lumay, G., Luyten, J., 2015, Rheological behavior of β-Ti and NiTi Powders Produced by Atomization for SLM Production of Open Porous Orthopedic Implants. Powder Technology, 1/283: 199–209.
[404] Yamaguchi, H., Fergani, O., Wu, P.-Y., 2017, Modification Using Magnetic Field-assisted Finishing of the Surface Roughness and Residual Stress of Additively Manufactured Components. CIRP Annals, 66/1: 305–308. https://doi.org/10.1016/j.cirp.2017.04.084.
[405] Yan, W., Lu, Y., Jones, K., Yang, Z., Fox, J., Witherell, P., Wagner, G.J., Liu, W.K., 2020, Data-driven Characterization Of Thermal Models for Powder-bed-fusion Additive Manufacturing. Additive Manufacturing, 36:101503. https://doi.org/10.1016/j.addma.2020.101503.
[406] Yang, S., Evans, J.R.-G., 2007, Metering and Dispensing of Powder; The Quest for New Solid Freeforming Techniques. Powder Technology, 178:56–72.
[407] Yang, Y., Zhao, F., 2021, Closing the Material Loop in Additive Manufacturing: A Literature Review on Waste Recycling. IOP Conf Ser: Mater Sci Eng, 1196:012008. https://doi.org/10.1088/1757-899X/1196/1/012008.
[408] Yasa, E., Kruth, J.-P., Deckers, J., 2011, Manufacturing by Combining Selective Laser Melting and Selective Laser Erosion/laser Re-melting. CIRP Annals, 60/1: 263–266. https://doi.org/10.1016/j.cirp.2011.03.063.
[409] Zafar, M.Q., Wu, C., Zhao, H., Du, K., Gong, Q., 2021, Numerical Simulation for Electron Beam Selective Melting PBF Additive Manufacturing of Molybdenum. The International Journal of Advanced Manufacturing Technology, vol. 117:1575–1588.
[410] Zaman, U., Rivette, M., Siadat, A., Mousavi, S., 2018, Integrated Product-process Design: Material and Manufacturing Process Selection for Additive Manufacturing Using Multi-criteria Decision Making. Robotics and Computer-Integrated Manufacturing, 51:169–180. https://doi.org/10.1016/j.rcim.2017.12.005.
[411] Zhang, F., Wang, L., Zhao, H., Qiu, Y., Wang, G., Zhang, J., Tan, H., 2020, Interaction Between Powder Particle And Gas-liquid Interface of the Melt Pool During Laser Solid Forming Process. Optics and Lasers in Engineering, 129. https://doi.org/10.1016/j.optlaseng.2020.106065.
[412] Zhang, S., Lane, B., Whiting, J., Chou, K., 2019, On Thermal Properties of Metallic Powder in Laser Powder Bed Fusion Additive Manufacturing. Journal of Manufacturing Processes, 1/47: 382–392.
[413] Zhang, S., Gong, M., Zeng, X., Gao, M., 2021, Residual Stress and Tensile Anisotropy of Hybrid Wire arc Additive-milling Subtractive Manufacturing. Journal of Materials Processing Technology, 293/4:117077. https://doi.org/10.1016/j.jmatprotec.2021.117077.
[414] Zhang W., Mehta A., Desai P.S., Fred Higgs C. 2017. Machine learning enabled powder spreading process map for metal additive manufacturing (AM), Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF, pp. 1235–1249.
[415] Zhang, Y., Bernard, A., Harik, R., Fadel, G., 2018, A new method for single-layer-part nesting in additive manufacturing. RPJ, 24:840–854. https://doi.org/10.1108/RPJ-01-2017-0008.
[416] Zhao, C., Parab, N.D., Li, X., Fezzaa, K., Tan, W., Rollett, A.D., Sun, T., 2020, Critical instability at moving keyhole tip generates porosity in laser melting. Science, 370/6520: 1080–1086. https://doi.org/10.1126/science.abd1587.
[417] Zhao, L., Song, L., Santos Macías, J.G., Zhu, Y., Huang, M., Simar, A., et al., 2022, Review on the Correlation Between Microstructure and Mechanical Performance for Laser Powder Bed Fusion AlSi10Mg. Additive Manufacturing, 56:102914. https://doi.org/10.1016/j.addma.2022.102914.
[418] Zhao, X., Lian, Q., He, Z., Zhang, S., 2019, Region-based Online Flaw Detection of 3D Printing Via Fringe Projection. Measurement Science and Technology, 31:035011.
[419] Zhihao, F., Lubin, L., Longfei, C., Yingchun, G., 2018, Laser Polishing of Additive Manufactured Superalloy. Procedia CIRP, 71:150–154. https://doi.org/10.1016/j.procir.2018.05.088.
[420] Zhu, J., Zhou, H., Wang, C., Zhou, L., Yuan, S., Zhang, W., 2021, A Review of Topology Optimization for Additive Manufacturing: Status and Challenges. Chinese Journal of Aeronautics, 34/1: 91–110. https://doi.org/10.1016/j.cja.2020.09.020.
[421] Zhu, Z., Lou, S., Majewski, C., 2020, Characterisation and Correlation Of Areal Surface Texture With Processing Parameters and Porosity of High Speed Sintered Parts. Additive Manufacturing, 36:101402.
[422] Zobeiry, N., Humfeld, K.D., 2021, A Physics-informed Machine Learning Approach for Solving Heat Transfer Equation in Advanced Manufacturing And Engineering Applications. Engineering Applications of Artificial Intelligence, 101:104232.