

Transient Physical Effects in Electron Beam Sintering

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Reviewed, accepted September 14, 2006

Abstract:

The extensive use of the electron beam in manufacturing processes like welding or perforating revealed the high potentials for also using it for solid freeform fabrication. First approaches like feeding wire into a melt pool have successfully shown the technical feasibility. Among other features, the electron beam exhibits high scanning speed, high power output, and beam density. While in laser-based machines the fabrication is working in a stable way, transient physical effects in the electron beam process can be observed, which still restrict process stability. For instance, a high power input of the electron beam can result in sudden scattering of the metal powder. The authors have developed an electron beam freeform fabrication system and examined the above mentioned effects. Thus, the paper provides methods in order to identify, isolate and avoid these effects, and to finally realize a reproducible process.

Introduction

Since the introduction of the first metal processing additive layer manufacturing machines in 1994, their development is proceeding with an enormous speed. Meanwhile, eight different companies are competing on the world market [1]. For all machines, the process implied is almost similar: A laser beam is used to solidify metal powder which is formed in layers. Most obvious distinctive features are the means of positioning the laser spot on the building plate, the composition of the powder material and the mechanical realization of forming a powder layer. At least one equipment manufacturer, the Swedish company ARCAM AB, has started the usage of an electron beam as an energy source for the solidification of the powder. The enormous potentials of this energy source [2] have been implied partially with a machine receivable on the market. Up to now, only a few independent scientific papers deal with the material related quality of the parts built on such a machine.

State of the Art

The electron beam (EB) offers a variety of process advantages and disadvantages in comparison to laser technology [2, 3, 4, 5, 6]. The functional principle is shown in figure 1. The EB consists of accelerated free electrons (from a heated cathode) which are focused on the desired spot. This is provided by so called "electro-magnetic lenses". Due to the fact that the electron beam even collides with air molecules, a vacuum environment is obligatory. On the surface of the powder which is positioned on the building plate, the electrons are being decelerated suddenly. In this way, all kinetic energy of the moving charge carrier is converted into thermal energy which is used for rising the powder temperature up to the sintering or melti

point. By the sequential formation of a powder layer of a defined thickness, a three-dimensional part is being built up.

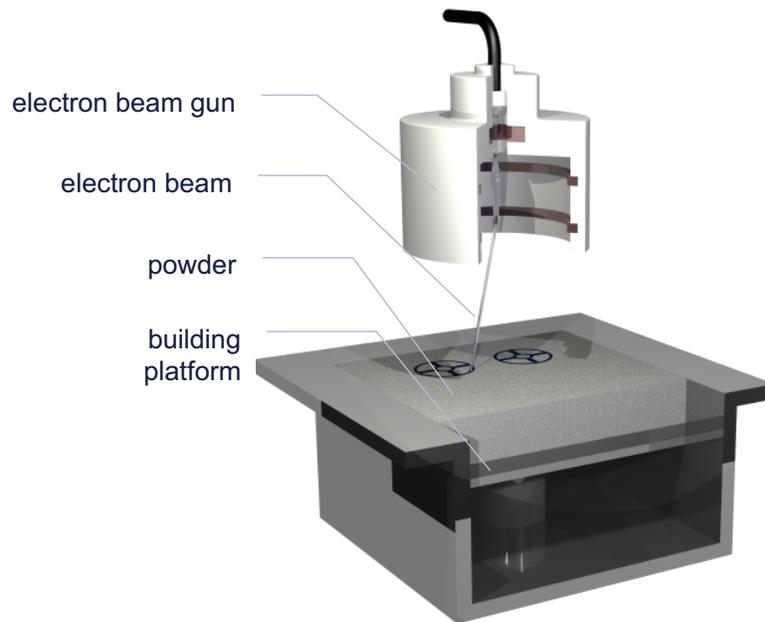


Figure 1: Functional principle of electron beam sintering

Due to the enormous positioning speed of the beam spot, an even solidification of the powder can be achieved, which is necessary for avoiding self-equilibrating stress. Furthermore, the machine installed at the *iwb* (Institute of Machine Tools and Industrial Engineering of the Technical University of Munich) is capable of realizing a beam power of 10 kW, which is a multiple of the power output of today's laser based machines (see Figure 2).

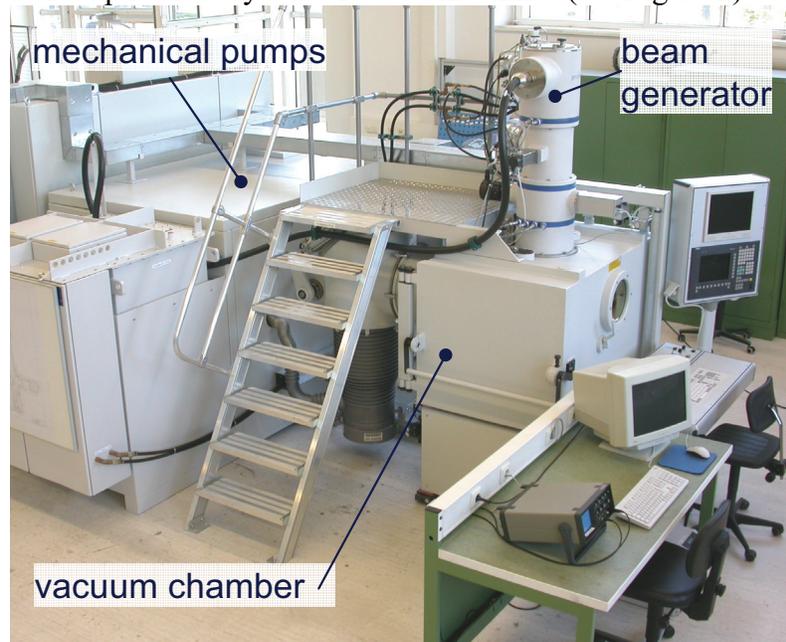


Figure 2: Experimental machine at the *iwb* plant

The complex vacuum and beam technology of EB machines is technically mature and reliable due to the fact that EB welding, perforating and coating are longtime used manufacturing processes in the industry. At first glance, the vacuum technology seems to be unfavorable. Expensive pumps and the time-consuming evacuation of the building chamber are often mentioned. It takes roughly eight minutes of cycle time for evacuating and venting the machine with a chamber that has a size of 600 l at the *iwb*. Due to this achieved time, there is no loss of time compared with the preheating in lasersintering technologies. The vacuum technology rather avoids oxides and nitrate in the powder [7]. Moreover, the depth of penetration into the powder is a lot higher in EB sintering than in using a laser, because the reflectance of accelerated electrons is minimal compared to the photons.

Despite of the increased effort for the system engineering in EB sintering compared to the laser sintering a lot of potentials arise which have to be realized. Against this background, the *iwb* application center in Augsburg started the research project “Process development for EB sintering of metal parts” in 2001. Core of the project is the modification of an EB welding machine. For this purpose, such a machine was equipped with a mechanism for applying layers of metal powder in the vacuum chamber. Likewise, control systems were adapted to the requirements of additive technologies. In cooperation with nine enterprises, among them powder manufacturers, simulation experts, software developers, EB welding machine manufacturers and customers, the technology was developed within 3 years in such a way that it became possible to build the first three-dimensional test specimens.

At the current state of the art, there is only little knowledge about the interaction between EB and metal powder. The past publications are limited to the examination of obtained results in selective EB melting. The physical effects which occur in EB sintering or melting and their influencing variables have not been examined yet. Therefore, in this paper the occurring effects are examined, the causes for these effects are analysed and methods for realizing a stable building process are presented.

Sintering single Layers

At the beginning of the development of electron beam sintering, researchers at the *iwb* single layers of different metal powders were sintered on metal plates in order to obtain fundamental characteristics of the influencing variables [8]. Circular slots in those metal plates assured the sintering of a specific amount of powder. The experiments were carried out with different powder materials (for example CuSn20, H11, FeNi, mixed Powder CuSn20 + H11, NdFeB). In the first few experiments the powder immediately spread like in an explosion when hitting it with the EB. Only preheating the powder indirectly via a hot metal plate could reduce this effect (Figure 3).

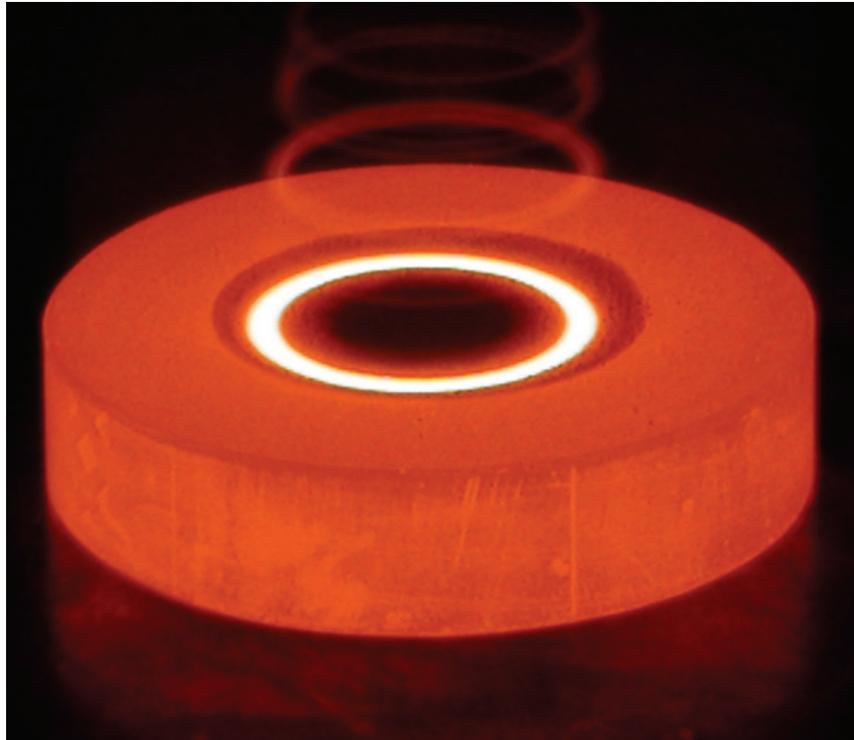


Figure 3: Preheated metal plate

On the basis of this procedure numerous experiments were conducted. In this way, process parameters for a variety of powder materials were detected. By setting up these process parameters, the obtained layer quality was smooth and completely sintered. In diagram 1, the quantitatively evaluated test results for one sort of powder (H11) are shown over the frequency and beam power. The evaluation took place via a weighted rating (in percentage) of the following result characteristics:

- surface finish: 22 %
- holes in the surface: 22 %
- pores: 18 %
- delamination: 14 %
- color due to maximum temperature: 11 %
- grooves due to beam path: 9 %
- spillings in the process: 4 %

Thereby, the weighting took place on the basis of the experiences in research and application of additive technologies. It can easily be recognized, that good results in this experiment depend on a low frequency, which is equivalent to a low scanning speed. On the other hand, the beam power obviously can be varied in a greater range in order to obtain even an connected layers.

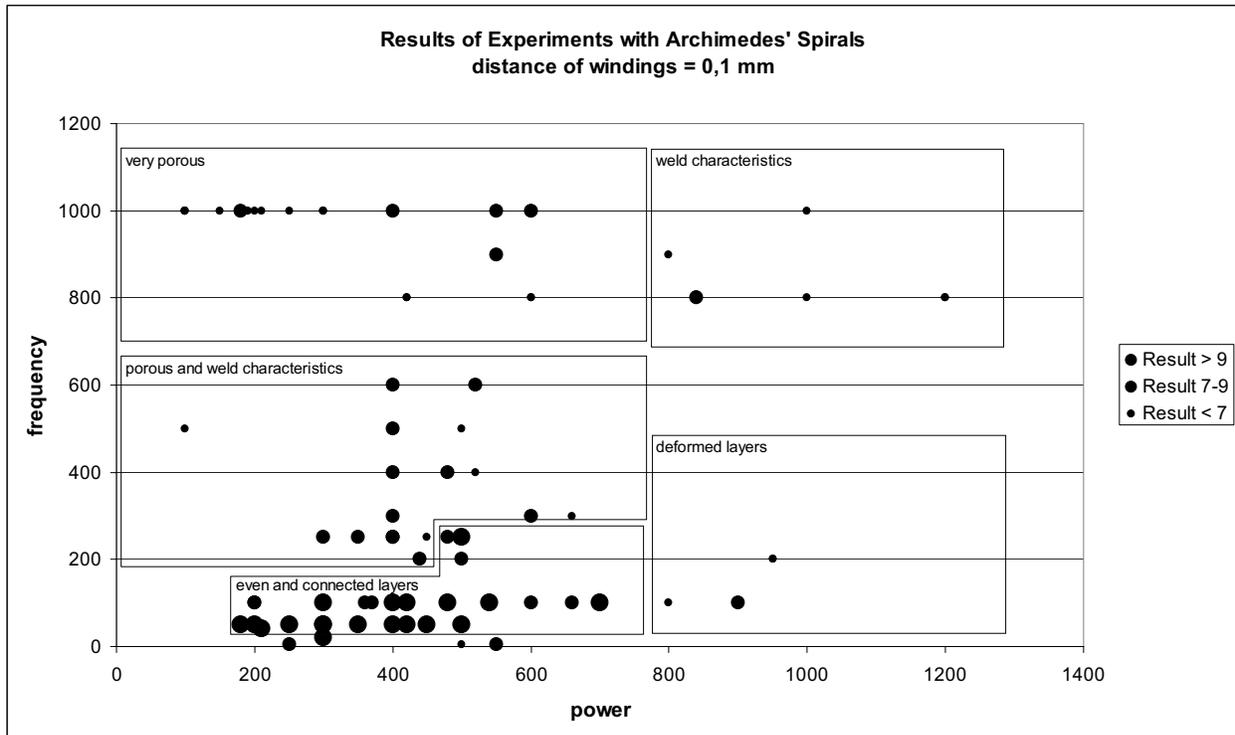


Diagram 1: Results of experiments depending on beam power and frequency

By the qualitative evaluation (figure 4) the parameter range can be classified in good (10) and bad (0) test results. The preheating process was kept constantly at a powder temperature between 800° C and 900° C.

Deformed Layer (2,4) Plain, connected layer (9,7)

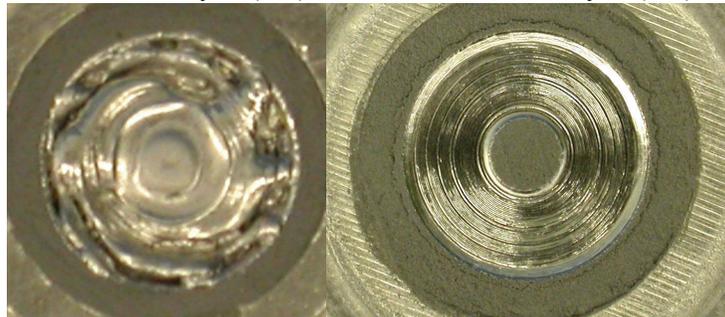


Figure 4: Classification of experiment results

However, preheating causes two negative effects. The surrounding powder is also slightly sintered by the preheating procedure and thus can only be removed manually only with increased effort. Additionally, the process time is extended, since not the entire beam power can be used for immediately sintering the cool powder.

Therefore, the procedure of sudden spreading of the powder was examined precisely. The photographs of a high-speed camera (figure 5) show the strong development of the effect. Here, the beam power was set to 400 W with a circular beam path onto the metal powder. In a comparative experiment, this effect cannot be examined when sintering the powder with a 2 kW

laser beam. Hence, the physical effects which are a potential as a cause for spreading could be limited to the following three: Water residues in powder, momentum and electrostatic charge. Other thermodynamic effects like the spreading of the powder due to a sudden evaporation were excluded, otherwise spreading also should have occurred within the laser experiments. Further investigations were focused therefore on the analysis of the effects and the development of measures to reduce these effects.

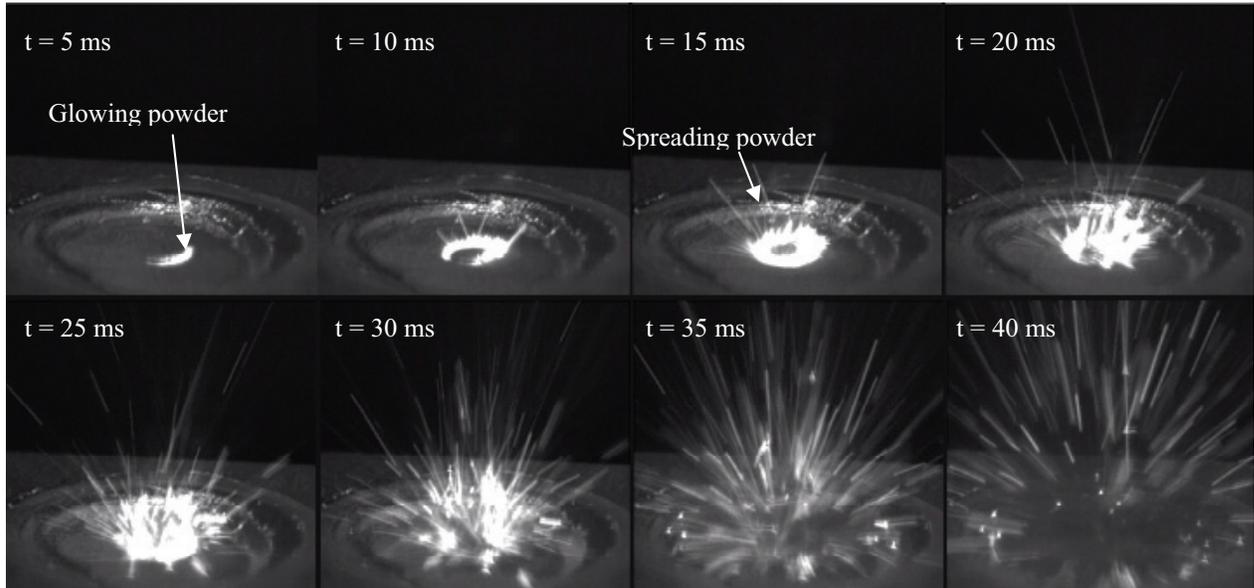


Figure 5: Spreading of one powder layer (100 Hz, H11, 4 mA, 100 kV, no preheating)

Physical Effects

In order to avoid or contain the shown spreading, first of all an accurate knowledge of the impact of the physical effects stated above is necessary. In the following, the three effects are described and their impact is estimated on the basis of empirical and quantitative considerations.

Afterwards, possible counter measures are discussed on basis of this examination.

Water residues in the powder:

For the effective use of the electron beam a pressure of $4 \cdot 10^{-5}$ mbar is produced in the vacuum chamber. This is achieved by a combination of roots, rotary vane, turbomolecular and diffusion vacuum pumps. Despite this high vacuum, the air humidity settles in the walls of the chamber. For this reason, an ultra high vacuum can be achieved only with difficulty. Even with constantly running pumps the vacuum cannot be increased, since the water molecules escape from the walls of the chamber, when sufficient low pressure is attained. This effect is also the cause for a usual method for producing ultra high vacuum within the range of 10^{-11} mbar. The vacuum chamber is constantly heated to approx. 80 °C and evacuated during several days [9]. Thereby, the water inclusions evaporate and the vacuum can be increased into lower ranges. While filling up the powder reservoir, the air humidity can store itself due to the large surface of the grains. If the electron beam hits the powder now, the stored water can evaporate explosively. This explosion is caused by the enormous 1700 times volume increase. This intense effect can therefore be seen as a reason for spreading. However, this effect could be avoided or contained by a preliminary heating of the powder in the vacuum chamber. Through different preliminary heatings of the

powder, this theory could be disproved. The powder still spreads when hitting it with the EB. Additionally, the powder was preheated to 100 °C in the vacuum chamber and while keeping this temperature for several hours, the vacuum pressure was observed. If water storages were present in the powder, the vacuum pressure would have had to rise measurably because of the evaporation. Likewise, this effect was not observed. In the long run the evaporation of the water storages and thus the spreading of the powder would have to arise also within laser sintering. The comparative experiments specified above and the past experiences with laser based additive technologies do not confirm this.

Momentum:

The electrons reach a speed of 0,548 v/c₀ during an accelerating voltage of 100 kV. By the deceleration of the electrons in the powder, the momentum of the electrons will transfer to the particles. This momentum could likewise be a cause for the spreading. For calculation of this effect, the acceptance is met, that the entire momentum of the electron beam turns completely into the powder. Thereby, the powder is hurled perpendicularly upward out from the working surface.

- Rest mass of an electron m₀ = 9,11·10⁻³¹ kg
- Speed of light c = 2,9979·10⁸ m/s
- Electron charge e = 1,602·10⁻¹⁹ C
- Acceleration voltage U = 100 kV

The speed after going through the accelerating voltage is calculated from the given values:

$$v = c \cdot \sqrt{1 - \frac{1}{\left(1 + \frac{e \cdot U}{m_0 \cdot c^2}\right)^2}} = 1,644 \cdot 10^8 \frac{m}{s} \tag{1}$$

The momentum under consideration of special relativity is calculated thereby as follows:

$$p_e = \frac{m_0 \cdot v}{\sqrt{1 - \frac{v^2}{c^2}}} = 1,79 \cdot 10^{-22} \text{Ns} \tag{2}$$

An electron possesses thereby the relativistic momentum of 1,79·10⁻²² Ns. After momentum transmission on the grains, the kinetic energy of these grains is converted into potential energy. Therefore, the grains are hurled perpendicularly upwards. Assuming that all powder grains in the sphere of influence of the jet lift themselves by 10 mm, the necessary initial speed of the grains (v_k) can be calculated. This speed leads to the needed momentum (p_k) and the required number of accelerated electrons (A_r). With this number the duration (t_r) of EB impact onto the powder can be calculated.

- Beam spot diameter
- r = 0,1 mm
- Beam current I = 1mA

Mass of a powder grain $m_g = 1,11 \cdot 10^{-10}$ kg
Diameter of a powder grain $f = 3,0 \cdot 10^{-5}$ m
Height of hurled powder $h = 10$ mm

$$v_g = \sqrt{2 \cdot g \cdot h} = 0,140 \cdot \frac{m}{s} \quad (3)$$

$$p_g = m_g \cdot v_g \cdot \frac{r^2}{f^2} = 1,727 \cdot 10^{-4} \text{ Ns} \quad (4)$$

$$A_r = \frac{P_g}{P_e} = 9,648 \cdot 10^{17} \quad (5)$$

$$t_r = \frac{A_r \cdot e}{I} = 15,46 \cdot s \quad (6)$$

According to this calculation, the electron beam would have to affect the powder for a duration of 15 seconds in order to produce the momentum necessary for lifting it on a height of 10 mm. However, not only the powder directly hit by the EB, but also the surrounding powder actually spreads within approx. 1.2 seconds. In the experiments some powder grains actually were lifted 0,95 m up to the filament and the entire powder bed was hurled at least 100 mm beyond the working surface. Besides, no change of the spreading could be caused by altering the accelerating voltage (100 kV, 80 kV and 60 kV) which changes the electron beam momentum. This shows that the momentum is not applicable as a causal physical effect.

Electrostatic charge:

A further reason for spreading of the powder is potentially the electrostatic charge of the powder particles. This effect arises, if single powder particles are charged electrically, because the electrons cannot flow off. Since the electrons of the beam are distributed in the powder, all particles are electrical negatively charged and thus repel themselves mutually. In preliminary experiments it was stated that the powder possesses practically electrically isolating characteristics. This also corresponds with the preceding calculations of the powder's properties according to Sih and Barlow [11]. No current is flowing, because the contact areas of the grains are too small. Only if temperature is rising, the electrical conductivity of the powder approaches rates of bulk material, since single sinter bonds connect the grains. For the estimation of the impact of this physical effect the Coulomb force is used, with which the arising forces between two charged particles can be calculated. The charge per powder particle is measured by the number of grains and the number of electrons, assumed that the EB hits the powder with 100 W power.

Beam current $I = 1$ mA

Irradiation time $t = 1$ s

Number of grains hit by beam $A_g = r^2/f^2$

Electric charge of the EB Q

Electric charge of one grain Q_k

$$Q = I \cdot t = 1 \cdot mC \quad (7)$$

$$Q_g = \frac{Q}{A_g} = 9 \cdot 10^{-8} \cdot mC \quad (8)$$

On the assumption that only two of the powder grains with the appropriate charge quantity are located next to each other, their repulsive forces can be measured using the formula for Coulomb force:

$$F = \frac{1}{4\pi\epsilon} \cdot \frac{Q_g^2}{f^2} = 2,426 \cdot 10^{-6} N \quad (9)$$

The result is a force which is multiple times larger than the weight of a particle of $1.08 \cdot 10^{-9} N$. The electrostatic charge of the powder particle is thereby clearly identified as the major effect for the spreading of the powder. Besides that, the effect of the spreading is propagated to the adjacent powder. Though the irradiation time is set to 1-2 s., the powder in a radius of about 50 mm is hurled. As soon as the powder which is exposed directly to the EB is spread, the electrons can diffuse into the building plate and charge again surrounding powder particles.

Thus, it could be shown that primarily the electrostatic charge of the powder grains is a capital cause for the effect for spreading the powder.

Counteractive Measures

In the following, five methods are discussed as counter measures. These measures particularly aim to accelerate the flow of electrons off the powder and thus to avoid the identified effect of the electrostatic charge.

1) Keying of the building plate: The smooth surface of the building plate manufactured by milling offers little contact area to the powder grains of the first layer. From the keying of the surface of this plate more edge contacts and/or larger contact areas between powder and plate result, whereby the flow of the electrons is facilitated. Investigations showed that this proceeding has only small influence on the spreading. This is to be explained with the fact that already the first coated powder layer consists of several powder particles laminated one above the other. Thus, the lowest powder particles cause only a small portion of the total resistance of the powder.

2) Preheating the powder: From preheating the powder, sinter bonds [9] result between several powder particles, which enable a fast flow of the electrons and thus, the electrical conductivity of the powder material increases. Yet, these sinter bonds can cause a high expenditure for the removal of remaining powder after the building process. This fact leads to problems particularly with complex or internal geometries, for instance, conformal cooling bores in the parts.

3) Enlargement of the building platform: The impact of the building platform during the irradiation is comparable to a condenser. A thin plate charges itself crucial faster since it can store relatively few electrons. In experiments the thickness of building plate was varied between 12 to 15 mm. A clear improvement of the process reliability was determined and more power was placed on the powder. However, the spreading of the powder could not be avoided.

4) Decrease of electrical resistance to the grounding: The discharge of the building plate is reduced due to the long way from the powder to the grounding. The electrons have to flow

through the building plate and the parts of the mechanism beneath the plate. For proper grounding, a copper electrode was put directly from the building platform to ground potential. Above all, this measure showed substantial influence on the effect of spreading.

5) Use of adapted powder systems: Gas atomization produces spherical grains. These particles have only small areas of contact. By the use of water atomized and therefore non-uniform grains, the reliability of the process could be increased. The different shapes of the particle cause increased electrical conductance between the powder surface and the building platform (see Figure 6). A relevant portion of process stability was reached with this changeover.

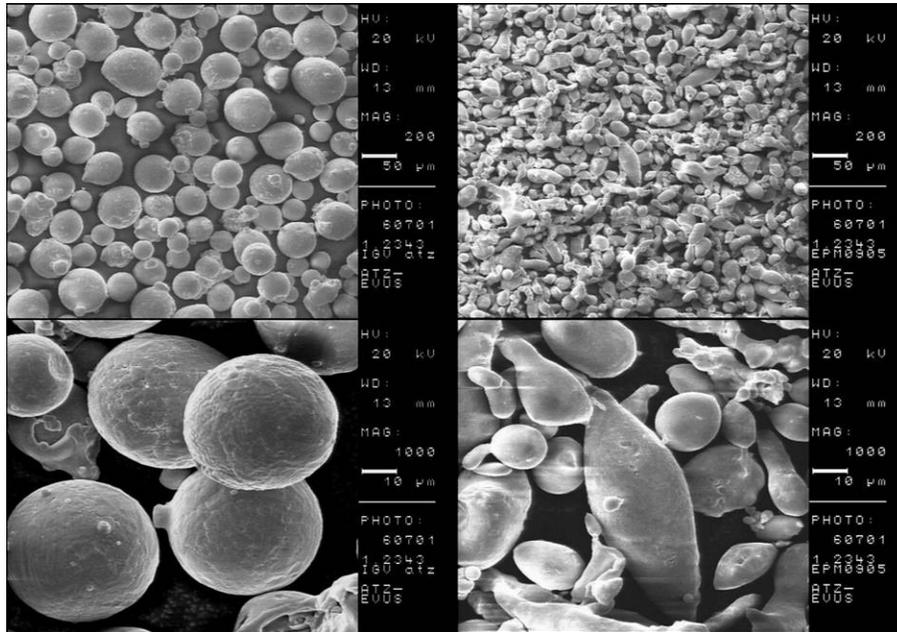


Figure 6: SEM micrographs of gas and water atomized metal powder (H11)

Altogether, a stable process could be accomplished with the measures mentioned. Spreading of the powder could be avoided the most by preheating and additional grounding of the water atomized powder. In Figure 7 the estimated impact of all measures is shown. This estimation is based on the maximum power that could be placed onto the powder together with the possible reduction of preheating. However, preheating the powder can not completely be replaced at the current conditions of the research. Additionally, the entire available energy of the electron beam (10 kW) cannot be put onto the powder. In order to avoid the spreading completely and to place more energy into the powder for sintering or melting, more comprehensive research work on EB sintering process is necessary.

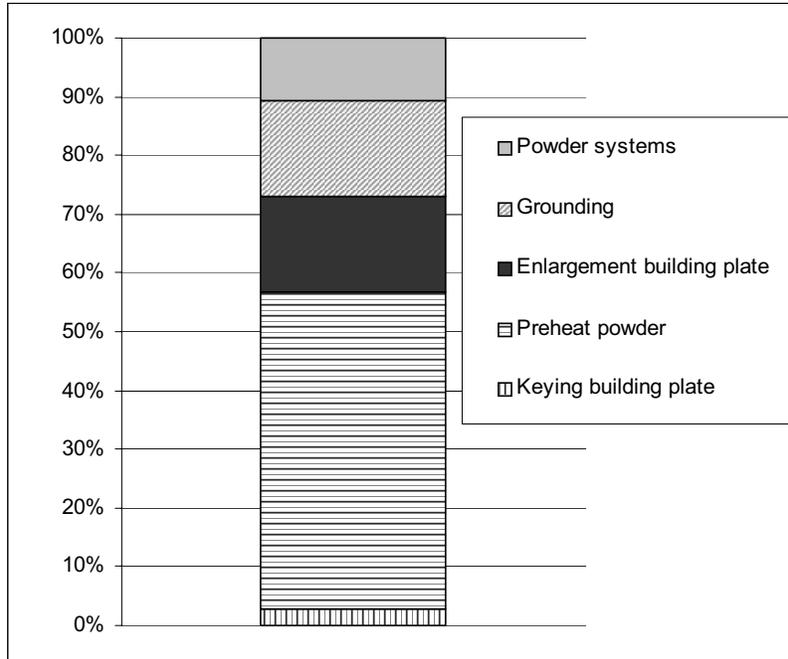


Figure 7: Estimation of impact of the measures

3D Sample Parts

The technical conversion of the presented measures realized a reliable process of EB sintering and thus, the possibility to produce three-dimensional parts. The parameter values of the experiments with single layers were used as a basis. These values were transferred only with small alterations for the first powder layers. Further layers are however characterized by a changed scanning strategy. This is mainly due to the changed temperature level. On the building plate and on the first two to three layers the temperature level is even higher because of the preheating. While the layer-based building process continues, the powder temperature differs in areas, where afore sintered material lies underneath the specific layer. In these areas the temperature raises more than in nearby areas because of the higher heat conductivity underneath.

By adjustment of the parameters beam power, preheating time, and exposure time the temperature can be leveled, so that specimens consisting of up to 120 layers could be developed (see Figure 8). From these specimens micrographs of the inside (A, B) and of the edge zone (C) were taken.

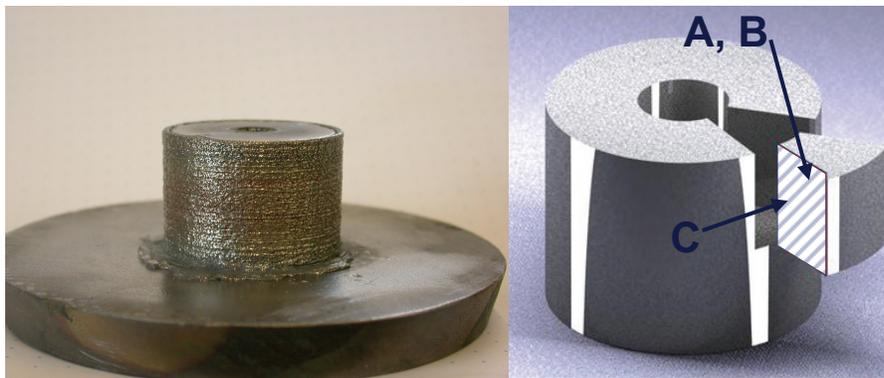


Figure 8: Specimen (H11, 30 x 30 x 25 mm) with building plate and CAD rendering

The fabricated specimens were supplied to different measuring and testing methods after removing from partly sintered powder. Apart from visual checks of the surface quality and measurements of the specimen dimensions, also hardness tests were accomplished as well as micrographs of cross sections.

The analysis showed the fact that the specimens were hardened after the fabrication due to the fast cooling in the vacuum chamber. The structure in the specimens consists mainly of martensite and an interstage structure, which causes a hardness of 55 HRC. The cross section sample in figure 9 shows a continuous layer structure. Here, dark ranges were twice exposed to the EB, whereby different material properties result.

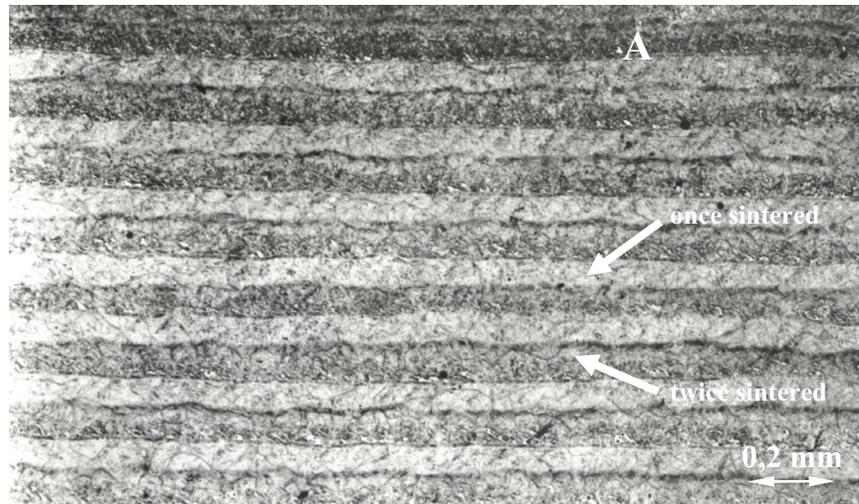


Figure 9: Micrograph, 50-times magnified

In a further magnification (see figure 10) it is recognizable that the material does not possess any sinkholes. The black circles consist of oxide deposits, which adhered at the surface of the powder particles before the sintering process. These can be avoided by the production and storage of the powder in inert gas.

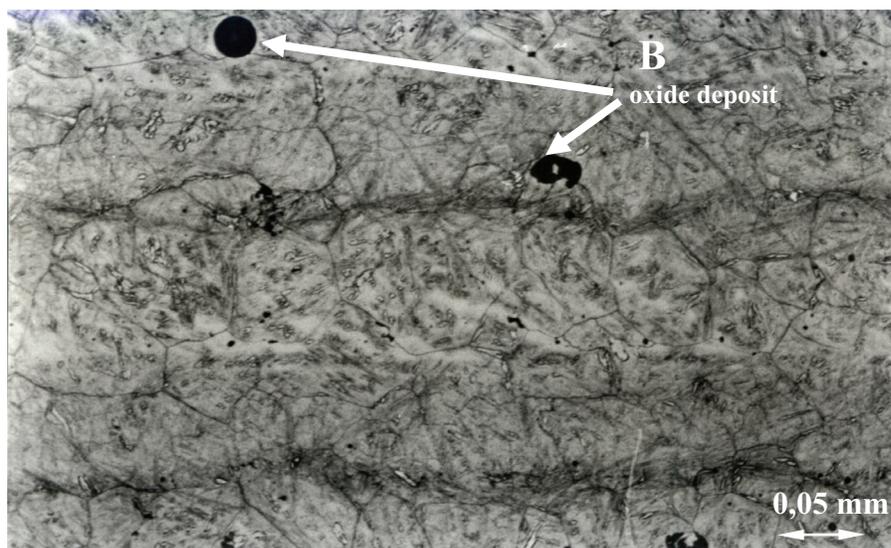


Figure 10: Micrograph, 200-times magnified

In the edge zone between the sintered specimen and loose powder (see figure 11) the number of pores from right (sintered) increases to the left (loose powder). In the center of the picture thin intergranular heat cracks are visible, which probably were created due to different cooling rates of both zones perpendicularly to the building direction.

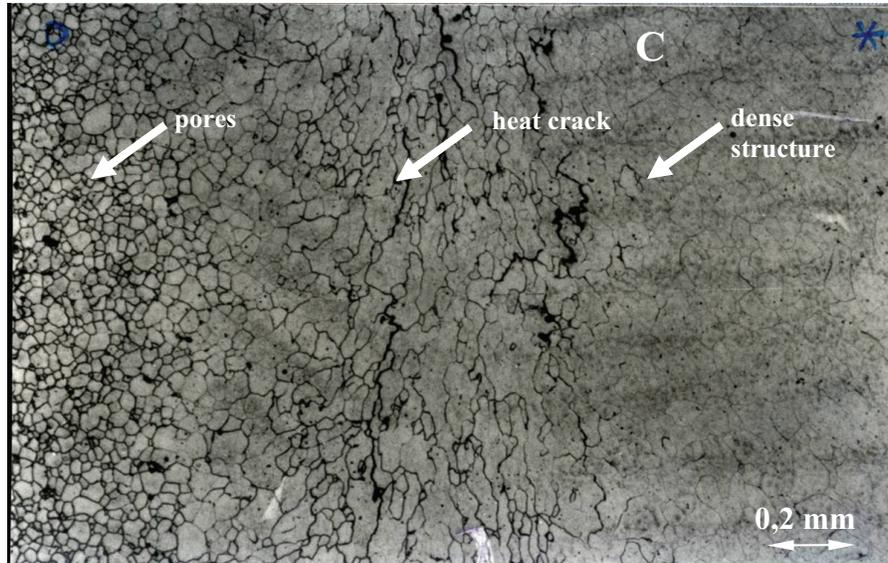


Figure 11: Micrograph of the edge zone, 50-times magnified

However, it is clearly recognizable that the specimens are not only sintered, but completely melted. The built structures do not exhibit characteristics of a metallic powder any more. The additive fabrication of the specimens is very clearly recognizable in the structure. Improvements in the processing (irradiation strategy and cooling speed after the building process) are particularly necessary regarding the edge zones, since heat cracks arise there.

Perspectives/Conclusion

The presented work points out the different potentials of the electron beam sintering and melting technology. Compared to the laser, there is higher beam power and faster control of the beam position available with an EB. These advantages are used already to a considerable degree; however, the potentials of the electron beam are not exhausted comprehensively. The beam-material interaction of the electron beam differs very distinctively from the laser beam. Here, electrostatic charge effects in the powder arise, which at first obstructed the stable manufacturing process of specimens. As a cause for this, the extremely low electrical conductivity of the powder was identified. Thus, the powder is charged, it repels itself and spreads in the vacuum chamber like in an explosion. Preheating the powder and the reduction of beam power are first counter measures, which though increase the process time. From the analysis of the physical effects and the micrographs, the adjustment of the processing and the use of an optimized powder material were derived. Thereby, the electrostatic effect was so far reduced that three-dimensional specimens can be manufactured. Further research work must concentrate on the optimized energy impact into the powder. Therefore, comprehensive basic knowledge is necessary regarding the beam-powder interaction, which will be accomplished in the course of the further research work at *iwb*.

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