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Additive manufacturing using selective electron beam melting

Additive manufacturing encompasses all the procedures which build up a component layer by layer on the basis of a three-dimensional computer model. Additive building-up permits complex geometrical shapes which are subject to hardly any restrictions and thus could not be implemented with conventional manufacturing procedures or only at great expense. Similar to selective laser beam melting, selective electron beam melting (SEBM) is a powder-bed-based additive manufacturing process in which the powder particles are locally melted completely and consolidated by the beam. The electron beam permits the processing of high-melting and reactive metals in a vacuum as well as a high construction rate for additive manufacturing processes due to high power densities and quick deflection speeds. This article not only describes the installation setup and the process sequence during SEBM but also introduces the material classes investigated until now, selected applications and the numerical simulation of this procedure.

1 Introduction

For decades, technological progress and high competitive pressure have led to the shortening of the time span from the product idea to the placing of a product on the market. This contrasts with a continuous increase in the complexity and with the current trend towards the individualisation of components and systems. In this field of tension, conventional manufacturing procedures are increasingly reaching their limits while additive manufacturing is opening up new possibilities for process innovations and the implementation of totally new product properties.

Additive manufacturing technologies are suitable for manufacturing technically sophisticated products, above all as single items and in small-scale series. On the basis of three-dimensional virtual models, the manufacturing can be carried out at any time in nearly any location, especially close to the place of use too. Additive building-up permits complex geometrical shapes which are subject to hardly any restrictions. Due to this property, it is possible to manufacture components and finished parts which could not be implemented with conventional manufacturing technologies or only at great expense. Thus, topologically optimised and functional components may, for example, raise the efficiency and productivity of means of transport and technological installations.

In the case of additive manufacturing, components are manufactured by joining in layers. In particular, powder-bed-based procedures in which individual powder layers are locally melted completely and consolidated by a beam source are suitable for the processing of metals [1]. The most widespread beam source is the laser (selective laser melting, SLM [2]). However, the electron beam (selective electron beam melting, SEBM [3]) which permits quicker process management due to its higher power density stands out for the processing of high-melting and reactive metals [4].

Experts from industry and science from all over the world discussed the great potential of this technology at the "1st International Conference on Electron Beam Additive Manufacturing" EBAM 2016. The conference subjects range from the preliminary processing of the powder via process management and process observation right up to the post-processing of the components. This article takes up the idea of this conference and links the great potential of selective electron beam melting with research-related applications. The main topics of this article are the description of the SEBM technology including possible materials, applications and numerical simulations.

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KEYWORDS

Electron beam melting, additive manufacturing, simulation and calculation, material questions

2 Selective electron beam melting

Selective electron beam melting is, just like all the other layer-based technologies, integrated into the process chain of additive manufacturing. This encompasses the elaboration of a three-dimensional virtual computer model of the component to be manufactured, the preliminary processing of this data by dividing it into individual layers with a constant layer thickness, the manufacturing and the post-processing. In the post-processing, the manufactured components are removed from the powder bed by means of sandblasting with the same powder. The powder recovered in this way can be reused for the process. Depending on the application of the components, the surface can then be post-treated even further, e.g. in order to reduce the roughness inherent in the process.

The possible material diversity of selective electron beam melting is restricted to electrically conductive materials, i.e. metals. Since electrons interact with the atmosphere, the manufacturing takes place in a vacuum chamber which is usually regulated to a pressure in the range of $2 \cdot 10^{-3}$ mbar using a controlled helium inflow. The electron beam gun with a typical power of up to 3 kW and an accelerating voltage of 60 kV is mounted on the vacuum chamber. Beam diameters of 100 to 1,000 µm are achieved depending on the quality and type of the cathode and on the utilised power. Electromagnetic coils can be used in order to move the electron beam at deflection speeds of up to 10,000 m/s without any inertia. Two powder tanks and one rake are installed in the interior of the vacuum chamber in order to apply the layers in the construction space with a mobile process platform. The components of the vacuum chamber and the individual process steps of the manufacturing are illustrated on Fig. 1.

In a first step, a defocused electron beam scans the entire surface of the powder layer several times in order to set the preheating temperature. Depending on the utilised material, this varies from 300°C for pure copper [6] right up to 1,100°C for some nickel-based alloys [7]. This process step is extremely important for the process stability. One challenge facing this procedure is the charge dissipation of the electrons via the powder bed. If this is not guaranteed, it results in the so-called “smoke“ phenomenon with which the top powder layer, so to speak, explodes because powder particles are thrown out of the layer. This inevitably leads to the termination of the process. Due to the slight sintering of the particles during the preheating, it is possible to guarantee a sufficient electrical conductivity. The inflow of helium up to $2 \cdot 10^{-3}$ mbar supports the stable process management. The helium atoms are positively ionised by the electron beam and can subsequently dissipate the negative charge from the powder bed. Furthermore, the entire powder bed supports the component due to the sintering.

In a second step, the regions belonging to the component geometry are melted completely with a focused electron beam. Depending on the geometry, different process strategies which may be composed of a combination of contours and hatches at typical scanning speeds of 4 m/s and 10 m/s are used here. In this respect, the contours can optionally be processed in the so-called multibeam mode in which up to 100 contour positions are melted completely in quasi-simultaneous operation. This is possible due to the high maximum deflection speed of the electron beam. A hatch describes an area which is melted completely in a meandering shape with certain line spacing, typically between 25 µm and 150 µm. As standard, this scanning pattern is rotated by 90° in each layer.

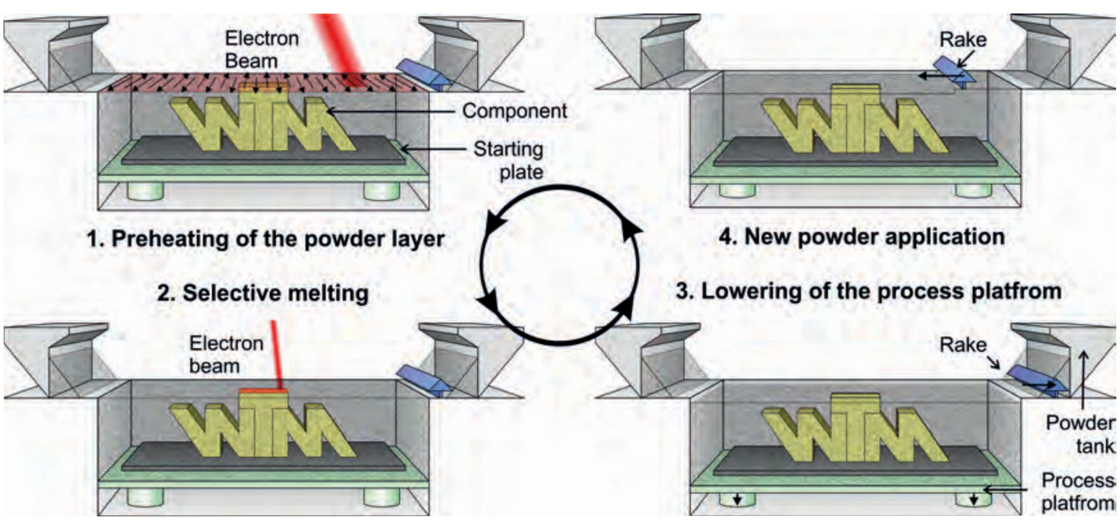

Fig. 1 • Process chain of selective electron beam melting: After the preheating of the entire powder layer with a defocused electron beam (1), component regions are completely melted selectively according to the computer model (2). After the consolidation and the solidification, the process platform is lowered by one layer thickness (3) and a new powder layer is applied (4); cf. [5].

After the solidification, the process platform moves one layer thickness downwards. Depending on the powder size and the material, it is possible to implement layer thicknesses between 50 µm and 150 µm. A new powder layer is applied in the last step. For this purpose, the rake firstly moves in the powder pile in front of the powder tank. This makes a sufficient quantity of powder fall on to the other side of the rake. These particles are now distributed in the build tank. For the next layer, this process takes place inversely at the other powder tank. The resulting material properties of the manufactured components are essentially dependent on the quality of the powder. A high relative density of the powder layer is desired in general and is guaranteed by a high flowability of the powder. For this reason, spherical powder particles with sizes between 40 µm and 105 µm from an atomisation or rotation process are used in most cases. The proportion of the fine fraction under 40 µm and on satellites (minute particles adhering to normal powder particles) should be kept as low as possible since these drastically reduce the electrical conductivity and the flowability.

Table 1 • Overview of the investigated material groups for the SEBM process; cf. [3].

Material group	Alloys	Sources
Cobalt basis	Co-Cr-Mo-C(-N)	[8], [9]
Copper	Pure copper	[10], [6]
Iron	Pure iron	[11]
	316 L	[12]
	H13	[13]
Niobium	Pure niobium	[14]
Nickel basis	IN625	[15]
	IN718	[16], [17], [18]
	CMSX-4	[7]
	Rene142	[19]
Titanium	Pure titanium, TiAl6V4	[20]
Titanium aluminide	Ti-Al-Cr-Nb(-W)	[21], [22]

3 Materials

Currently, there is just one manufacturer which commercially offers installations for selective electron beam melting (Arcam AB, Sweden). Therefore, the commercial availability of materials which can be processed with SEBM is still extremely restricted at present. However, in the research field, a large number of alloys have already been successfully processed into totally leak-tight components. In this respect, the number of available materials and material systems is constantly increasing even further and is thus extending the potential application possibilities of this procedure. Table 1 gives an overview of the materials already processed with SEBM today.

At the beginning of the introduction of the procedure at the end of the 1990s, interest primarily centred on tool steel, e.g. in order to implement casting shapes with cooling operations close to the contours. Today, attention is focusing on applications in medical technology or in aviation. In association with these, the materials mainly processed with SEBM have also been developed away from steels (316L and H13) towards Co alloys (Co-Cr-Mo-C) and, above all, towards titanium (pure titanium and TiAl6V4). Moreover, nickel-based alloys (e.g. IN718) and, to an increasing extent, titanium aluminides are playing major roles nowadays.

The great advantage of the SEBM procedure is being shown with regard to the extension of the material range, precisely for complex material systems, since the high local cooling rates result in very fine and homogeneous structures. This leads to outstanding material properties. In this respect, the structural fineness may be two orders of magnitude below that of cast alloys [7]. Moreover, there are approaches for using suitable beam manipulation strategies for the targeted setting of the structure according to the requirements [17]. For example, the typically columnar structure in the building direction can be transformed into an equiaxed structure by the intended formation of new nuclei, Fig. 7 (left).

In general, material properties which are the absolute equal of or frequently even considerably better than those of conventional manufacturing technologies can be achieved nowadays with the correct process strategy. The production of completely leak-tight components is a matter of course in the meantime. The powder quality tends to constitute a problem since gas pores introduced into the

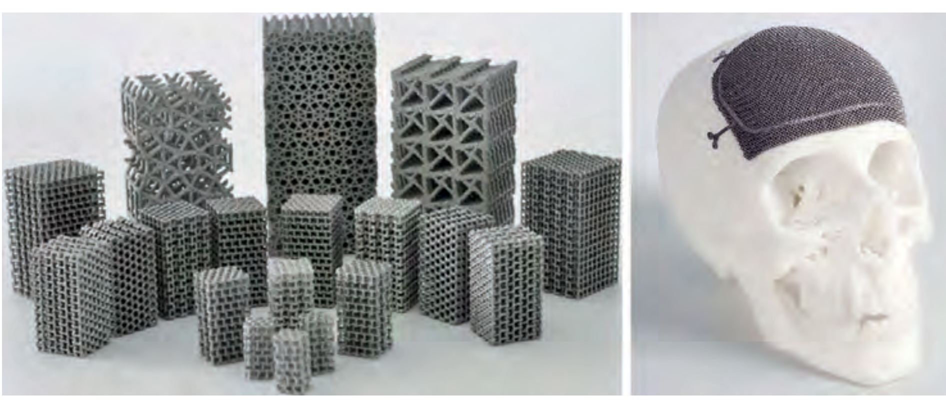

Fig. 2 • Various cellular structures made of TiAl6V4, in part with auxetic strain behaviour (negative transverse contraction) (left), skull implant made of TiAl6V4 with an open-pore structure for medical technology (right); source: www.arcam.com.

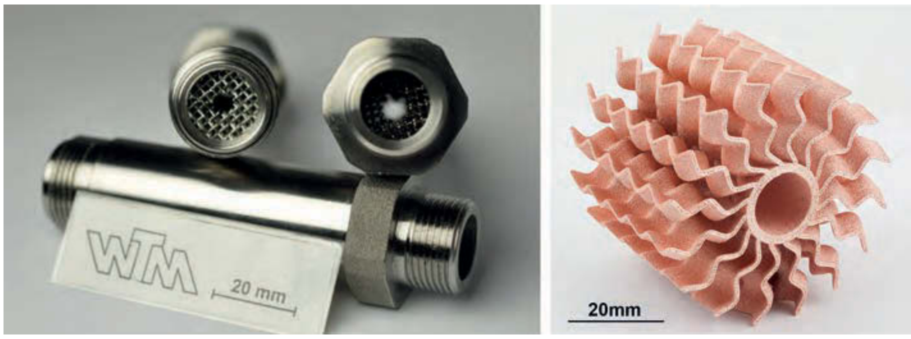

Fig. 3 • Structured reactor made of catalyst-coated TiAl6V4 in order to release hydrogen from a liquid organic hydrogen carrier (LOHC) (left), prototype of a heat exchanger structure made of pure copper (right).

powder by the atomisation process can be found in the component after the SEBM process. That explains a frequently arising residual porosity of max. approx. 0.5% which, however, can be removed, for example, by downstream hot isostatic pressing (HIP), in so far as this is necessary.

4 Applications

One major advantage of additive manufacturing is the almost unrestricted design freedom. This is particularly great in the case of SEBM since the powder bed not only serves as a support for any overhangs but also has a high mechanical stability due to the slight initial sintering in the preheating step, e.g. also in comparison with SLM. In connection with the low inclination to distortion as a result of the high preheating temperature, hardly any supporting structures are needed for SEBM and, apart from totally finished cavities (from which the powder can then no longer be removed), there are unlimited freedoms with regard to the component designing. In this respect, the great variability of the electron beam permits the simultaneous production of the geometry and the structure and thus the setting of the material properties. However, it is necessary to take account of the in-situ heat treatment due to the increased process temperature and its influence, for example, on precipitation processes. A few possible applications of SEBM are shown below.

The SEBM procedure makes it possible to manufacture cellular structures which could not be manufactured in this way by conventional means, Fig. 2. Thus, hybrid structures consisting of solid and porous regions are applied in medical technology today, e.g. as implants which are adapted to the patient and can be supplied in an exact-fitting form within just a few days on the basis of a scan of the patient's bone structure. That increases the success of the treatment and reduces the operation stress for the patient. Moreover, metamaterials are easy to produce with the SEBM procedure. These materials receive their properties from their structures. For example, it is possible to manufacture materials with negative Poisson's ratios, so-called auxetic structures, or even materials with an acoustic band gap which completely eliminate mechanical oscillations in a certain frequency range.

Moreover, cellular structures can be utilised in order to design structured reactors with adjusted reactions [23]. One example of this is illustrated on Fig. 3 (left). The reactor was manufactured from TiAl6V4 with SEBM and serves as the carrier material for a subsequent catalyst coating. The reaction to be carried out in it is the release of hydrogen from perhydro-N-ethylcarbazole, a liquid organic hydrogen carrier [24]. With regard to the heat transport and the pressure loss, the structured reactor is far superior to the classic powder bed reactor. Furthermore, only additive manufacturing is feasible for reactor elements such as the illustrated flue gas tube for the quick dissipation of the gaseous hydrogen or even integrated cooling ducts. The combination of the high thermal conductivity of pure copper with the design freedom due to SEBM also makes it conceivable to manufacture complex heat exchangers which can be exactly oriented to an existing heat transmission problem, Fig. 3 (right).

The SEBM technology shows further advantages during the processing of high-temperature materials such as nickel-based alloys and titanium aluminides (TiAl). The possibility of making the electron beam scan over the powder bed in a defocused mode at high deflection speeds during the preheating permits a high energy input without melting the powder completely. Thus, the entire powder bed can be constantly kept at temperatures above 1,000°C during the construction phase. With this strategy, residual stresses, particularly in thick-walled components, can be reduced effectively and high-performance materials such as TiAl can be processed.

The use of TiAl for rotating parts, e.g. turbine blades or turbocharger wheels, is particularly attractive as a result of the low density and the low moments of inertia. Until now, more complex components made of TiAl have been manufactured almost exclusively by means of centrifugal casting. Selective electron beam melting constitutes an alternative with various advantages. The SEBM process works in a vacuum. Therefore, no contamination takes place in spite of the high affinity of the TiAl materials to reactions with other elements. Moreover, any reactions of TiAl with the crucible material and thus any possible changes in the properties can be avoided since it is set up in the powder bed without any tools. The rapid solidification leads to extremely fine microstructures and a homogeneous distribution of the alloying elements. Any demixing processes are suppressed. In the case of electron beam melting, supporting structures which turn out to be small in comparison with the casting residues in the centrifugal casting procedure are utilised in a targeted way for the formation of distortion-free components. In interplay with the powder recycling after the manufacturing, this results in good material utilisation.

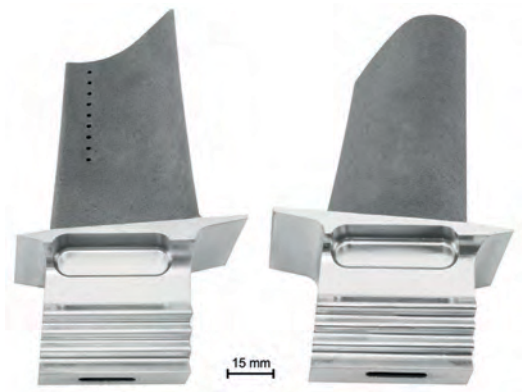

Fig. 4 • Additively manufactured turbine blade made of a nickel-based alloy with a cooling structure (front and rear sides). The blade root has been post-processed mechanically. The blade shows the as-built condition.

The specified advantages can also be transferred to the processing of nickel-based alloys with high γ contents. In combination with the design freedom, it is possible to implement turbine blades with optimised cooling structures, Fig. 4. It is disadvantageous that the high construction space temperatures and the associated sintering process lead to a material-locking joint between the individual powder particles in the powder bed (formation of sintering necks). These joints prevent the powder from simply falling out of the regions with difficult accessibility (cooling structures). Therefore, post-processing is required. Within the framework of the development activities, investigations are currently being conducted into promising procedures for the post-processing of cooling structures. Furthermore, high surface roughnesses (Ra > 25 µm) arise during the SEBM process due to the installation-specific beam diameter (> 150 µm), the software for controlling the beam and the utilised powder fraction (45 to 150 µm). Mechanical and electrochemical post-processing procedures are utilised for the subsequent reduction in the surface roughness.

5 Simulation

Today, many different materials can already be processed with selective electron beam melting. In part, process windows are available for a stable procedure with sufficient material properties of the manufactured components. However, these findings are mostly bought at a high price in the form of many experiments. For this reason, a lot of mechanisms which give rise to certain material properties have not yet been understood correctly until today. Process observation constitutes a major problem since, for example, temperature measurements can be taken to an inadequate extent only. Furthermore, many processes, such as the molten pool dynamics, take place on a very small timescale with which measuring systems have difficulties with regard to the resolution. For this reason, an accompanying numerical simulation is extremely sensible in addition to experimental work. On the one hand, the high-dimensional spaces of the process parameters such as beam power, scanning speed, line spacing, layer thickness, powder sizes etc. can be delimited to sensible subspaces before any experimental work. On the other hand, it is possible to investigate and identify the underlying mechanisms of the material consolidation and the resulting material properties.

The resulting material properties are dependent on the qualities and compositions of the powder and the powder layer. For this reason, a mesoscopic simulation approach which is capable of ensuring the resolution of the individual powder particles is ideally suitable for identifying the underlying mechanisms. A three-dimensional mesoscopic simulation with the powder bed, the molten pool including the molten pool dynamics and the electron beam is portrayed on Fig. 5. Furthermore, the most important physical phenomena during selective electron beam melting which are considered by the simulation are listed on Fig. 5.

The most important aspect during the simulation of selective electron beam melting is the correct modelling of the thermal balance of the process. Nearly all the modifications to the process parameters have influences on

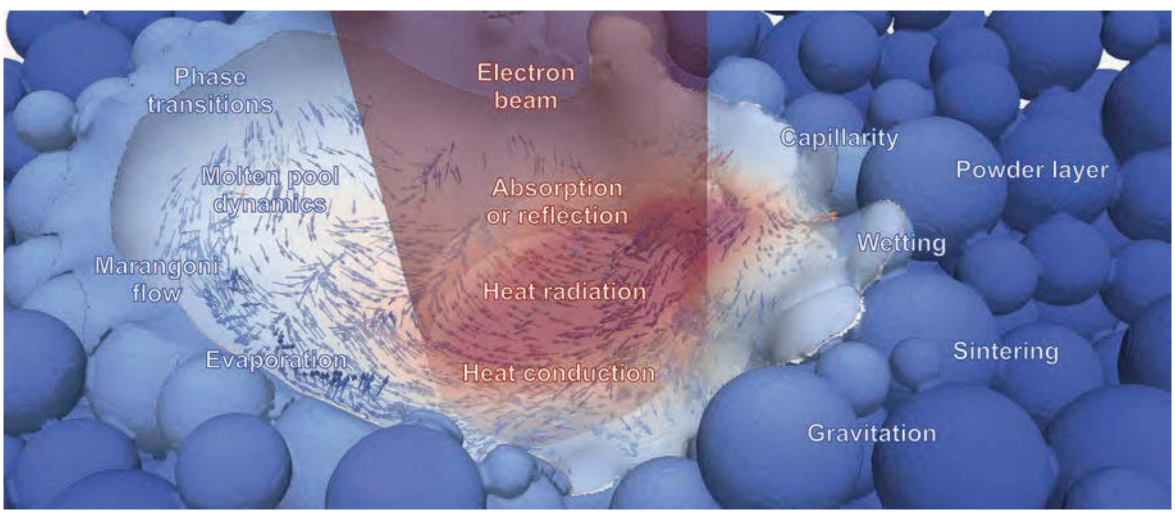

Fig. 5 • Essential physical phenomena during selective electron beam melting. Representation of the powder bed (blue), the electron beam (red) and the molten pool (temperature distribution from white to red) including the molten pool dynamics (arrows) [5].

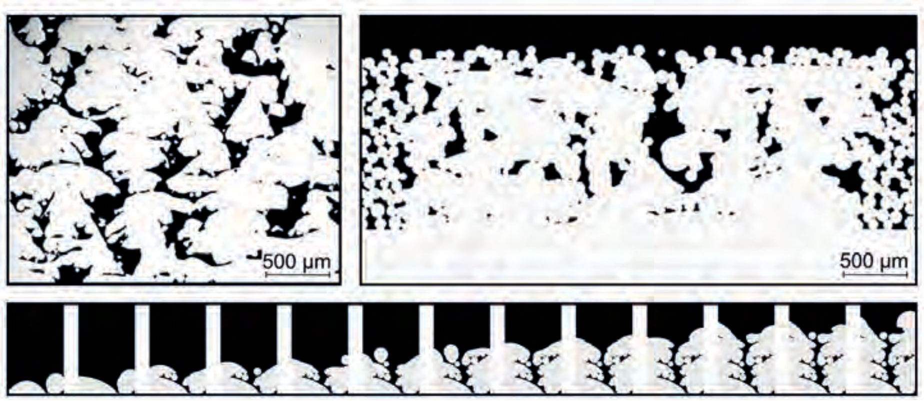

Fig. 6 • Tunnel porosity in the experiment (top left) and in the simulation (top right) during the manufacturing of cube specimens made of TiAl6V4 using hatches without contours. Representation of the origination of the tunnel porosity by the simulation (bottom) [28].

the heat conduction, the energy input by the electron beam or the heat loss caused, for example, by heat radiation or evaporation. Furthermore, a lot of material parameters are temperature-dependent and thus sensitive to correct modelling. The complete melting of the material results in a molten pool whose dynamics are essentially determined by capillarity, evaporation pressures, wetting effects, Marangoni flows and gravitation. During the solidification, the temperature gradient and the solidification rate have decisive influences on the occurring microstructure unless this is destroyed once again by solid phase transformations.

By applying numerical simulation [25...27], it was possible to explain different phenomena arising during the SEBM process. One such phenomenon is, for example, the characteristic of tunnel porosity. Any kind of porosity should be minimised in order to achieve good mechanical properties. The porosity structures for an experiment (top left) and a simulation (top right) with existing tunnel porosity are illustrated on Fig. 6. It is possible to explain this phenomenon by considering the development of an imperfection over many layers in the simulation (bottom). Due to the low power of the electron beam and the stochastically unfavourable positions of the particles in the powder bed, the molten pool can be divided into two smaller ones. The surface tension curves both molten pools at the separating point and establishes a small imperfection. Since the melting depth with the electron beam is not sufficient in order to melt this defect completely, the molten pool is now separated at this defect time and time again and both parts are drawn to the sides of the defect by capillary forces. Thus, the imperfection may persist over many layers and the tunnel porosity occurs [28].

By choosing suitable parameters, though, it is possible to manufacture compact and leak-tight components which no longer differ in the transverse sections. However, both columnar-crystalline and polycrystalline structures, as illustrated on Fig. 7, can be recognised on EBSD (electron backscatter diffraction) orientation maps. One aim during the manufacturing is to be able to set this structure freely in order to exert targeted influences on material properties in a component. Experimental results show that the solidification direction of the molten pool plays an essential role in this respect. The greater the deviations from the building direction are, the more likely a polycrystalline structure is to result from the formation of new grains on the bottom of the molten pool. However, it is unexplained why this does not coincide with the classic model for CET (columnar-to-equiaxed transition). On Fig. 7 (right), the solidification rates at the solidification front are illustrated over the temperature gradient from data in the numerical simulation for two different sets of parameters. These results contradict the CET in two aspects. Firstly, the formation of new grains would be expected at the end of the solidification of the molten pool on the basis of the results whereas new grains form at the bottom of the molten pool. Secondly, the assignment of columnar-crystalline and polycrystalline structures should be precisely opposite to the process parameters on the basis of the solidification conditions [29]. These contradictions could be revealed with the aid of numerical simulation and are currently the subject of the research into the modelling of the texture characteristic, especially the formation of new grains, during selective electron beam melting.

6 Concluding remarks

Selective electron beam melting is suitable for manufacturing technically sophisticated products and offers the possibility of processing high-performance alloys. In this respect, additive building-up permits complex geometrical shapes which are subject to hardly any restrictions. These possibilities are reflected in the diversity of the technological applications. Nevertheless, the further industrial success of this procedure needs continuous research into new materials, better process observation and process control as well as understanding for process and component optimisation measures.

At present, a wide material range of the most diverse material systems is the subject of the research. In this respect, the complexity of the materials and the requirements on the processing are increasing continuously. Out of numerous application possibilities as individual components and small-scale series, reactors as a combination of cellular and solid structures and turbine blades with internal cooling ducts were described here.

In addition to applications of this procedure, simulation is an important pillar for better understanding of the process. The development of the tunnel porosity or the texture characteristic was specified as an example but many other subject fields such as alterations in the alloy

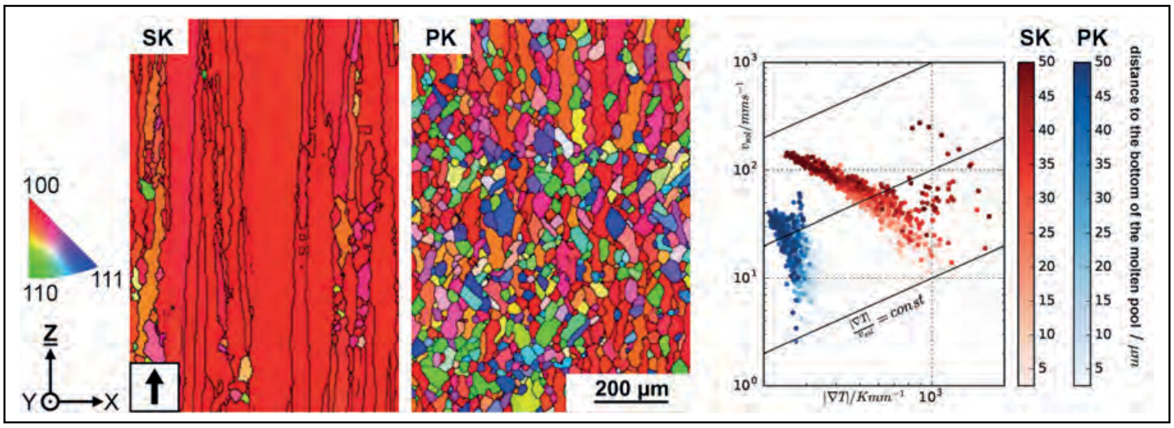

Fig. 7 • EBSD orientation maps in the longitudinal direction parallel to the building-up direction show the transition from a columnar-crystalline (SK) structure to a polycrystalline (PK) structure with IN718 by modifying the line spacing and scanning speed process parameters (left). Simulation results of the solidification rate v_{sol} over the temperature gradient $|\nabla T|$ at the solidification front. At an increasing distance away from the bottom of the molten pool, the temperature gradient becomes flatter and the solidification rate increases (right). [29].

composition due to selective evaporation [30] or dimensional accuracies resulting from residual stresses and distortion [31] are the subjects of the research here.

Apart from these research fields, the connections between material properties, process strategies and process optimisation must be investigated in greater detail. With this knowledge, it should, in the future, be possible to replace the control of installations with a regulation system whose decision algorithms can be obtained by combining experiments and simulations, based on process observation, in order to be able to manufacture high-quality products in a reproducible way.

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