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Laser based additive manufacturing in industry and academia

Michael Schmidt (2)[a,b,*], Marion Merklein (1)[b,c], David Bourell (2)[d], Dimitri Dimitrov (3)[e], Tino Hausotte[f], Konrad Wegener (2)[g], Ludger Overmeyer (2)[h], Frank Vollertsen (1)[i], Gideon N. Levy (1)[j]

[a] Institute of Photonic Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
[b] Graduate School in Advanced Optical Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
[c] Institute of Manufacturing Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
[d] Laboratory for Freeform Fabrication, University of Texas at Austin, Austin, USA
[e] Stellenbosch Technology Centre, Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa
[f] Institute of Manufacturing Metrology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
[g] Institute of Machine Tools and Manufacturing, ETH Zürich, Zürich, Switzerland
[h] Laser Zentrum Hannover e.V., Hannover, Germany
[i] Bremen Institute for Applied Beam Technology and University of Bremen, Bremen, Germany
[j] TTA Technology, Switzerland

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ABSTRACT

Additive manufacturing (AM) is pushing towards industrial applications. But despite good sales of AM machines, there are still several challenges hindering a broad economic use of AM. This keynote paper starts with an overview over laser based additive manufacturing with comments on the main steps necessary to build parts to introduce the complexity of the whole process chain. Then from a manufacturing process oriented viewpoint it identifies these barriers for Laser Beam Melting (LBM) using results of a round robin test inside CIRP and the work of other research groups. It shows how those barriers may be overcome and points out research topics necessary to be addressed in the near future.

1. Introduction to laser based additive manufacturing

The first CIRP keynote paper dealing with additive manufacturing (AM) was published in 1991 [119] showing the long history of this technology. Since then several keynote papers with the scope on AM as a prototyping [122] and a manufacturing technique in general [134], on consolidation phenomena of the used powders [123] and on AM for nano-manufacturing [136] have been published. Moreover, specific applications like the use of AM for building implants [12] and turbomachinery components [111] have been discussed in detail.

But during the last years due to progress in computation power and systems technology laser based AM has advanced to a technology with high potential for industrial application. As to date no process oriented overview on the specific capabilities and challenges of laser based AM in industry is available, this keynote paper intends to fill this gap and to identify the challenges and thus future research topics leading to industrial application. The paper starts with information on laser based AM in general with a special focus on industry and quality to give a broad knowledge basis. Then it focuses down to Laser Beam Melting (LBM) of polymers (LBM-P) and of metals (LBM-M) to give detailed process oriented knowledge on the currently most promising technologies.

1.1. Additive manufacturing and lasers

1.1.1. Introduction to additive manufacturing

Additive manufacturing is defined by ISO 17296 and ASTM F2792 to be "the process of joining materials to make parts or objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [99]. The salient distinguishing feature of AM relative to conventional manufacturing processes is the computer-driven layer-by-layer construction or build-up of the part without the use of part-specific tooling. The standard categorizes AM into seven divisions based on the binding mechanism and the feedstock morphology or delivery. Three of these seven divisions make use of a laser: vat polymerization, powder bed fusion, and directed energy deposition. The laser power used for these processes spans from some Watt to several Kilowatt and applications differ from design prototypes to structural components.

In addition to vat polymerization, powder bed fusion and directed energy deposition, there are other AM processes which are not laser-based. Similar to laser-based powder bed fusion is the electron beam-based technology. Material jetting uses the same

* Corresponding author at: Institute of Photonic Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany.
E-mail address: Michael.Schmidt@fau.de (M. Schmidt).

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feedstock as stereolithography, but jets droplets of the photopolymer using standard inkjet methods into a chamber exposed to the appropriate wavelength of light for crosslinking. Binder jetting uses inkjet technology to jet a solvent or adhesive into a powder bed. Fused deposition modeling is the most commonly employed AM technology for private use. It is based on forcing feedstock in liquid or semi-liquid form through a moving orifice to lay down a track of deposited material.

1.1.2. Historical evolution of lasers in additive manufacturing

The development of additive manufacturing may be divided into three time frames: pre-history, precursor processes and modern AM [23]. AM pre-history dates over 100 years back and predates the laser and modern computer. These processes are additive in nature and include photosculpture [14,22], lithographic part construction [20], and weld build-up [11]. AM precursor processes (1965–1982) capture all elements of modern AM processes, but these inventions predate distributed computing and were never commercialized. Modern AM processes include all the familiar AM technologies and were initiated in the mid-1980s.

One of the earliest precursor AM processes utilizing a laser is embodied in a US patent filed in 1968 [222]. Non-tactile methods were proposed to capture the geometry from an existing object and to use crossed lasers in a volume printing method to recreate the geometry of the object additively [222]. The process is similar in principle to two-photon polymerization in terms of the motion of an active spot in space to form the part, but the owner of named patent never implemented the concept in practice. In 1972 a French patent application was filed that captured the salient features of directed energy deposition [36]. Fig. 1 shows an image from the application, complete with one or more lasers (7 and 7a), powder (2) with a deposition system (8, 9), and a part (1).

A US patent was filed in 1979 for what is now known as laser sintering [91]. This was followed by researchers in Japan and the United States who filed separate patents for what is now known as stereolithography in 1981 and 1982, respectively [87,112].

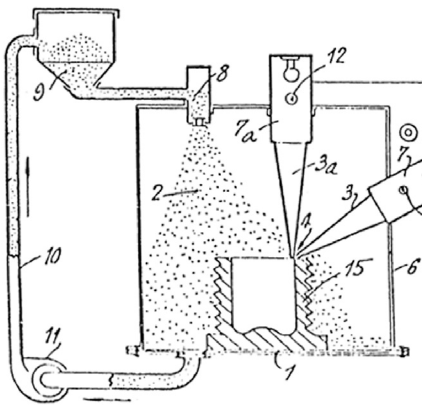

Fig. 1. Process for part construction using directed energy deposition [36].

1.2. Overview of laser based additive manufacturing processes

This section briefly explains the laser based processes using metal and polymer as base materials. Not only the principle functionality is explained but design, data preparation and postprocessing as well as quality assurance are addressed to show that the process should be seen as part of a whole process chain. The section industry, including the use of AM in Industry 4.0, shows the potential role of AM in different industrial sectors as well as in neighbouring technologies. A comparison in mechanical characteristics as well as an assessment on the growing relevance of AM conclude the section.

1.2.1. Classification of laser based AM processes

One of the most relevant classifications of laser based AM processes is the one suggested in ISO 17296 [97]. It takes the material type used as first criterion and so distinguishes between AM processes for metals, polymers, ceramics, and biological materials. Laser based AM processes share the same manufacturing principle, although each process might have its own range of usable materials, procedures, and applicable situations [82]. The principle behind laser based AM technologies lies in the use of a laser beam to provide thermal energy for the melting and consolidating of the additive materials, or to provide light quanta of a certain wavelength to initiate a chemical curing reaction in vat polymerization [133]. The starting materials used in laser based AM processes can be in the form of powder (metals, ceramics, and polymers), liquids (resin), or solids (paper, plastics, and metals) [253]. According to Ref. [70], the basic types using powder material include Laser Sintering (LS), Laser Beam Melting (LBM), Electron Beam Melting (EBM), and Laser Metal Deposition (LMD). The powder fusion mechanisms include solid state sintering, liquid phase sintering, chemically induced binding, and full melting [221]. The laser based AM processes that use liquids and solids as starting materials are Stereolithography (SLA) and Laminated Object Manufacturing (LOM), respectively. The following section gives an overview of the laser based AM processes.

1.2.1.1. Metal based processes. The ISO 17296-1 standard suggests the following classification tree for metal processing AM (Fig. 2).

LBM is one of the most common AM processes because of its ability to manufacture fully dense metal parts with complex geometric features and mechanical characteristics comparable to conventionally fabricated structures. The basic machine components for an LBM machine include a high intensity solid state laser source, a beam deflection mechanism, a building platform, a powder feed container, and a roller or scraper that deposits the powder, as shown in Fig. 3. The initial steps involve creating sliced data from a 3D model of the part by converting it into a standard file for the AM machine system. Another initial step may involve pre-heating the powder in order to improve the absorption of the laser, to reduce the temperature gradients, and to improve wetting properties [33].

Furthermore, in LBM of polymers, a pre-heating device is used to keep the temperature during the process above the crystallization temperature. During the LBM process, powder is spread on the platform and the computer controlled laser beam selectively scans the powder. The scanning of the laser beam results in full melting and consolidation of the powder. After the layer is complete, the build platform is lowered by a distance equivalent to the thickness of the layer and fresh powder is spread onto the platform. The procedure is repeated until the completion of the part.

In LS, the powder is partially molten or heated to the sintering point, unlike in LBM where there is full melting [154]. The components of an LS machine are similar to those of LBM machines [104]. Heat fusible powder is used and pre-heated to a temperature below the sintering point before scanning occurs. The scanning of

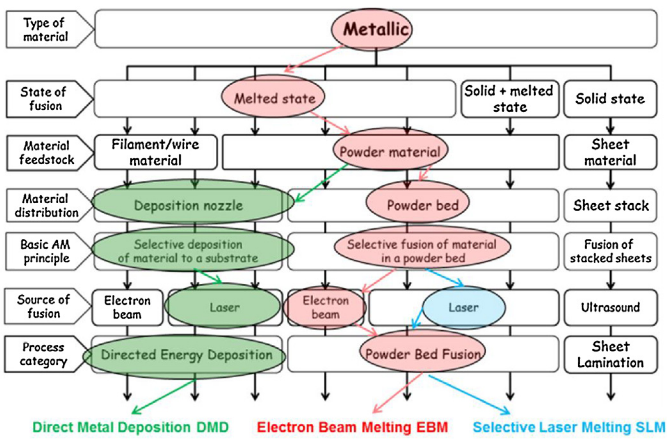

Fig. 2. Morphological box for metal based AM processes [97].

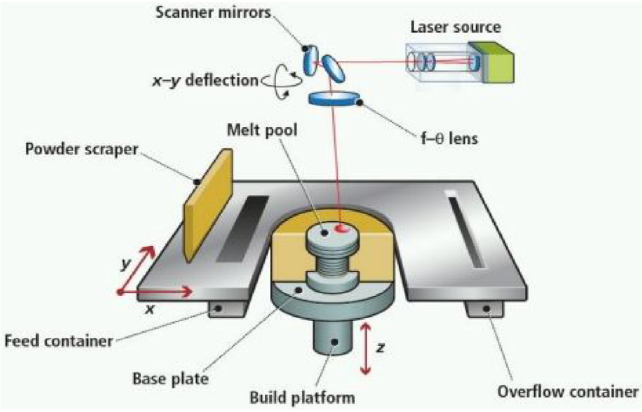

Fig. 3. Exemplary sketch of the Laser Beam Melting process [261].

the laser provides the additional energy required for sintering or partial melting of the particles. It is possible to distinguish between direct and indirect LS. In indirect LS, the powder is mixed with a polymer binder to improve the sintering process; this increases the density and strength of the part produced [203]. The binder can be in the form of a liquid or a solid with a lower melting point than the other powder particles to melt the particles together [44]. The starting mixture can be in the form of a powder or slurry. A literature analysis shows that the use of slurry is gaining more attention [53,226,262]. When the binder is put into the liquid state during sintering, the fusion process is called liquid phase sintering [139]. A de-binding process is then performed to remove the polymer followed by sintering of the particles in a furnace. In direct LS, there is no added binder and the interaction of the laser with the powder particles will be sufficient to bind the particles [44]. In general, all weldable materials can be used for LBM processing, which include pure metals (Al, Cr, Ti, Fe, Cu), compounds (e.g. Fe-Cu, Fe-Sn, Cu-Sn), alloys such as nickel based, cobalt based, stainless steel, tool steel materials, and, titanium alloys such as Ti–6Al–4V [227].

There are several processes that have recently been referred to as LMD. In LMD, the powder is supplied by a nozzle, as shown in Fig. 4. LMD can have different names such as Direct Metal Deposition (DMD), Laser Metal Deposition (LMD), Direct Laser Deposition, Laser Engineered Net Shaping (LENS), Laser Cladding, Direct Energy Deposition and Laser Deposition Welding [130]. LMD involves the use of a laser beam that is focused on a work piece, thereby producing a melt pool. Metallic powder is simultaneously injected into the melt pool. Single weld tracks are placed next to each other in order to form a single layer. A near net shape geometry can be generated by adding several layers on top of each other. Fig. 4 illustrates the work principle on an example of the LMD process [55].

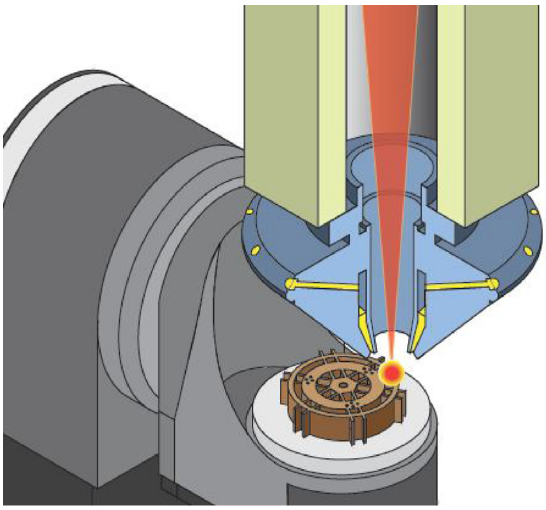

Fig. 4. Exemplary sketch of the Laser Metal Deposition process.

In LMD, the powder can be fed co-axially or laterally by an inert gas stream (helium or argon). Layer thickness can vary from 0.1 mm to several millimeters depending on the process parameters (velocity, powder feed rate, and laser power) [169]. The process can be utilized in the repair of worn out high value components, the building of new components, and the application of wear resistant and corrosion resistant coatings [56]. LMD has the advantage that it uses a 0.5 mm–3 mm laser beam diameter which is confined to localized areas resulting in a reduction in residual stresses and the heat affected zone [224]. This is different from conventional repair techniques such as tungsten inert gas (TIG) and metal inert gas (MIG) welding, which involve a large temperature increase in the part and a weakening of the base as a result of the wide temperature distribution in the working region of the part. Like LBM, LMD is compatible with most weldable materials and thus a broad range of pure metals and alloys can be used. High melting point alloys such as titanium based alloys [69,254], tool steels [96], nickel based alloys [46] and stainless steels [269] are well suited for this process.

Wire based deposition systems utilize a wire to build the part. Wire based LMD systems are ideal for the production of larger components that have a moderate complexity. The advantages of using wire when compared to the use of powder include cleaner working environment, and higher deposition rates and efficient resource consumption since all of the wire that is fed is effectively used [13,86]. Furthermore, metal wire is cheaper than powder. The materials that have been investigated for wire deposition systems include Inconel 625 [46], Inconel 718, and TI6Al4V. In wire deposition, special process strategies like hot wire strategies [141] or central wire feeding [167] are currently under investigation.

1.2.1.2. Polymer based processes. Stereolithography (SLA) is an AM process in which parts are built by the scanning action of a computer controlled laser beam on a vat of liquid resin photopolymer using a movable platform [151]. The photopolymer cures and solidifies when it comes in contact with an electromagnetic wave of an appropriate wavelength. Thus, low-powered lasers are mostly used. Subsequently, the build platform is lowered by a distance equivalent to layer thickness [164]. Fresh resin is then spread over the solidified layer and the process is repeated layer by layer until the part is complete (Fig. 5). The excess resin is drained and the part is washed to obtain the build part.

SLA has many advantages, such as superior dimensional accuracy and smooth surface finish [146]. Thus, typical applications are principally prototypes and nonstructural parts with good dimensional control and surface finish. According to Ref. [151], the smallest details in SLA are in the range of 50 μm–200 μm in size. Resins used in SLA include low molecular weight polyacrylate and epoxy macromers. Non-reactive diluents like methylpyrrolidone or water can be added to reduce the viscosity [151]. Ceramic particles can also be added to make polymer ceramic composites. Research has also focused on the production of bio-degradable

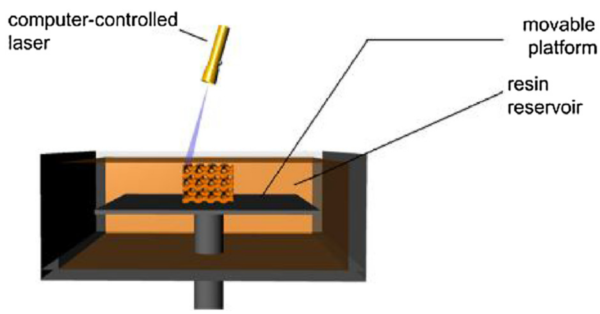

Fig. 5. Schematic representation of building a part with the stereolithography process [151].

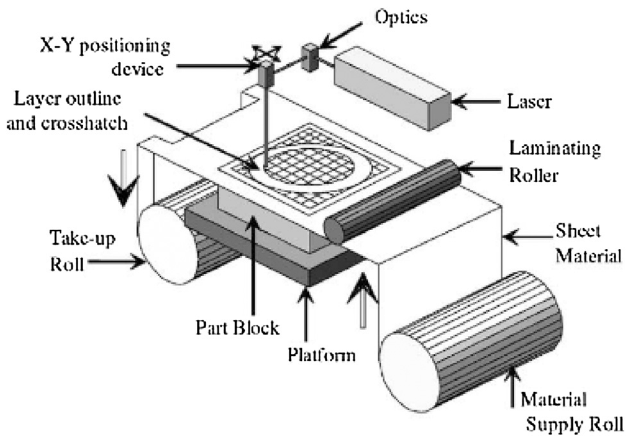

Fig. 6. Exemplary sketch of Laminated Object Manufacturing [249].

resins (polyethylene, polyglycol, and lactide based resins) [199,217].

On the other hand, challenges with SLA include the need for support structures, the inability to process metals, high cost, and limited availability of resins [129]. Stereolithography has been investigated for producing micro-products, which can be referred to as micro-stereolithography [239].

In Laminated Object Manufacturing (LOM), an adhesive layer is deposited on the platform using a heated roller. A computer controlled CO_2 laser then cuts the required cross section and a fresh layer is spread on the platform. The procedure is repeated until the part is complete [249]. Fig. 6 shows a schematic representation of the LOM process.

Materials that can be used in LOM include plastics, fabrics, synthetic materials, composites, and also sheet metals [93]. However, the challenges of LOM include waste of material from the cutting process, post production time for eliminating waste, and high power consumption [138]. Another challenge is that poor control of the laser beam may result in penetration into the previously cut layers causing dimensional instability and an increase in power usage [3]. The process has been further investigated for the production of metallic parts using sheet metals, which are bonded using ultrasonic consolidation [181] and resistance welding.

1.2.2. Design for laser based AM processes

As AM has a completely opposite manufacturing approach compared to conventional subtractive manufacturing, it has its own design restrictions. AM offers new degrees of freedom for design, which at the same time require the development of adapted design rules. Basic rules were summarized for geometrical standard elements that often reoccur by designing technical parts [2].

Parts produced with AM processes show a poor surface quality. The influencing factors for the quality are manifold. However, experimentally developed design rules can help to increase the surface quality. There has been an experimental study to develop design rules for AM of polymers and metals based on geometrical standard elements [2]. According to the findings of the study, the cross sectional area of the build parts should remain constant or become smaller during the build process so the thermal energy can be distributed uniformly. If the cross sectional areas of the layers are increased relative to the initial cross sections, discoloration arises due to an excessive increase in the introduced thermal energy. It was also noted that sharp edges should be avoided as this would result in form defects. To avoid this, edges should be rounded and blunted. Another important finding is that overhangs of more than 45° from the vertical should be minimized as they possess a poor surface quality and may collapse due to thermally induced stresses [2].

Parts with enclosed voids must be avoided. This is because excess material is removed after the part is completely built. If the void is enclosed, the material cannot be removed. In order to reduce the costs associated with the production of AM parts, lattice structures can be employed [259]. Lattice structures also have the advantages of high strength, low mass, and high energy absorption characteristics, which makes them applicable for high added value medical and aerospace components. A deeper review of Design for Additive Manufacturing processes can be found in Ref. [225].

1.2.3. Data preparation and post processing requirements

The first step for most AM processes involves developing a model of the component to be manufactured using CAD software. The model is then translated into an STL file [129]. The STL file creation converts the geometry in the CAD file into small triangles which describe the external closed surface of the original CAD model [70,253]. This process is known as triangulation or tessellation. The STL file is a simple data format which describes every triangle using three points (x,y,z) and the normal vector to distinguish between the inside and outside of a surface [253]. This allows the calculation of multiple slices from the CAD data. However, errors such as undesirable gaps and facets degeneracy can occur during triangulation. In order to reduce the errors, the number of triangles can be increased, leading to an increase in the size of the file [164]. In the next step, the STL file is imported into a specific AM software for pre-processing. Pre-processing involves selecting the orientation of the part for building, provision of support structures if necessary, and slicing the model [164]. For automation of pre-processing steps, research is also focused on the development of mathematical optimization procedures for build orientation and strategies to gain a high degree of filling of the build space. One of the major tasks of data preparation is to select appropriate support structures to prevent the collapse of overhanging surfaces during building, which might cause distortion of the parts [238]. On the other hand, the amount of support structures should be minimized to reduce costs, material consumption, and build time. Hence, a method has been proposed to reduce support structures and to optimize the part position in the build chamber based on defining the optimum of the build orientation by the use of three dimensional implicit functions [220]. This optimization method allows significant weight savings in comparison to support structures designed by voxel-based methods [220]. Moreover, the software allows for estimating the build time and material requirements. The information from the software is then fed into the AM machine system.

The AM machine must be properly set up regarding the build parameters (energy source, layer thickness, time) before building starts. After building the part, support structures are detached and excess material is removed to retrieve the part. Parts made by SLA are post cured with ultraviolet light to fully cure the generated part, thus improving the mechanical strength [151].

For powder based processes, the excess powder is partly recyclable [159]. Post processing procedures such as heat treatment can be applied in order to improve density, tensile strength, and appearance, as well as to reduce residual stresses of the parts produced [213].

The surface integrity of parts manufactured by powder based processes can be improved by abrasive sand blasting, further machining, and acid etching [120]. Surface machining is also critical in improving the dimensional accuracy and appearance of the parts [32]. A common approach to improve mechanical properties of a part in AM is hot isostatic pressing (HIP) and additional heat treatment [19]. Other researchers used pressure infiltration and warm isostatic pressing on LBM parts [203]. Ref. [213] proposes the use of vacuum heat treatment. Coating and polishing can also be done in order to improve the physical appearance of the parts produced [32].

1.2.4. Quality assurance in AM production chains

Currently, additively manufactured parts exhibit significant variations in part quality, such as dimensional tolerances, surface properties, the level of internal material defects and related mechanical properties [168]. Besides a broad standardization, a total quality management system for additive manufacturing is mandatory if the technologies shall be used for high-quality industrial applications. This has already been emphasized in 2006 [135], when industrial additive manufacturing was at its early stages. A quality management system aiming for a full certification of additively manufactured parts needs to cover the whole processing chain. Starting from qualification of the raw materials over the additive manufacturing process steps, also the quality aspects of the final parts produced, including finishing, etc., must be regarded. Therefore, quality gates have been introduced between the different steps of the processing chain [135], as shown in Fig. 7, with clearly defined approval values for specific properties and parameters.

However, there are many influencing factors in the AM process chain that have to be considered. A more comprehensive overview on influencing factors has been given in Ref. [196] and is shown in Fig. 8 for powder-bed based AM processes LBM-P and LBM-M.

Nearly 130 influencing (input-) parameters across the SLM process chain have been reported [182]. Moreover, 49 parameters are described in Ref. [168], including whether they are pre-defined (such as for instance material density) or controllable. Along the process chains of LBM-P and LBM-M, five aspects have the strongest impact on the process output: ‘Equipment’, ‘Material’, ‘Production’, ‘Batch’ and ‘Part’ connected with ‘Finishing’. Especially for the material parameters, it is important to distinguish between polymer and metal powders, as plastic powder is usually not used as-delivered but rather recycled, mixed, and sieved by a LBM-P service company under its own responsibility.

As AM is the ideal manufacturing technology for small series or single parts, indirect indicators of the quality play a major role for part quality. Possible process monitoring signals are optical and acoustic process emissions, but also camera observations, two dimensional temperature measurements and eddy current measurements of the built in process. Hence, sensor concepts can monitor different signals like acoustic noise, solid-borne noise,

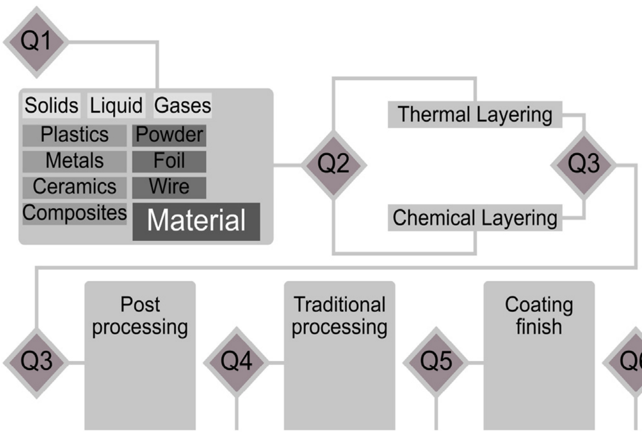

Fig. 7. Quality chain description for layer manufacturing [135].

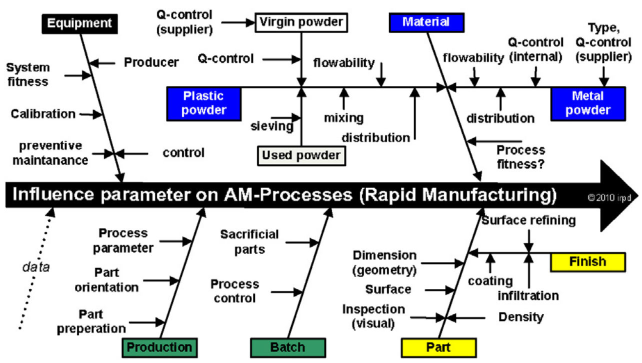

Fig. 8. Ishikawa diagram: influencing factors within an AM process chain for LBM-P and LBM-M [10].

reflected laser light, or radiation emitted from the melting process (e.g. the melt pool) in order to receive information about possible processes inconsistencies. Efficient quality control therefore relies on the identification of relevant operating parameters and on a continuous process monitoring, i.e. measuring and analyzing those parameters during the process. Furthermore, process conditions and in-service behavior during the manufacturing process chain have to be documented at the same time. As there are many processing parameters, the quality control system should include as a first step only the process parameters that have the most significant influence on the final part quality. Additionally, the quality defining parameters on part level have to be defined with respect to the industrial sector depending requirements. A quality management system for powder-bed based AM-systems is suggested in Fig. 9. It includes the definition of control and measurement needed within the whole process chain.

Very important for AM technologies is the continuous control, observation, measurement, and documentation of the main processing parameters (e.g. laser power), the powder layer quality (e.g. by optical layer observation) and the powder properties [223]. For metal AM systems, at least the powder properties as shown in Fig. 10 should be measured and monitored. This includes the monitoring and control of the quality of the powder layer [39] and the powder flowability, which can be measured and assessed in a very reliable way [216].

Non-invasive in-process monitoring solutions are another important aspect of the process chain to enable defect detection in the consolidated material. Process monitoring can be based on melt-pool monitoring, but further monitoring solutions need to be developed in order to assess not only the quality of the manufacturing tool, but also the quality of the consolidated material. Process monitoring is also the source for the development of future closed-loop feedback control structures. Such process monitoring solutions need to be correlated with Non-Destructive-Testing (NDT) data taken from the final produced part, in order to build up knowhow on how to interpret monitoring data, and to generate intervention and acceptance limits for defect types and sizes, as discussed in Refs. [52,271].

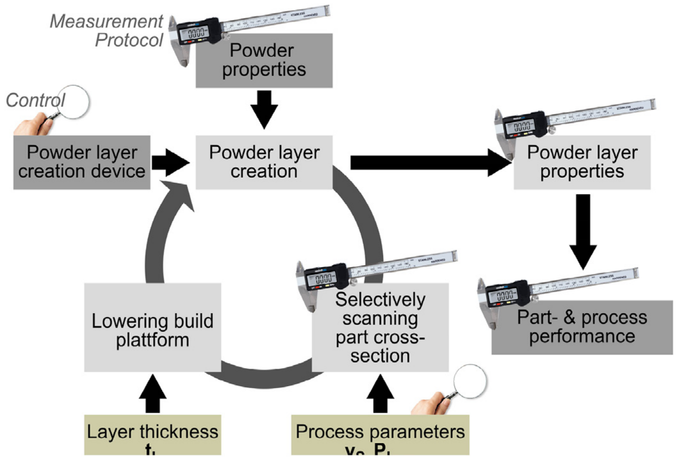

Fig. 9. Quality management system for powder bed based AM [215].

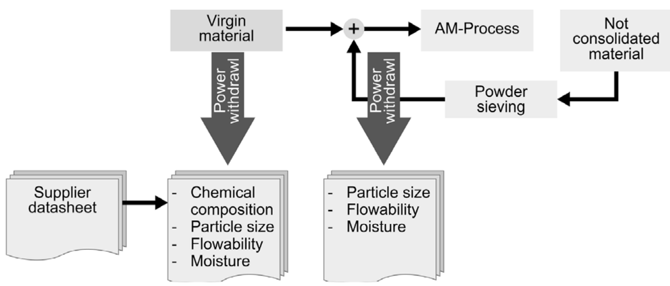

Fig. 10. Powder quality parameters [216].

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On the level of the final part, many parameters can be of interest, such as:

- Material density
- Mechanical material properties (strength, E-modulus, elongation at fracture)
- Surface quality, including the surfaces which are overhanging with regard to the build direction
- Dimensional and geometrical accuracy

The availability of quality management procedures will provide a basis to improve the AM process chain capabilities, and to enable the direct certification of a final part without NDT of every single piece. However, certification also includes the definition of specific protocols and standards, which are not yet available. Hence, there is a great need for the development and implementation of specific procedures and standards.

1.2.5. Industrial applications and Industry 4.0

Applications of manufacturing processes in industry are mainly driven by costs and opportunities. AM introduces an additional benefit to the manufacturing process chain: a nearly unlimited freedom of design.

Fig. 11 displays the influence of geometrical complexity on the final production costs. This relation is especially valuable for smaller series production and for parts with higher geometric complexity, as the costs for AM only slowly increase with complexity in comparison to conventional technologies, for instance milling. Hence, design for AM has to be taken into account in order to benefit from the design freedom of AM and to make future manufacturing economically competitive. This also means that a fairly fundamental redesign of parts has to be performed.

Fig. 12 shows a portfolio analysis of varying manufacturing processes and where AM will find its place in the future. In consideration of quantity and geometric complexity, AM processes are eligible for complex shaped parts produced at low quantities. However, AM is advancing in regions right now occupied by cutting and investment casting.

The other side of the coin is that reliability of AM processes and the material quality of additively manufactured parts are unproven. The poor surface quality and limited geometrical accuracy of AM parts often require post-processing to achieve certain geometrical features. This requirement is often overlooked but is typical for all kinds of primary forming processes like casting. Finally, AM processes are slow compared to conventional processes like milling, forming, and investment casting. Those drawbacks clearly outline required research.

From the approximately 100 different AM processes only a very small number can be used for industrial applications. Only a few of the laser based AM processes have been effectively used in industry. LBM-P is the best established. However, others, such as SLA for polymers and LBM-M and LMD for metallic parts are also used to a lesser extent.

Some industrial sectors are forerunners in the application of AM due to special requirements, as indicated in Table 1. Naturally, costs always play a significant role and, besides those industrial sectors, numerous applications exist, where the balance of costs and benefits promotes the application of AM.

AM can provide benefits during different steps of the whole life cycle of a product and hence, additively manufactured parts can outperform conventionally manufactured parts. In Fig. 13, a comparison of total energy consumption is shown.

During the production phase, significant benefits can be realized if a redesign of the whole system is undertaken or if expensive tools can be avoided. During the use phase, savings are due to enhanced part performance, energy savings, and reduced delivery times, whereas the end of life phase requires less energy input due to the reduced amount of material per part.

AM is considered as being the ideal manufacturing process for the aims of Industry 4.0. Industry 4.0 is the consequent implementation of internet technologies in the industrial value creation process. AM technologies fit into this concept, because manufacturing can be carried out without any hardware preparation. The data, which may be kept within a data cloud, are all that is

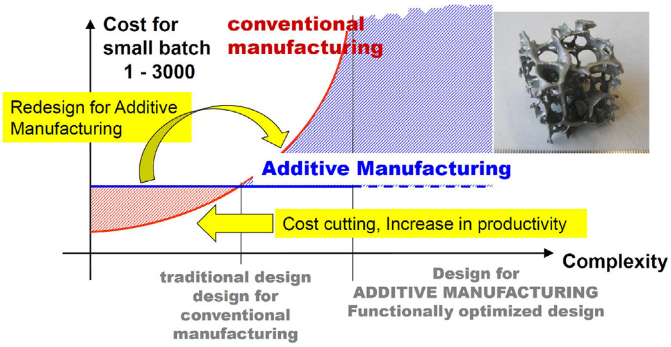

Fig. 11. Freedom of design by AM; courtesy of inspire icams.

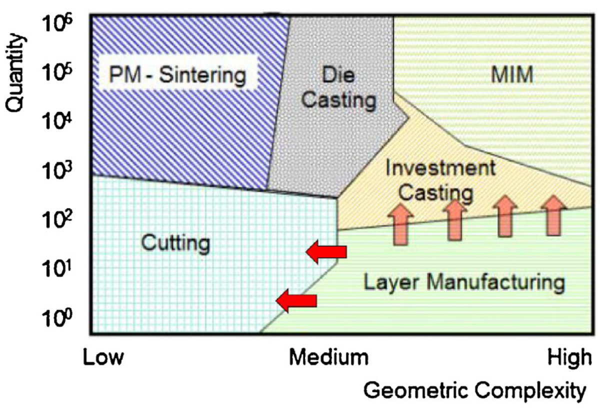

Fig. 12. Portfolio analysis concerning economically preferred manufacturing processes, including powder metallurgy (PM) sintering, and metal injection molding (MIM), considering quantity and geometric complexity [134].

Table 1
Requirements of forerunner industrial sectors regarding the application of AM.

Indust. sectors	Requirements
Aerospace	Lightweight
Energy	Freedom of design, avoid fine casting, individual repair coupons
Dental	Individualized product, reduced lead time
Medical and prosthesis	High complexity, individualized products
Art and Design	Freedom of design
Automotive	Lightweight and cost
Machine Tools	Conformal coolant supply
Mold and die	Functional integration, conformal cooling, lubrication, sensing and actuation, repair
Repair	Energy, mold and die, high investment goods

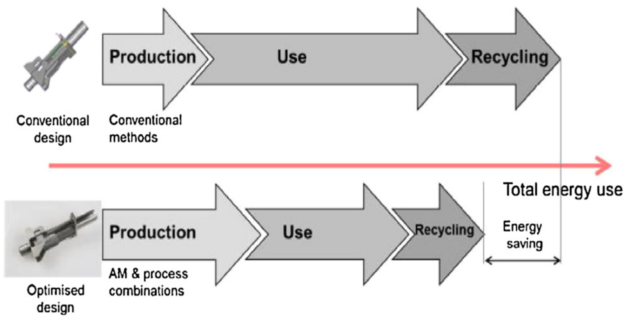

Fig. 13. Life-cycle of a product from production to the use-phase and recycling; courtesy of inspire icams.

needed besides a "printing device" (the AM machine). But still, it must be kept in mind that AM is, in most industrial cases, embedded within a process chain and fulfills just one single process step. The process steps before and after must not be neglected in the business models.

Considering all available manufacturing machines for consumers in the private sector, AM is directly linked with the internet for exchanging manufacturing data. Due to the already existing virtual networks and the still low investment requirements for home-use machines, AM technologies will gain even more interest in the private sector in the near future. CAD files and manufacturing programs can be downloaded and licensed. At the same time, spare parts and consumables are already traded via internet. Conventional industrial manufacturing has higher requirements and is thus more reluctant towards democratization of manufacturing. There are some typical scenarios of AM under Industry 4.0 that are on track for becoming reality, such as remote monitoring and state analysis of AM-machines. Furthermore, by means of AM sensors, actuators and also data storage and identifiers, as for instance RFID chips, can be embedded directly during part manufacturing. Moreover, AM can enable scenarios where orders are placed via online platforms so that the user can directly enter the scheduling plan of the different builds. Moreover, pay-per-use-concepts, bidding, and advertisement of free capacities will also be reality.

1.2.6. Comparison of laser based AM processes

Out of a large number of additive manufacturing technologies, just a few have been established for industrial applications. For the fabrication of metal components, the following three technologies have to be taken into account: LBM of metals, LMD, and EBM. At the same time, three technologies are of major significance for the generation of polymer parts. Those technologies are: SLA, FDM, and LBM of polymers. EBM and FDM are included to compare laser based technologies to established non-laser based solutions. In 0 these technologies are characterized in detail (Table 2):

1.3. Comparing the industrial and research significance of laser based AM processes

Industrial significance of a production technology is measurable by the number of systems sold and by revenue data of companies over time. The developments of both have been analyzed and compared for laser based AM industry available in the Wohlers Report 2016.

Fig. 14 illustrates the growth of worldwide annual machine sales for two virtual groups of companies, as well as the

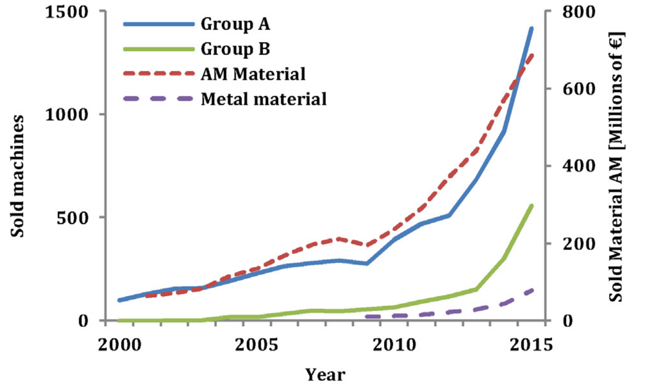

Fig. 14. Worldwide annual machine and material sales; continuous lines refer to the number of sold machines (left vertical axis) and dashed lines refer to the sold material value in Million € (right vertical axis). Group A only consists of companies manufacturing laser based AM machines and group B represents manufacturers of LBM-M and LMD machines. The red dashed line represents AM material, whereas the violet dashed line shows metal AM materials sold over time [252].

development of material sales in the AM market. Group A includes manufacturers of LBM-M/-P systems, LMD, and laser based stereolithography. Group B only consists of manufacturers of laser based metal AM systems, LBM-M and LMD. The dashed graphs indicate the revenue in € of AM and AM metal powder sales. The overall trend shows a remarkable growth of the laser based AM industry in the last five years. This leads to an increase in reliability and competitiveness of these laser based AM processes, which accounts for the enhanced presence of AM topics in the media, trade fairs, and educational programs.

Consequently, small businesses are implementing their first systems and multinational companies are beginning to use laser based AM for production of small series of complex parts. Additionally, laser based AM serves as a widespread tool for accelerated prototyping. In terms of profitability and future purchases, laser based AM machines are dominating the top ranked brand related systems shown.

To date, the majority of laser based AM machines are running at service providing companies, but multinational companies are beginning to adapt their supply chains and to start integrating laser based AM methods into their own production environments [252]. During this decade, expiring patents like [43,107,150] are going to open the market for new competitors manufacturing laser based AM machines. Nearly 50 % of the manufacturers listed in [252] have sold their first machine in the last 5 years. This will probably accelerate the production volume of machines and materials [252].

Table 2
Comparison of different AM processes (sources for mechanical properties are shown next to the specific material).

Process	LBM-M (= Laser Beam Melting of metals)			LMD (= Laser Metal Deposition)			EBM (=electron beam melting)			SLA (=stereolithography)	FDM (=fused deposition modeling)			LBM-P (= Laser Beam Melting of polymers)		
Energy source	Fiber laser			Fiber laser			Electron gun			UV laser	Heating			CO_2 laser		
resolution	Very high			Low			High			High	Medium			Medium		
Material providing mechanism	Powder bed			Powder nozzle			Powder bed			Liquid bath	Wire feed			Powder bed		
Atmosphere	Inert gas			Inert gas supplied by nozzle			Vacuum			Air	Air			Air		
Support structure requirement	Yes			No (5-axis motion)			Yes (less)			Yes	Yes			No		
Common materials	316L, 1.2709, AlSi10Mg, IN718, Ti6Al4V, Al, Ti			316L, H13, IN718, Ni-based alloys, Ti6Al4V			TiAl, Co-Cr-Mo, Fe, H13, IN718, Ti6Al–4 V			Photopolymers: epoxy resins, acrylates, elasto-mers (similar to ABS, PP)	Thermoplastics: ABS, PA, PE, PLA, PET, TPU, PLA, PVA; silicone rubber			Thermoplastics: PA, PEEK, PP, PS		
Material manufactured	In718[a] [231]	Ti-6Al–4V [237]	316L[a] [24]	In718[c] [63]	Ti-6Al–4V [47]	316L* [256]	In718[b] [190]	Ti-6Al–4V[c] [158]	CoCrMo[c] [65]	PP-like Poly1500" from Materialise, medium values	PA12[b] (Stratasys conditioned)	PEEK[c] [180]	PC[b] (Stratasys)	PA12[c] (Materialise)	PEEK [c] [16]	PS[c] (EOS PrimeCast101)
Ultim. tensile strength in MPa	1400	1250	740	828	1163	640	1108	1200	1450	31	46	74	68	48	90	6
Yield strength in MPa	1180	1125	580	473	1105	473	869	1150	510	–	32	51	–	–	–	–
Elongation to failure in %	20.4	6	49.5	28	4	36	22.1	25	3.6	20	30	7	5	20	3	0.4

All values are best values reported by material manufacturers or independent reports, if not otherwise indicated. Build direction of sample: [a]vertical, [b]horizontal, [c]no information, *average values.

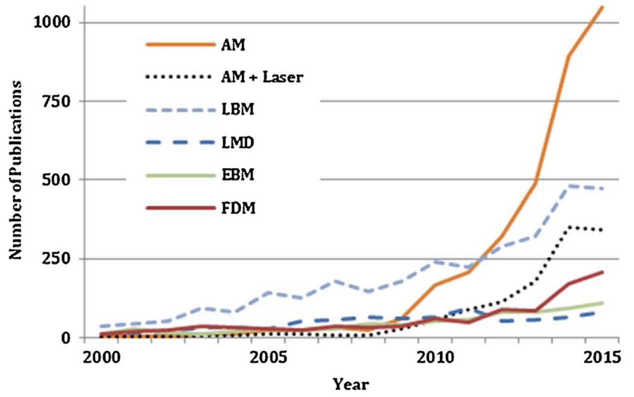

Fig. 15. Number of publications regarding a Scopus keyword research: The graph shows the keyword "Additive Manufacturing" (AM), the combination "Additive Manufacturing" and "Laser", "Laser Beam Melting" (LBM), "Laser Metal Deposition", "Electron Beam Melting" (EBM), and "Fused Deposition Modeling" (FDM). For LBM, EBM and FDM, different keyword searches were summed up: LBM: "Selective Laser Melting", "Powder Bed Fusion", "Direct Metal Laser Sintering", "Selective Laser Sintering"/LMD: "Laser Metal Deposition", "Direct Metal Deposition", "Laser Engineered Net Shaping", "Directed Energy Deposition"/EBM: "Electron Beam Melting", "Electron Beam Freeform Fabrication"/FDM: "Fused Deposition Modeling", "Fused Filament Fabrication" [77].

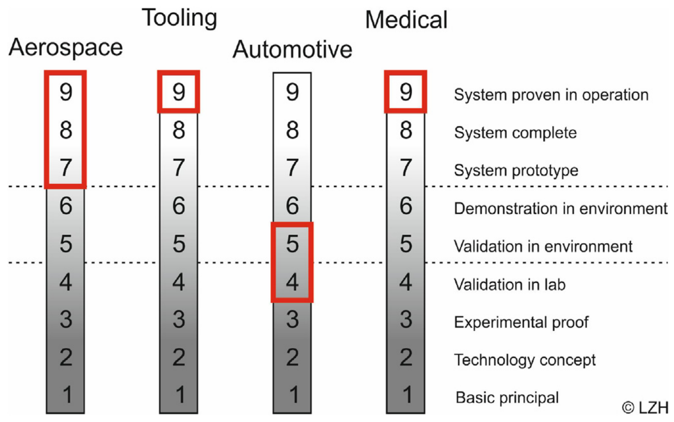

Fig. 16. TRL for AM series production, according to Refs. [131,162].

Research significance can be estimated by the number of publications and researchers or institutes concentrating on a specific topic. The research intensity in AM topics rose significantly due to the rising number of universities involved and increasing governmental interest.

During the last decade, the large investments of governments and companies in additive manufacturing have led to research initiatives and a growing number of researchers working in this field [252]. A keyword study has been conducted based on the Scopus database for a qualitative analysis of these developments. The search was restricted to articles and conference papers in the years between 2000 and 2015. Because of the disparity of utilized terms, multiple searches with different keywords were conducted. Fig. 15 illustrates the contributions of the worldwide AM research community for different keywords, which increased similar to the industrial growth during the last five years. Additionally, the graph shows that this growth is connected to the increasing number of laser based AM research topics, which are indicated by dashed lines.

Summarizing, there is a strong increase in both research and industrial interest in laser based additive manufacturing. This strongly encourages cooperative activities between industry and academia.

2. Technology readiness level and research status of Laser Beam Melting in powder bed

As shown in the last section, LBM to date is the most researched and technically one of the most promising AM processes. After the more general overview LBM will be presented now in higher detail. Knowledge on the current state of the technology from technology readiness over machine market to process research will be given.

2.1. Technology readiness level of LBM

The Technology Readiness Level (TRL) is a measurement system that enables the assessment of the maturity of a particular technology. The TRL system was originally introduced by NASA to evaluate space equipment [148].

It is also used to assess the maturity of general technical equipment. The scale ranges from TRL 1 (Basic principles observed) to TRL 9 (Actual system proven in operational environment) [162]. Regarding the field of application, AM products are reaching up to TRL 9 in most of the use cases for polymers as well as metal parts (see Fig. 16) [31,131]. In the automotive industry, this technology is only used for applications at TRL 4-5. In this area of series products, it is mainly used for prototypes. However, tooling, which is at TRL 9, is also important for the automotive industry, so the low TRL for automotive applications is related to direct automotive products. Nevertheless, an increase of LBM in automotive applications is expected and the use of LBM products in TRL 9 series production is predicted [31]. This concerns especially the weight saving potential of AM products [90], which is a key factor for manufacturing series aircraft components by AM [160,163].

2.1.1. TRL of LBM-P

LBM technology is a popular AM technology for polymers [31]. System manufacturers like EOS GmbH have been providing industrially established systems for many years so that these systems reach TRL 9. However, the products are mainly used for prototype applications supposedly up to TRL7 [67]. The use of well-established powder materials, like polyamide PA12, PA11, PA6, and PA2200, polyether ether ketone (PEEK) and polystyrene (PS), as well as variants from these materials [194], enable a production of TRL 9 in general.

Polyolefins like polyethylene (PE) and polypropylene (PP) were introduced into the LBM process several times. However, these materials are not yet industrially used. Elastomeric polyolefins like polyurethane (TPU) and thermoplastic elastomers (TPE) are commercially available but difficult to process [194]. Therefore this group can reach a maximum TRL 7.

LBM polymer parts which are, for example, used in medical applications at TRL 9 have to be improved further in order to reach equivalent TRLs in other applications like automotive or aerospace. This concerns general build strategies [48] as well as the post treatment of the parts to enhance the surface quality. Therefore coatings are applied and rough surfaces can be sandblasted or filed in order to achieve smooth surfaces which are easy to clean. Furthermore, the powder materials need improvement to allow building parts with better mechanical properties [27].

2.1.2. TRL of LBM-M

The Laser Beam Melting (LBM) process for metals was commercialized in 2002 [70]. In 2003, the first series production of LBM parts was launched for the fabrication of individual tooth implants [145]. Therefore, the technology reached TRL 9 for some medical products in a very early stage.

Now this technology is growing strongly; there was an increase of approximately 54.7% in 2014 over 2013. Several machine manufactures offer industrial LBM machines, supposedly at TRL 9, for aerospace, tooling, automotive, and medical application. As already shown in 0, a large variety of materials are commercially available for this process.

Especially the aircraft industry is promoting LBM of titanium, since a lot of weight can be saved due to a load adapted part design,

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which can only be realized by LBM. Recent advances now allow the use of LBM for series production and therefore the fabrication of TRL9 products [163].

Furthermore, special machine systems have been developed in order to process precious metals like gold and silver powder materials. They are mostly used in the small market of jewelry applications. Since jewelry products have no technical function, the TRL of LBM of precious metals can be roughly estimated between TRL 7 and TRL 9 [31,67]. Moreover, powder losses have to be considered in particular when using precious metals.

Copper and copper alloys are at an early stage of development. Some copper alloys which are suitable for the LBM process were identified, but processing of pure copper has not been demonstrated yet. Major challenges are the high reflectivity for LBM standard laser systems as well as the high thermal conduction of the material [15]. Therefore, LBM of copper reaches only up to TRL 4.

Processing magnesium and magnesium alloys by LBM is of great interest for manufacturing biodegradable implants and lightweight parts. The basic principle (TRL 1) was demonstrated early in 2009 [74,166]. In 2015, the technology could be successfully used for manufacturing a first implant series for medical tests with a machine system fulfilling industrial requirements [73], so TRL 4 was reached. In that stage, solutions for improving the process and therefore the TRL, e.g. by the use of special alloys, were given [72]. Furthermore, the manufacturing of hybrid components using different materials is still in development. Several investigations prove the feasibility at lab-scale (up to TRL 4) [142,266], but the manufacturing of hybrid components has not yet been established in an LBM production environment. Further efforts have to be undertaken, especially to handle different powder materials in one process chamber, in order to improve the TRL.

2.1.3. Challenges for implementation in manufacturing environments

The challenges for the implementation of LBM in a manufacturing environment can be divided into three sections: costs, personnel, and the LBM technology. The key to a successful industrial use of LBM lies in a comprehensive and realistic cost justification. When LBM or other AM technologies are implemented in a production environment, the advantages of LBM have to be used to manufacture the products. This concerns the design as well as the possibility for customization. Business cases where traditional manufacturing processes without any changes in product design are simply replaced by LBM will probably fail [31].

The successful application of LBM is connected to supervised personnel who know about the advantages and restrictions of LBM. Engineers and technicians have to be trained towards designing parts which are best suited for LBM [2] and a safe operation of LBM machines [67].

Other points to consider are post processes and monitoring of the processes used in the manufacturing environment to maintain a high and reliable quality. Process monitoring is a big issue concerning quality assurance in industrial manufacturing. Some manufacturers already provide machines with monitoring systems, e.g. based on melt pool monitoring (Concept Laser) or powder bed monitoring (EOS, SLM Solutions) [31]. However, there is no full process control available yet, due to the reasons already shown in Section 1.2.4.

Depending on the manufacturing procedure, most parts require post-processing to remove support material, which has to be evaluated for industrial use. To achieve certain properties, further treatments can follow, e.g. to reduce internal stresses (tempering) or to scale down surface roughness (shot peening, machining, electro-polishing) [31,67].

The LBM machine systems are stand-alone full-working systems. However, further efforts regarding organization, infrastructure like powder storages, and ventilation systems, as well as process and occupational safety are necessary for an implementation in an industrial environment. The whole manufacturing environment has to fulfill the national laws on industrial and employee safety as well as laws on the protection of the environment [67,152].

The LBM process itself is very complex and several parameters have to be considered to set up the process, as already shown in Fig. 8. Therefore, the development of a database, which includes quality aspects as well as mechanical properties for specific LBM materials, is difficult since AM in general is not adequately understood nor characterized. Especially the aerospace industry needs definitions for qualification requirements, technologies to detect defects, and methods for verifying key process parameters [234]. Hence, standardization is strongly necessary also for other industrial sectors [152].

2.1.4. Standardization activities

Using Laser Beam Melting in industry requires standardized specifications and regulations to communicate on a given standard about parts and methods [234] and to be able to rely on the output quality. Therefore, efforts have been made by different associations to provide generally applicable standards.

The American Society for Testing and Materials (ASTM International) formed the ASTM F-42 committee to standardize additive manufacturing terminology in 2009. The first standard, focusing on the terminology regarding AM, was ASTM F2792-10 [8,88,234]. By February 2015, 13 industry standards on additive manufacturing were published, where two of them have been developed together with ISO TC 261 (ISO: International Organization for Standardization). The aim of the F42 committee, which currently has more than 300 voluntary participants in 22 countries working on 20 items, is to develop congruent standards on terminology, specifications, or reporting data to support the introduction of AM to different industrial sectors [31].

The ISO TC 261, which currently has 19 participating and four observing organizations, has been working since 2011 on standardization of additive manufacturing processes, hardware, and software process chains, quality parameters, vocabularies, and more. The focus of those standards is placed on the recognition of market needs and responsible reactions to industrial changes [31]. ISO 17296-2, published in January 2015, becomes DIN EN ISO 17296-2 in 2016 [98].

Another example is the Verein Deutscher Ingenieure (VDI; Association of German Engineers) that published a guideline with recommendations for additive manufacturing processes and rapid manufacturing containing basics, definitions, and processes in December 2014. In June 2015, a material data sheet about Laser Beam Melting of the aluminum alloy AlSi10Mg was added. The latest VDI guideline was published in December 2015 [194,242]. Parts of VDI 3405 were at the basis of the development of ISO/ASTM DIS 52792 and ISO 17296-2 [251].

Despite those efforts to standardize additive manufacturing, further standards have to be developed, e.g. concerning the processing of aerospace alloys under similar environmental conditions as when using conventional manufacturing methods [234] or to receive standardized methods for measuring and verifying additive manufactured medical models [189].

2.1.5. Overview of commercially available LBM systems

This chapter gives a short overview of providers of Laser Beam Melting system technologies. EOS for example, a German company founded in 1989, manufactures equipment for AM of metals and polymers. EOS has trademarked the terminology for its metal AM-process as Direct Metal Laser Sintering [88]. EOS sells a number of machines for metal powder materials and polymer powder materials. Additionally, EOS and Cooksongold developed PRECIOUS M 080. First presented in 2014, this machine is used for the jewelry and watch industry, thus it processes precious metals as for example gold, silver, platinum, or alloys from precious metals. Moreover, EOS includes new digital scanning, better global thermal control using spot pyrometers, laser power monitoring, and improved powder supply management [25]. Continuous thermal control and laser power adaption (EOSAME) are recent features, which are included in the EOS P 396 models for homogeneous part properties independent from the sample position.

ReaLizer GmbH (Germany), now part of DMG Mori Seiki, introduced its first selective laser melting system for steel in 1999. Today, five different systems are commercially available: SLM 50, SLM 100, SLM 125, SLM 250, and SLM 300. The LBM systems from Realizer enable high-resolution parts, thin layers, and small features, and are therefore often used for dental and jewelry applications [31].

Powder bed and laser-based manufacturing machines are also developed by SLM Solutions GmbH, another German machine provider. The Laser Beam Melting process at SLM Solutions is called selective laser melting (SLM®). In general, SLM sells open systems, so customers can use their own powders or develop their own parameters for special applications [88]. SLM Solutions offers systems with different construction volumes according to customers' needs. To stay competitive, EOS and SLM Solutions extended their patent license agreement by a further cross-license agreement on their current patents concerning Laser Beam Melting and sintering of metals [187].

Concept Laser GmbH, which is also from Germany and which was recently taken over by General Electric, is also developing machines for LBM-M, which is named laser cusing by Concept Laser [88]. The company sells different machines with different construction volumes depending on the dimensions of the manufactured parts. Within the portfolio of Concept Laser are also certain tools which can be adapted to their machines in order to assure a certain part quality. With tools like QM Meltpool 3D or QM Coating it is possible to monitor the melt pool and the powder layer deposition process.

In the early 2000s, Trumpf already had some LBM machines on the market but had to withdraw those due to low demand at this early stage. However, in 2014 SISMA S.p.A. (Italy) and Trumpf GmbH & CO. KG (Germany) agreed on a joint venture for 3D printing to share their know-how, personnel, and capital. The aim was to develop laser metal 3D printing machines for industrial series manufacturing [161]. In 2015, the portfolio was extended by plug and play solutions for Laser Beam Melting in powder bed. The process is called laser metal fusion (LMF). A smaller machine, TruPrint 1000, was presented at the Formnext fair in 2015, while two larger systems, TruPrint 3000 and TruPrint 5000, have been presented at the Formnext fair in autumn 2016.

Besides the German machine providers, Renishaw from the UK and 3D Systems are global players in selling LBM system technology. In 2016, Renishaw announced a new machine system for AM series production offering a high degree of automation. 3D Systems has offered metal powder bed fusion technology since 2013, after taking over Phenix Systems from France [31].

The Dutch company Additive Industries B.V. commercialized a metal AM system (MetalFab1) in 2015 that offers automatic handling of the workpieces for building and heat treatment. The aim is to optimize metal powder bed fusion to bring it from "lab to fab" by automating processes and by using modular systems such as an integrated heat treatment unit. The result is increased productivity, flexibility, and reproducibility [173, 232]. Additive Industries also focuses on a shared AM facility (AddLab) with selected lab partners to do joint research on metal AM [31].

With the expiration of several key patents in 2014, e.g. the patent US5597589 describing the technology of Laser Sintering filed by Deckard in the early 1990s, the companies Ricoh (Japan) and Prodways (French) joined as LBM-P machine designers. Additionally, start-ups like Sinterit (Poland), Sharebot (Italy), and Sintratec (Switzerland) are trying to introduce low-price LBM-P systems in the market. Even open-source projects were initiated as, for example, "OpenSLS" started by a research team of the Rice University (USA). Additionally, using the Formnext fair 2016 as an example, Matsuura (Japan), AddUp (France), or OR Laser (Germany) can be named as upcoming companies in the AM market.

2.2. Research status of LBM

2.2.1. Fields of research

Recent and future trends for system technology research are forced by driving questions of the industrialization of these technologies. An increasing output of parts and at the same time process stability for higher part quality moves into the focus of research and development. By the introduction of laser sources with output power up to 1 kW it was possible to increase the build rate by a factor of 4 for the production of AlSi10Mg parts reaching part densities above 99.5% [29]. As a consequence of increasing the laser power, a careful choice of optical element material is obligatory. In a state of the art LBM machine, a time dependent focus shift at a constant output power of 200 W could be traced back to the material of the optical components. The beam caustic could be stabilized by a change from BK7 to fused silica glass [127], as shown in Fig. 17.

To expand the range of usable materials and at the same time decrease process induced defects like thermal cracks and residual stress, pre-heating of the substrate plate and thereby the surrounding powder material is required. Hence, an experimental set-up has been developed that is capable of realizing pre-heating temperatures above 1200 °C by inductive heating. This enabled processing Ni-based super alloys as well as ceramics [83]. To meet the requirements on product quality regarding porosity and surface roughness, experiments at KU Leuven were carried out which combined LBM and selective laser erosion (SLE). By operating the applied laser in a Q-switched pulsed mode, an improvement of the parts' surface was realized [261]. At the same time, the beam source could be used for re-melting each layer, improving the final part density [120].

Additive manufacturing (AM) provides parts that are, compared to conventional manufacturing, cost intensive. However, the design freedom and the aptitude for specific applications are delivering significant advantages compared to subtractive manufacturing.

Steels with higher carbon content and super alloys are challenging to process because the process specific high cooling rates result in thermally induced crack formation. The high temperature dynamic enables the processing of components of Fe-base metallic glass [174]. To deal with process induced residual stresses, an approach that uses a subsequent local laser *heat treatment results in a reduction of residual tensile stress at* part surfaces of up to 70%. The amplitude of the reduction is dependent on the applied line energy [205].

From the experience of other powder based manufacturing technologies, it is known that one key factor for successful processing is the selection of the appropriate material. As there is just a small range of powders qualified for AM processes, characterization methods and standards need to be established in order to guarantee constant powder quality. Hence, experiments of flowability characterization on more than twenty Fe- and Ni-based powders have been carried out and a useful methodology has been identified which was proposed for standardization in

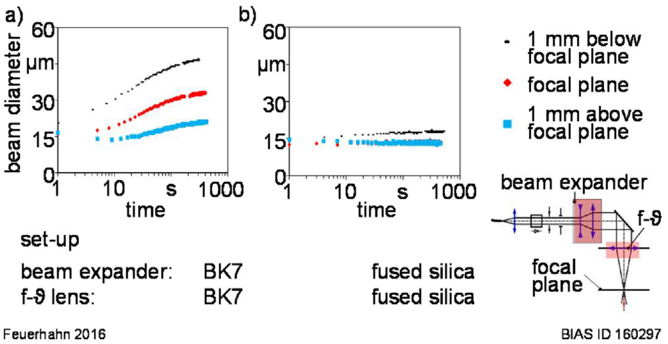

Fig. 17. Time dependent change of the beam diameter in static measuring planes characterized using different lens material: a) BK7, b) fused silica [233].

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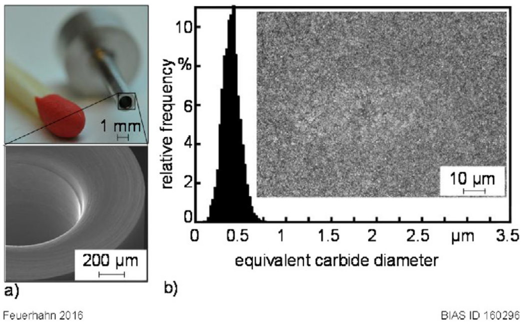

Fig. 18. a) Micro blanking and deep drawing tool with cutting edge and drawing radius, b) Carbide precipitation after hardening and three time tempering at high temperatures of secondary hardening tool steel X110CrMoVAl 8-2-1 processed by LBM-M.

ASTM or ISO [216]. Material selection and process settings have an influence on the resulting part properties. Besides these, the part position and orientation also has an influence on the dimensional and geometrical accuracy and surface quality, as it was derived from experimental investigations on the influence of [117].

In various fields, LBM parts show benefits due to specific process characteristics. An often used benefit is the integration of additional functions, e.g. a sheet molding compound with surface compliant heating channels for the production of appropriate fiber reinforced plastic aircraft components [60] or a simple forging die with conformal cooling channels [94]. Design freedom and lightweight construction united in LBM are strong benefits for many aircraft and space applications, e.g. a generated micro pump operating in a two-phase cooling loop for small satellite applications [250].

Another field is micro production where another benefit of AM can be utilized. Because of the short interaction time between laser and powder, there is just a small melt pool in the range of 100 µm in diameter and a very fine grained microstructure is realized. This was successfully quantified and utilized by manufacturing micro forming tools of high hardness tool steel [61] with very fine carbide precipitation [198], as shown in Fig. 18.

The major general challenges of LBM are limitations in dimensional accuracy and entrapment of powder in cellular structures. However, these research challenges will not prevent further spreading of applications [209].

2.2.2. Key topics of research

From the previous sections three key topics of research, namely process monitoring, simulation and new material development, can be extracted, which are discussed separately in the following.

2.2.2.1. Process monitoring. The parameters influencing the part quality are manifold and the impact of changing process parameters and their correlation with process defects are not fully understood. Hence, in the course of the ongoing and upcoming industrialization of AM technologies, process monitoring becomes more and more important and needs to be further developed. On one hand, this is motivated by a desire to deepen the understanding of the process and on the other hand to achieve higher process stability. Most monitoring systems are based on thermal detection, thus several approaches have been investigated. A two-color pyrometer and a CCD-camera, which are coaxially mounted in a LBM set-up with a high temporal resolution of 50 µs, were investigated [264]. In order to study the melt pool behavior, a high speed near-infrared CMOS camera and a large area silicon photodiode sensor have been applied for real-time process monitoring and have achieved data processing rates up to 10 kHz [38]. Successful integration of a thermal imaging system for the determination of the temperature distribution in the powder bed and the melt temperature and homogeneity analysis of the surface temperature has been performed [246]. Process observation with an IR-camera and evaluation regarding process errors originating from insufficient heat dissipation have been investigated as well as the limits for detecting pores and other irregularities by observation of the temperature distribution [118]. The introduction of ratio pyrometric evaluation to laser materials processing [113] could be applied to LBM to determine the peak temperature as well as the size of a heat input [165].

2.2.2.2. Simulation. Various approaches for different cases of LBM process simulation have been investigated. For the simulation of the selective electron beam melting process, a non-linear thermomechanical model that takes into account large temperature changes, phase changes, and temperature dependent parameters has been investigated [183]. Also a numerical simulation of the EBM process has been performed. Within this, physical phenomena involved in the process, such as thermal conduction, melting, solidification and the fluid dynamics of the melt, were taken into account [192]. Methods for heat input modelling were discussed in terms of their suitability for the application in build-up process simulation [200].

To estimate the shape distortion behavior after the detachment of parts from the supports and the substrate a heat input reduction model was utilized. The numerical simulation was evaluated by experiments with a maximum deviation of 26% to the experimentally obtained values [172].

For modeling and simulation of selective laser sintering a discrete element model was employed, in which the powder particles were represented by individual spheres of varying sizes. For the process simulation, a laser passed over the particle layer in a zig-zag pattern while the laser intensity was assumed to be uniform and the penetration as a function of depth was modeled via the Beer–Lambert Law [186].

Currently, a very advanced CFD model has been developed to simulate the thermodynamics of LBM [108,110]. The model shows good agreement with high-speed camera measurements. Moreover, the so called CALculation of PHAse Diagrams (CALPHAD) method has proved to be applicable for the simulation of LBM [212]. By the use of this method the thermodynamic properties can be predicted for multi component systems, which allows the simulation of the microstructural properties [211].

2.2.2.3. New material development. The challenging requirements of industrial applications demand the development of new alloys which combine the material specifications to ensure light weight and high strength properties. Scalmalloy® is an aluminum based alloy developed for aerospace applications combining these properties. At the same time, the alloy is adjusted to LBM processes [171]. Early investigations on processing zirconia-alumina ceramic parts by LBM showed promising results. Implementation of a high temperature preheating system using a CO_2 laser in an experimental LBM set-up was necessary to avoid thermal crack formation and to realize processing of various layers. The ceramic part is created and formed by solidification from melt [248]. Biomedical applications have a high demand for shape memory alloys like nickel titanium (NiTi). In order to achieve the desired phase transformation criteria for functional components, a precise control of the process parameters and atmosphere is required [214].

Materials with high hardness, like hard metals or metal matrix composites, are of high great interest to be manufactured additively. This is due to the high costs associated with subtractive processes. Investigations of processing tungsten carbide by LBM have been performed by various researchers. The initial powder particle density strongly influences the resulting part porosity as described for tungsten carbide with a cobalt matrix [75]. In a process chain, tungsten carbide cobalt tool inserts were produced by LBM and subsequently joined to tool steel injection mold forms to reduce wear at the injection spot position. The benefit of wear resistance has been proven by a hot sand blasting test at high temperature [114]. Recent investigations on hard metal processing have been performed with agglomerated and pre-sintered tungsten carbide-cobalt achieving no higher densities as investigated before even though a higher line energy was applied [233].

3. Current capability of LBM-P and key phenomena

Now the focus again is set narrower in LBM-P. The state of the art in knowledge on the process itself as well as influencing factors is given and the key phenomena currently hindering an easy application in industry are discussed.

3.1. Material specifications and part properties

Laser melting of polymers normally involves thermoplastic polymers. When heated up, all those thermoplastic materials will change from a hard (solid and glassy) structure to a softer (tough leathery or rubbery, solid or non-pourable) structure and finally turn into a viscous flowing melt [124]. A clear distinction should be made between (semi-)crystalline and amorphous thermoplastics, which differ in the way and the temperatures at which those transitions occur. Semi-crystalline polymers have a glass transition temperature that is below or around room temperature and a distinct melting temperature that is above 100 °C at which a significant volume change happens. Amorphous polymers do not have a clear melting temperature range. They have a glass transition temperature that lies around 100 °C and above which the material will gradually evolve to a leathery, rubbery, and finally liquid state as the temperature increases, without clear transitions [124].

The semi-crystalline polymers mostly used with LBM-P are polyamides (nylon) like PA6 [176] and PA11 [25] and especially PA12 [34,50,54,175] as a single material or blended or reinforced with other materials or nanoparticles [78,116,245]. Some reports have focused on polyethylene (PE) [77,185], polyoxymethylene (POM) [124,184], polypropylene (PP) [270], polycaprolactone (PCL) [92,263], the high-temperature polyaryletherketones PEEK [16,197], and on elastomeric types (e.g. TPE) [42].

Typical amorphous polymers used are polystyrene (PS) [126,265], polycarbonate (PC) [17,58], and polymethylmethacrylate (PMMA) [124,240]. In Table 3 a selection of powder materials and associated properties are listed.

Table 3
Selection of materials mostly used for LBM-P.

Material	Suppliers	Tensile Modulus (MPa)	Tensile Strength (MPa)	Elong. at break (%)
PA6	Rhodia			
PA11	EOS, Advanced Laser Materials, Exceltec, Arkema	1350–1600	37–48	3–45
PA12	EOS, 3DSystems, CRP Technology, Advanced Laser Materials, Exceltec, Arkema, 3D Systems	1550–1700	36–50	4–24
PA compounds	EOS, 3DSystems, Advanced Laser Materials, Exceltec, 3D Systems	2200–6100	25–72	1.3–12
HD-PE	Diamond Plastics	2000	21	5.5
PEEK	EOS	4250	90	2.8
PeKK	Oxford Performance Materials	3940	83	2.5
PP	Diamond Plastics, Microfol Compounding GmbH & Co. KG	1750–2500	22–25	2.5–10
TPE	Advanced Laser Materials, EOS, 3D Systems	7.4–80	1.8–8	70–200
TPU	Materialise		27	400
PS	EOS, 3D Systems	1600	2.84–5.5	0.4

3.2. System technology

Typical industrial machines differ in the size of the build chamber (50 l–220 l), the number of lasers and scan heads, the recoating mechanism (roller or blade devices), and the maximum processing temperature. Most commercial machines have a maximum processing temperature of around 200 °C which eliminates high temperature polymers such as PEEK. A machine with a maximum temperature of 385 °C – the EOSINT P 800 – is available from EOS.

The laser sources themselves have not changed significantly since the 1990s. Polymers only show good absorption behavior in the far infrared and ultraviolet regimes, hence, CO_2 laser sources are still dominant. Some research has been conducted into fiber lasers, but this is only possible if the feedstock material has special additives (e.g. carbon black) that can absorb the laser energy [25].

Key differences between the commercial machine systems are their software interfaces and the options for different process parameter sets. Parameters are often restricted to certain sets provided by the machine manufacturer and thus cannot be chosen freely by users. This is an issue, especially for researchers. Potentially, custom-made machines have considerably more freedom although maintaining consistency, particularly with regard to the heating distribution and control, which has been the main issue experienced [79].

Process control and optimization are still a challenge for current research and technology development. To date there is no active feedback system capable of monitoring the part surface topography and adjusting build parameters accordingly. However, as shown in Section 2.1.5, system improvements allow homogeneous part properties independent from the sample position.

3.3. Benchmark studies

In a benchmark study, the mechanical and geometrical properties of samples built out of various polymers using different kinds of layer manufacturing processes have been compared [109]. The processes included stereolithography (SLA), fused deposition modelling (FDM), Poly-jet, LBM-P, three-dimensional printing (3DP), and Laminated Object Manufacturing (LOM). It was verified that the SLA process is advantageous in hardness, accuracy, and surface roughness of the parts, and the Poly-jet process provides advantages in tensile strength at room temperature. The LBM-P process was advantageous in compressive strength and manufacturing speed, the 3DP process in speed and material costs, and the LOM process in heat resistance.

In 2013 a VDI inter-laboratory benchmark study was conducted to compare the mechanical properties of PA12 tensile test samples delivered by seven participants. The results of these studies were compiled in the VDI standard 3405 part 1 [241]. The geometry of the test specimens complies with the DIN EN ISO 3167 standard. They were tested in accordance with DIN EN ISO 527 [242]. One main result was the continuous discrepancy of the mechanical properties of tensile testing samples built with different orientations inside the build chamber.

This was also confirmed by a round robin study conducted in 2015 by a collaborative effort inside CIRP. The study included methods for microstructural, geometrical, and mechanical characterization of plastic samples. Six participants delivered samples built out of PA12 with different orientations that were analyzed by e.g. mechanical tensile testing (DIN EN ISO 3167, Typ A), tactile geometric measurements with a coordinate measuring machine (CMM) and X-ray computed tomography. As a result, the deviations between the mechanical properties of parts built with different build orientations were traced back to distinctive microstructural sample characteristics and parameter features [155,219].

3.4. Mechanical and geometrical characteristics

Generally, the layerwise process leads to part properties depending on build direction. Parts are usually weaker along the build direction (z) which expresses itself in lower tensile strength and a shorter elongation at break with a larger scatter compared to specimens built in the x–y-plane [25,71,188]. According to Ref.

[242], the tensile strength of parts built out of PA12 varies between 25 MPa and 50 MPa along z and between 40 MPa and 50 MPa along a direction in the x–y-plane. The respective elongation at break varies between 2 % and 15 % along z and between 7 % and 20 % in the x-y-plane. However, the latter values are still about one order of magnitude lower than values which are achieved by injection molding, where tensile strengths are in the same range [132]. This can be attributed to microstructural differences between laser-sintered and molded samples which will be discussed in Section 3.6

Geometrical characteristics and part accuracy can also vary strongly depending on the calibration of the AM machine, particle size distribution, and laser beam parameters for contour definition and cooling and post processing. System users observe that the accuracy of a part depends on its position and orientation in the building chamber and on the geometry itself, which limits the achievable tolerance [89,156]. Investigations based on round robin data showed that the conformity with the general dimensional tolerance indication "medium" according to DIN ISO 2768-1 can be reached with LBM-P using PA12 within a single build process, however, the rating "coarse" was achieved by most participants [219].

3.5. Process phenomena and limitations

The main process limitations are given by material and machine system specifications. The maximum overall part size is given by the dimensions of the building chamber. The particle size distribution and the beam spot diameter determine the minimal structure sizes (e.g. wall thicknesses) achievable. The build accuracy and the conformity with geometrical tolerances are also defined by particle and spot sizes, but also by pre-heating temperature variations and cooling procedure which both affect the crystallization shrinkage. The type of polymer sets the upper limit of the mechanical properties and defines the process temperature range needed. If the temperature of the powder as it is spread over the build area is too low, instant crystallization and thus curling in the previously scanned layer can occur [230]. Usually, the process temperature is set 3 K–4 K below the melt temperature for semi-crystalline polymers [25].

The rheology of the powder in the melt state is a limiting factor which requires a trade-off. On the one hand, the melt viscosity should be low enough to allow complete consolidation within the time scale of the process. On the other hand, it should also be high enough to prevent the molten material from sinking into the supporting powder bed. Too low viscosities result in high shrinkage, poor part accuracy, and surface quality (orange peel) [124,195]. Since viscosity correlates with the molecular weight level (MW) [124], the kind of powder material, production parameters, as well as aging confine the processability and the ideal process parameters. Pure polymers with melt viscosities in the range of a few tens to a few thousands poise (e.g. nylon and waxes) can be processed successfully and reach near full density [14].

Another general limitation is given by the layerwise generation of parts which leads unavoidably to anisotropic part properties. Especially the mechanical properties depend on the part orientation inside the building chamber which can limit the freedom of design for system users creating real functional devices. Another design limitation results from the general principle of a powder bed-based procedure. Hence, closed cavities as well as very small and too overly long channel-like structures at the same time are not possible because then loose powder cannot be removed from the part after processing.

For LBM-P the unfused powder surrounding a part serves as a fixture, no additional supports are usually needed. However, the unfused polymer powder degrades slightly each time it is exposed to elevated temperatures in the build chamber. Thus, unsintered powder can only be used a finite number of times and users must continually refresh the powder supply with new material.

The quality of the resulting part depends on a broad range of parameters which are largely determined by powder material and machine specifications.

Important powder material specifications are the optical, thermal, and rheological properties, which all are defined by the material base and powder condition (age, temperature, humidity, particle shape, particle size distribution, etc.). Typical machine based process parameters include powder bed temperature, feed bed temperature, powder layer thickness, recoater speed, laser beam energy, scan speed, scan spacing, number of scans, time between layers, build size, and heating/cooling rates [25,49,71,144,156]. The resulting mechanical behavior is nominally a function of the accumulated laser energy density, part bed temperature, and part orientation [34].

3.6. Key phenomena

This Section describes interdependencies between process physics and resulting properties that have to be addressed to obtain repeatable good results.

3.6.1. Temperature in the powder bed and the work piece

Since LBM-P clearly implies low cooling rates for the melted materials, high crystallinity of the resulting parts can be expected for samples built by LBM-P [79]. An increase in the crystallinity leads to an increase in tensile strength and stiffness, but at the detriment of the ductility, as they are the amorphous regions of a polymer that provide its ability to yield without breaking [115,147]. Consequently, the high amount of crystallization is a key phenomenon in LBM-P which is related to the process conditions as well as the type of powder material. The respective melting and crystallization temperatures of the powders determine the process window [6] and thus the general applicability and the sensitivity regarding inhomogeneous process temperature. It is known that inhomogeneous lateral temperature fields with variations of up to 10 K can yield mechanical and geometrical deviations depending on the sample position [77,247]. Moreover, part properties are also related to the temperature profile along the build direction in the powder bed which is determined by the machine design and the chosen temperature for the reverse powder bed heating. Typically, temperature values are settled near 130 °C. Hence, part temperature decreases in the powder bed until it is below the crystallization temperature, leading to a gradual crystallization and shrinkage during the build process [51]. High cooling rates combined with pronounced temperature gradients result in distortion and thus uneven part properties [201].

3.6.2. Porosity

Porosity is another key phenomenon of LBM-P. Resulting part properties, especially elongation at break [25,80], are significantly affected by pores. Because LBM-P is based on powder that is deposited and coalesced in layers, anisotropic pore formation occurs and leads to anisotropic behavior, where the ductility normal to the powder layer is worse than the in-plane directions. This is reasoned in the fact that pores tend to be aligned in the plane of the powder layers, which can facilitate brittle fracture upon perpendicular tensile load. Then, crack propagation is more directional in the plane and the critical crack size is reached more easily [219]. It has been demonstrated that elongation at break increases with decreasing porosity for tensile parts built out of PA12 in the x–y-plane [54]. However, for tensile parts oriented along the build direction, other groups showed that pore concentration (count of pores per volume) seems to be a stronger indicator than just the general amount of porosity (volume fraction of pores) [219]. Obviously, higher pore concentrations with smaller pores result in more interlayer connection failures than lower pore concentrations with larger pores at the same amount of porosity. Interlayer connection failures then lead to brittle mechanical behavior with a lower tensile strength.

The porosity morphology is initially determined by the powder layer bulk density. Here, an adequate flowability is crucial for the preparation of smooth layers with high bulk density when displaced by the recoating mechanism in order to ensure the lowest possible porosity upon Laser Beam Melting [25]. Moreover, the energy input affecting the coalescence process has a strong impact. If the laser beam area energy density is too low (<1.5 J/cm^2), high porosity values of over 5% can be observed when using PA12 powder [54]. Moreover, it has been shown that a direct relation between process temperature and pore density exists, whereas a high process temperature close to the melting temperature of PA12 seems to promote the coalescence process leading to fewer pores and better mechanical properties. This is valid for laser beam area energy densities exceeding 2 J/cm^2 [219].

3.6.3. Non-molten particles

Another feature which is unique to LBM-P processes are residual non-molten particle arrangements, which also affect the resulting mechanical part properties. The presence of particles with a higher crystallinity than the surrounding crystal structure leads to a composite-like structure where the intercrystal shape and interspherulite interfaces strongly affect the macro mechanics [267]. Strong intercrystal shapes may lead to positive effects (higher tensile strength. However, weak interfaces lead to rupture of the core from the matrix under relatively low stress resulting in rapid crack formation and propagation, and thus inferior mechanical properties such as low elongation at break (brittleness). Both trends were often observed during tensile testing studies [132,270].

Due to the layer-by-layer LBM-P process, residual non-molten particles are often arranged in the build plane. Pronounced coplanar arrangements contribute to weak mechanical properties with low elongation at break values, especially along the building direction [132,219]. Such formations represent a weak interlayer connection and might come along with enhanced porosity. However, since this is also valid for relatively low porosity values between 3 % and 4 %, coplanar residual non-molten particles seem to be the main reason for very brittle fracture modes with elongations at break below 10% [219].

Residual non-molten particles are the result of incomplete melting due to process deficiencies. Several key factors contribute to a complete melting and a successful coalescence. First, good absorption behavior allows the particle to reach a fully melted state without the temperature of the surrounding powder becoming hot enough for thermal degradation to occur, as discussed in Refs. [218,101]. Second, low layer thicknesses are advantageous since powder is a thermal insulator and thus prevents the laser energy from penetrating to the prior layer. Third, a high powder bed temperature close to the melting temperature improves the formation of the melt pool that penetrates the previous layer. Finally, an adequate laser energy input is essential for a high degree of melt during the LBM-P process [132]. It was revealed that only if all of these factors are considered, parts without residual non-molten particles can be realized. This was achieved by the combination of a small layer thickness of 100 μm, a powder bed temperature of 176 °C, and a laser beam energy of nearly 2 J/cm^2, resulting in parts with remarkable ductility with an elongation at break of around 20% along the building direction and over 30 % in the xy-plane [219].

3.6.4. Surface roughness

Another key feature of LBM-P built parts that varies from IM is the distinct surface roughness which is inherent to the process itself. The layer-by-layer process using powder as a building material induces at least two kinds of surface defects: steps due to the successive addition of layers (except when the surface is perfectly flat), also known as “staircase effect”, and a roughness in the dimension of the powder particles. The latter is due to particles that are either stuck to the softened surface illuminated by the laser or partially molten particles that did not get enough energy to be melted completely [243].

Generally, surface roughness is influenced by the particle size distribution, process parameters (especially laser beam energy at part contour), as well as the post processing technique [9]. Due to the layer-by-layer approach, the roughness also depends on the surface orientation which determines the appearance of the staircase effect [9,45]. It can be shown that inclination angles between 5° and 30° are more prone to poor surface quality [103]. Moreover, in Ref. [68] it is stated that a reduced layer thickness reduces also the staircase effect and therefore the surface roughness.

Measured surface roughness values depend on the measurement technique used [243]. Typical R_a and R_z values are in ranges between 6 μm to 15 μm and 40 μm to 75 μm respectively [179,232,243]. Optical measuring systems for areal measurements are able to deliver S_a values (DIN EN ISO 25178-2 and -3.) in the range of 10 μm–50 μm [81,219].

A direct relation between surface roughness values and mechanical properties of polymeric laser sintered samples has not been found so far. Methods dependent on surface analysis are of limited use as indicators of the mechanical properties [170]. However, it is also known that fractures start mainly in the notches of the coarse surface and thus surface roughness contributes to poor elongation at break [184]. Hence avoiding surface defects is essential for enhanced mechanical properties of laser-sintered samples.

4. Current capability of LBM-M and key phenomena

This chapter is the counterpart to Chapter 3 and sets the focus on LBM-M.

4.1. Material specifications and part properties

Physical and chemical metal powder characterization is a fundamental prerequisite for a reproducible and reliable LBM-M process. The measurands are size- and shape-distribution, morphology, density, absorption, chemical composition, humidity, flowability, and oxidation [210]. They confine the energy input [108] and even deposition of powder bed layers [210]. To reduce the shrinkage phenomena and cavities, a high bulk density of the metal powder is desirable [18,206]. The temperature dependent absorptivity of metal powders increases with shorter wavelengths and higher temperatures [18].

The particle size distribution influences the penetration depth of the laser-beam [62], which is multiply reflected and absorbed inside cavities in the case of higher layer thicknesses [110]. A wide particle size distribution including smaller particle sizes needs less laser energy to melt [24], provides a higher powder bed density, and reduces the surface roughness [143]. A narrow size distribution favors a homogeneous melting behavior and flowability [157]. Shape, morphology, and humidity affect the flowability because of possible agglomerations, friction, and van der Waals forces acting on the powder [157]. Oxides can increase absorption and are related to defects in built parts by serving as pore nucleation sites. Therefore, dry powder storage and drying procedures under shielding gas condition before the melting process are necessary. Knowledge of the chemical composition of the metal powder and the produced parts is essential for the process development since high process temperatures may cause vaporization of alloy constituents. Atomized metal powders may be contaminated and different batches may show variable chemical compositions. If the recycled powder is kept dry or inert gas protected and if the sieving procedure is done appropriate, the material can be reused several times without notable effects [7].

4.2. System technology

The LBM process uses a high intensity laser beam to selectively melt micro-sized metal powder in a layer-by-layer fabrication methodology to achieve fully dense 3-dimensional structures [207]. Although this fundamental process is identical for all LBM machine systems, there are differences between the design and operating methodologies for different machine systems. Variations can be found in the build dimensions, laser specifications, recoating mechanisms, optical design, and inert gas circulation. In addition to the inherent system technology variation, the fabrication process is also highly user dependent. The data preparation process involves the determination of part orientation, part position, and the design of a support structure. In addition to the system technology and user experience, process understanding plays a crucial role in the successful implementation of the technology [242]. A key demand from industrial users of LBM has been the development of new materials for specific applications [4].

Process parameters contribute to the relative density and surface topography of the fabricated structure [258]. The effect of user induced variations, such as surface re-melting in the LBM process, have also been investigated by various researchers [235]. It was found that although the re-melting of the top layer did improve the surface finish, it also altered the chemical composition and the oxide layer of the surface [235]. It was observed that in the case of Ti–6Al–4V, this led to a possible reduction in corrosion resistance and biocompatibility of the components. It has been observed that for materials such as M2 HSS, a lowering of the thermal gradient helps in the reduction of thermal stresses and the cracking observed in the structures [105]. For aluminum components, the influence of pre-heating on the distortion of components fabricated using LBM has also been reported [28]. Powder bed pre-heating is also reported to have a positive effect on the processability of magnesium using LBM [191]. Positive effects of pre-heating have also been observed for processing ceramics such as alumina and yttria-stabilized zirconia using LBM [44,140]. In addition to pre-heating, support structures also play an essential role in preventing part deformation and structural failures due to heat induced stresses, as illustrated in Fig. 19.

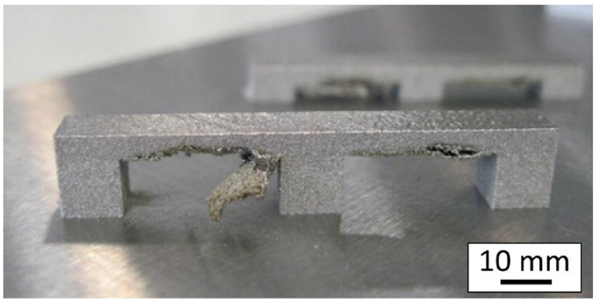

Fig. 19. Failure due to insufficient support at the overhang geometry; regarding [268] (scale bar added to allow rough estimation).

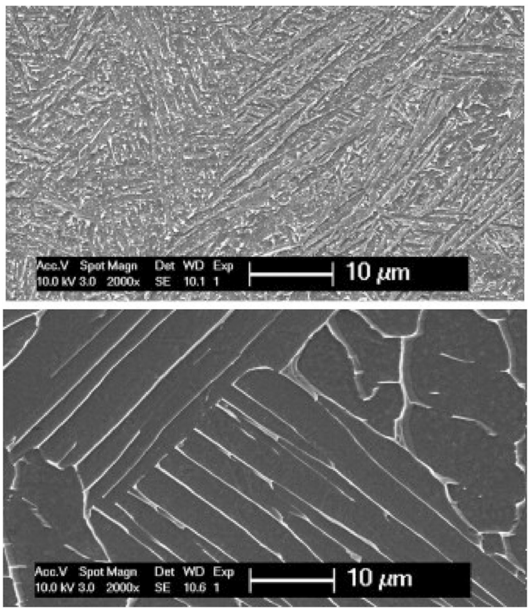

Fig. 20. Microstructure variations in Ti6Al4V produced by LBM after variations in post-build heat treatment at different temperatures for two hours at 780 °C (upper image) and 1015 °C (lower image) followed by fast cooling; lighter zones are β phase, dark zones are the α phase. [244].

Design of the support structures is user defined and is done in consideration to the material, part design, and system technology specification of the LBM machine system. Optimization of support structures for LBM has been extensively researched by various groups and machine manufacturers [102,177,268]. Another aspect of user influenced variation is the post build heat treatment which is essential for eliminating residual stresses and for inducing microstructural changes for specific mechanical characteristics [137]. As an example, Fig. 20 shows that the grain size is strongly depending on the heat treatment temperature. Both, scan parameters and post heat treatment properties define the microstructure and need to be considered as systematically coupled.

4.3. Benchmark studies

Parts fabricated using LBM can be characterized with parameters such as part density, surface roughness, mechanical characteristics, microstructure, and residual stresses [120]. It has been reported that the process variations and powder characteristics play a significant role in the structure, density, and mechanical characteristics of the fabricated structures [120,229]. Challenges in the LBM process include distortions due to heat induced stresses, surface roughness, porosity, lack of process monitoring capability, and problems with powder recoating mechanism [100].

The US National Institute of Standards and Technology (NIST), proposed a standardized test artifact for additive manufacturing [204]. The benchmark artifact, compared laser beam and powder bed based additive manufacturing processes with different binding mechanisms such as liquid phase sintering, full melting, and partial melting [125].

Other benchmark studies compared parts fabricated additively from Inconel 625 [260] and focused on comparing metal additive manufacturing processes based on different technologies such as micro-welding, direct metal laser sintering, laser sintering, and selective laser melting [1]. The selected artifact was an actual die for manufacturing of glass bottles with the benchmark criterion based on the application of the part as defined by the manufacturer (see Fig. 21).

Part 2 of the guideline VDI 3405 contains an inter-laboratory test for additively fabricated Maraging steel 1.2709. Samples fabricated using LBM are machined to the final dimension as per DIN 50125, shown in Fig. 22. Mechanical characteristics for the fabricated samples are determined for untreated, solution annealed, and hardened conditions.

The CIRP inter-laboratory round robin test, already mentioned in Section 3.3, did also focus on LBM-M. This test was designed to create process conditions that are representative of standard production conditions for LBM-M.

In addition to variations in build orientations, (as shown in Fig. 23), surface finishing, and post build heat treatments, the study also aimed at including the user's task to develop material specific process parameters for stainless steel 1.4540 [5].

Fig. 21. Benchmark artifact based on a additively manufactured blow molding tooling insert for manufacturing of glass bottles (dimensions 200 mm × 100 mm × 40 mm) [1].

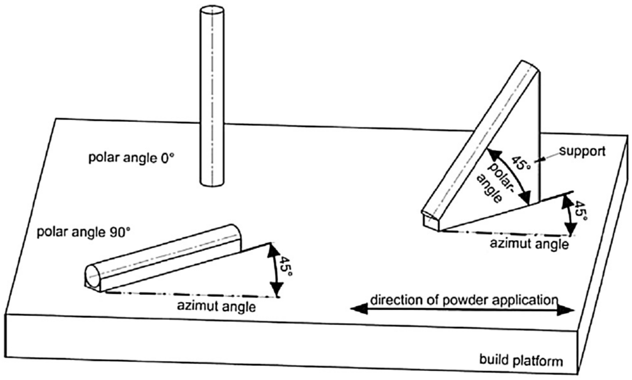

Fig. 22. Setup of VDI 3405 inter-laboratory test for LBM 1.2709.

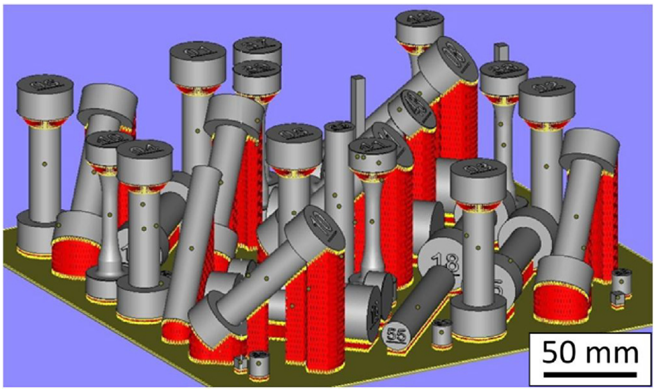

Fig. 23. Build design of the CIRP round robin test (support structures in red).

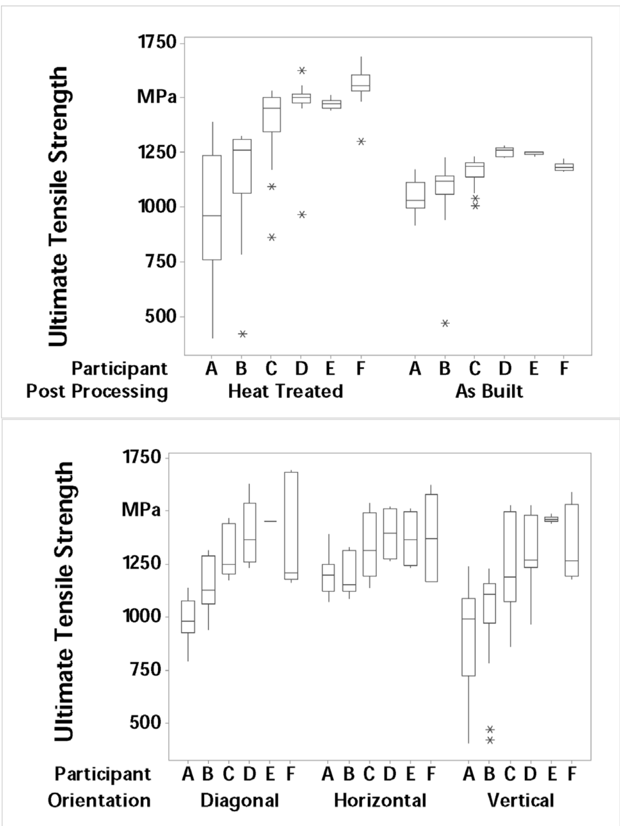

Fig. 24. Box plot of the observed UTS with variations in post processing conditions and build orientation for LBM-M of stainless steel 1.4540 for different participants A–F of the round robin test [5]; boxes show median and upper and lower quartile, whiskers show span of measurement values without exceptional outliers.

Participants of the CIRP inter-laboratory round robin test used commercial machines and were individually responsible for selecting process parameters along with the support design.

The results indicate a strong dependence on system technology and processing conditions (build direction and post processing) of the mechanical characteristics of the fabricated structures. Microstructural analysis of the samples also revealed variations in relative density and microstructure [5], as shown in Fig. 24.

4.4. Process phenomena and limitations

Parameters affecting the quality of structures fabricated by LBM-M can be broadly classified as system technology related, user influenced, and material specific. Some of the parameters that have been reported to have a direct influence on the quality of the fabricated structures include laser beam quality, power, focus position, scanning strategy, powder layer thickness, and powder bed temperature [182].

LBM-M consists of three main steps performed inside a sealed chamber. The first is the deposition of a thin metal powder layer (20 μm–200 μm) by a carbon fiber brush, a silicone rubber lip, a scraper, or a roller [26]. Second is the laser based melting of the powder with a galvanometer scanner using laser powers up to 1 kW and spot size diameters of 20 μm–700 μm [106]. The scanner is operated according to the processed and sliced CAD-model data (see Section 1.2.3) with scan-speeds of up to 2 m/s [157]. Third is the lowering of the substrate plate corresponding to the desired layer thickness. These three steps are repeatedly applied to fuse complete structures layer by layer [150].

LBM-M systems predominantly use fiber lasers [193] at 1070 nm because of a long lifetime and high laser beam quality. The LBM-M process is dominated by the laser–matter-interaction, hence by the applied scan-strategy consisting of the laser power, spot size, intensity profile, scan speed, and hatch distance. The scan strategy also defines the scan vector length and the direction for every segment of a layer. The resulting melt pool size and dynamics are influenced by thermodynamic interactions with the surrounding metal powder or bulk material, the directed gas stream [257], and consolidation phenomena [123]. Pre-heating of the powder bed decreases the temperature gradient of the melting process [37], and reduces residual stresses as well as distortion [106,191]. Moreover, when using low input energy it favors a better bonding [191]. The generation of a melt pool by the high energy input is influenced by gravity, buoyancy, surface tension, capillarity action, the Marangoni effect, and evaporation pressure [149]. The processed metal powders limit the possible process window as they vary in their chemical and physical properties. Those are the particle size distribution, particle shape, absorption coefficients, degree of humidity and oxidation, packing density of the deposited layer, and chemical composition [228]. The particle size distribution influences the penetration depth of the laser-beam [62] through multiple reflection phenomena and absorption inside of cavities in the case of higher layer thicknesses [110]. Thus, the laser energy deposited compared to bulk material is higher for powders [62]. Suitable inert gases are chosen according to the processed metal powder alloy, overflowing the powder bed to avoid melt oxidation. Furthermore, the gas flow carries away spatters, vapor, and heat by convection [110].

To manage the heating and cooling rates, which amount up to 10^8 K/s for LBM-M [41], and to mechanically support overhanging structures, support structures are created during data preparation [35]. Scan strategies are the most commonly used measure to influence the heat flow. Hence, planes are scanned in perpendicular chessboard-like segments and hatch angles are rotated in between consecutive layers to influence the microstructure [121]. Moreover, contours and neighboring scan vectors can be scanned with an overlap to avoid the generation of pores and voids [121]. Laser remelting is successfully used to increase surface properties by decreasing the surface roughness [10] and residual stress [205] leading to micro-cracking [84].

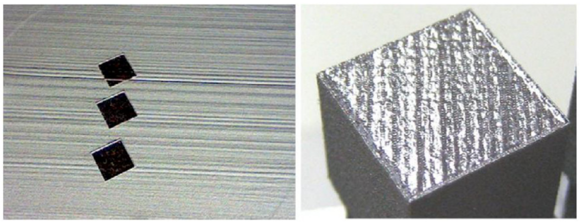

Fig. 25. Exemplary images of stripes on the powder bed (top view) and the consequent surface inconsistency on the structure [38]; dimensions unknown.

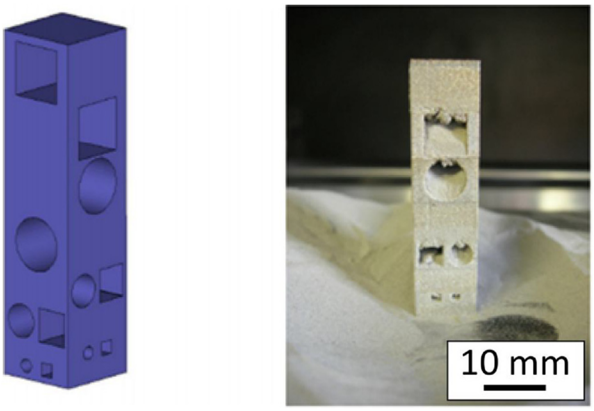

Fig. 26. Overhang features resulting in dross formation; regarding [153] (scale bar added to allow rough estimation).

The recoating mechanism and control over powder morphology and granulometry play a crucial role as inconsistencies in the powder bed are directly reflected on the fabricated structure [38], as shown in Fig. 25. Residual stresses can also lead to part deformations and cause reduction of mechanical strength of the parts. It has also been reported that modification of scanning strategies and heating of the substrate plate can help in reduction of the residual stress level [154].

In addition, the type of the processing gas (e.g. Nitrogen or Argon) has a significant effect on the surface quality of the structure and the relative density of the built parts [40]. For the LBM process, one of the major limitation is the geometrical freedom of overhang surfaces which require a support structure in order to avoid dross formation, distortions, curling, etc. [177] as illustrated in Fig. 26. Therefore, the application of Design for Additive Manufacturing (DfAM) plays an important role for the success of fabricating structures.

Inconsistencies with respect to the relative density of the structures have been reported with variations in build position and build height [5], as shown in Fig. 27. These inconsistencies have been reported to be a possible result of issues with the optical design and inert gas stream circulation of the system technology.

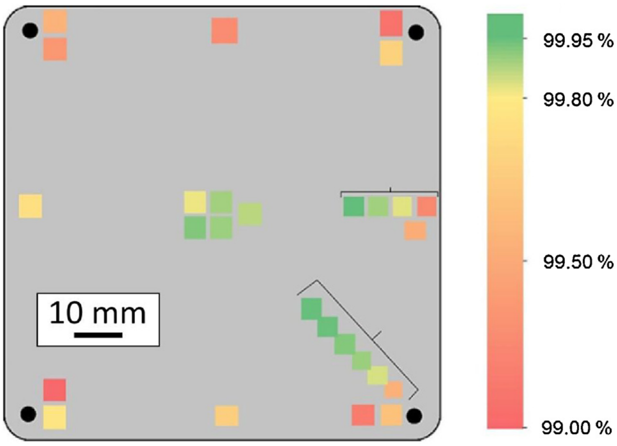

Fig. 27. Variation of relative density with build position for building identical $5 \times 5 \times 5$ mm cubes with 1.4540 powder with constant laser power and feed rate in a SLM Solutions SLM 280 HL machine; regarding [5] (scale bar added to allow rough estimation).

Gas flow within the process chamber has the primary function to remove the fume produced during the melting process. The presence of condensates in the beam path can lead to beam absorption and scattering and therefore affects the beam–powder interaction during the melting process [59].

The part orientation is another important means to influence the support structure volume required (e.g. avoiding overhanging structures), the build time (filling the x–y plane of a machine is usually much faster than building large parts in z-direction), and the post-processing costs (due to a decrease in surface roughness). Moreover, laser beam shaping is a possibility to produce homogeneous metallurgical bonding and to smoothen the thermal gradients [178]. The microstructure of the produced parts is influenced by the temperature gradients and the processing temperature due to the layer by layer manufacturing functioning as a repeated heat treatment [149].

4.5. Key phenomena

This section describes interdependencies between process physics and resulting properties that have to be addressed to obtain repeatable good results.

4.5.1. Thermal management

A defined temperature distribution is essential for achieving the desired structural characteristics from the fabricated parts. This is achieved by a combination of process parameters, platform heating, laser scanning strategies, and an appropriate particle size distribution. Smaller size particles have a higher tendency to vaporize whereas larger particles would require a greater amount of energy to achieve melting [128]. However, material properties such as absorption, density, and heat capacity are temperature dependent. The latent heat of fusion and vaporization play a role during phase changes. Properties such as thermal conductivity, reflectivity, and the melting point of the material affect the thermal management of the process [128]. Poor parameter selection leads to distortion and defects due to residual stresses that result from high thermal gradients.

It is also known that the melt pool size correlates with the build part microstructures and properties [21]. In addition, the solidified material re-melting phenomenon caused by the melt pool geometry may also be quite influential to part quality such as porosity reduction [76] and minimization of macro-segregation defects [236]. However, excessive re-melting may deteriorate part surface quality [66]. An effective scanning strategy has been reported to reduce distortion and warp in parts in addition to reducing the anisotropy and porosity [128]. The heat transfer rate locally varies in the structure. The downward facing surfaces have a high heat accumulation whereas the top layers do not undergo multiple irradiations and therefore have to be subjected to specific process parameters. Support structures prevent distortion resulting from thermal stresses by anchoring the overhang geometry of a part [95]. In addition they also help in the transmission of heat from the part structure to the build platform of the machine [102]. Platform pre-heating helps in the reduction of the thermal gradient between the surface being irradiated by the laser and the substrate plate. In addition to the reduction of residual stresses, it also anneals the buildup layer and acts as a deterrent to quenching [128]. Post-build heat treatment is adopted to reduce the high residual thermal stresses inherent in the structure after the LBM process. In certain cases, a heat treatment at higher temperatures is performed to obtain modifications in the microstructure of the alloys [30].

4.5.2. Build orientation

The primary motivation behind the selection of a build orientation is to achieve an efficient and economical build of parts with the various degrees of complexity in the design

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[128]. Build orientation has also been reported to have an effect on the mechanical characteristics of the parts. It has been reported that the fracture mechanism and crack propagation is affected by the directionality of the microstructure, which is dependent on the build orientation [208].

4.5.3. Powder characteristics

Metal powder characteristics such as particle shape and size distribution along with particle surface properties such as roughness, chemical composition, and the presence of liquid on the surface have a large influence on the powder flowability [255]. Studies comparing several batches of water atomized and gas atomized IN738LC powders reported high porosity in water atomized powders and a correlation between cracking susceptibility and variations in chemical composition from different powder batches [57]. However, it has been reported that powder reuse for LBM process does not have any deteriorating effect on the metallurgical or mechanical properties of the fabricated structures. A study on powder reuse of IN718 observed no significant change in powder characteristics after 14 iterations [7]. It was also reported that for Ti–6Al–4V, an increase in relative density was observed after 12 cycles due to an increase in the flowability of the powder [202].

4.5.4. Powder recoating

The recoating mechanism aims to achieve a consistent powder deposition on the layer and a high packing density of the powder [128]. In order to achieve this, specific powder characteristics along with a good recoating mechanism are essential. Commercial machines come with powder recoaters in the form of rollers or blades that could be too soft or too rigid. However, it is essential that contaminations to the metal powder do not occur from the blade material during the process.

4.5.5. Gas flow efficiency

Gas flow in the LBM machine is used to maintain the required inert atmosphere and as a cleaning mechanism for removing condensates (vaporized powder) from the build chamber [59]. An effective gas flow is essential to maintain consistent beam parameters at the interaction zone and to avoid contamination of the powder bed from the condensates. A non-uniform gas flow has been shown to have an influence on the mechanical characteristics of fabricated structures [59].

5. Future research

Several roadmaps for additive manufacturing exist worldwide. They represent different viewpoints and emphasis. A balanced industrial innovation road mapping is given in Ref. [64].

As many issues comprising material, process, and system technology are challenging, intensive and focused research has to be performed. The main tasks and efforts necessary to overcome existing barriers are discussed in this chapter. Developments of the last decade show that LBM is a promising, reliable, and complementary production method, not only for prototyping and mold fabrication, but also for highly individualized products like prosthesis and small serial production. Hence, a change from Rapid Prototyping (RP) towards Rapid Manufacturing (RM) and Rapid Tooling (RT) is predicted [134]. The real breakthrough of LBM depends on further improvement of the entities material, process, and system technology. Important aspects are, process accuracy and productivity [125]. Additionally, the embedding of LBM processes in an integral process chain needs to be discussed, as there are severe interferences between powder manufacturing and handling and the LBM process as well as between the LBM process and the subsequent manufacturing and finishing steps.

The chapters above clearly outline future research topics for LBM, from material development to process monitoring, part qualification and post-processing. The integration in an industrial environment should also respect safety issues.

5.1. Material qualification and development

Research on materials is a dominating topic since only a small portfolio of materials is available and qualified for laser based AM processes. To fulfill the requirements, for example for aerospace components, high performance materials have to be qualified. In addition to materials which are difficult to process or very demanding, new approaches to create complex material systems should be developed. Approaches like in-situ alloying and the generation of gradient multi-material systems seem promising.

One of the most important aspects is the definition of tight tolerances for the powder materials. Too wide tolerances, as they are present for e.g. Ni-based super alloys, can lead to segregation of the alloys resulting in defects like hot cracks in LBM-M.

A the same time quality assured series production for powder needs to be implemented. As materials and processes interact strongly, both have to be researched simultaneously. Design of material suitable for certain processes is necessary.

5.2. Data preparation and process simulation & modeling

Besides the material, the process strategy itself defines the final part properties. In order to tailor these properties, data preparation and process design based on simulation should be brought together. At the present state there are no software tools available to fulfill this task. Hence, first efforts might develop a universal file format that combines existing software tools for data preparation and process strategy. The final goal is an automated software tool defining a perfect process strategy in order to meet specified strength, accuracy and roughness requirements. This requires multiscale simulations of the process and iteratively running optimization strategies also changing part orientation and support structures.

5.3. Development of systems technology

Using process strategies designed by software tools will cut costs significantly. But to increase the economic efficiency for AM technologies, costs have to be further reduced. To do so, increasing the build-up rates using multi-beam systems, different laser sources like diode lasers and higher input powers together with higher layer thicknesses might be the right way. Beam shaping technologies are thought to be a promising way of increasing the output of LBM-M. Also the process combinations like laser based AM – for fine structures – and wire arc AM – for high buildup rates – is a future oriented approach. Automation of machines, enlarging the build envelope, atmospheric control and manipulation, like vacuum chambers, and the usage of different materials in one chamber are also on the list of future tasks. Furthermore, a combination of subtractive manufacturing like milling, grinding or turning with LMD within a single system, has already been introduced.

The main motivation for combined systems is the accuracy and surface quality possible after machining and the fact that the post processing step can rely on data of the AM process. Another approach is the combination of LBM with laser ablation or laser re-melting on the same system to improve final part's performance [261]. In this context there is a need for an integrated view on the process chain as a whole. Multiple process steps have to be aligned either in one machine or in a production line using automated handling systems to reduce manual labor and data exchange, to improve product consistency and quality, as well as increasing operator safety. The possible contamination of the workplaces with powder materials demands long term health studies, observation of the contamination for each process step, and the development of safety guidelines

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5.4. Process monitoring and quality assurance

To reach the desired final part properties the process has to be constantly monitored and adjusted if the pre-designed process strategy is not optimal. Process monitoring in laser based AM processes is not only important for the quality assurance of the final part, but also necessary to develop closed loop feedback control systems. In LBM-M a major focus has to be put on melt pool monitoring and on the development of a fundamental process understanding in order to predict process irregularities and define rules for adjusting processing parameters during manufacturing. This aspect is also of great importance for OEMs which are willing to integrate AM technologies within existing process chains. Quality assurance and documentation of processing parameters should also be used as input parameters for designing future process strategies. Hence, an extended loop, comprising process simulation, data preparation, the manufacturing process, and process monitoring comprised in a quality management system for AM, has to be the overall aim.

5.5. Post-processing

As the final properties of additively manufactured parts are also dependent on the post process treatment, research on post processing strategies has to be in the focus of future research activities. New production routes for new applications and materials demand new post processing routes, better understanding of heat treatment, surface preparation, and part finishing adapted to the results of the AM process step and resulting part properties. The part removal from the build platform and the removal of support structures also should be within the focus of research. In parallel, thermal post treatments in order to reduce and eliminate internal stresses which evolved during part manufacturing or for adjustment of the microstructure have to be investigated. Mechanical postprocessing can be very challenging when complex part geometries are built.

The final and most significant issue is surface finishing. The traditional methods can be used, but the efficiency is low due to geometric complexity and limited accessibility. Frequently the vibratory finishing process is applied. However, it requires much operational experience [85].

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