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High Power Selective Laser Melting (HP SLM) of Aluminum Parts

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Abstract

Selective Laser Melting (SLM) is one of the Additive Manufacturing (AM) technologies that enables the production of light weight structured components with series identical mechanical properties without the need for part specific tooling or downstream sintering processes, etc. Especially aluminum is suited for such eco-designed components due to its low weight and superior mechanical and chemical properties. However, SLM's state-of-the-art process and cost efficiency is not yet suited for series-production. In order to improve this efficiency it is indispensable to increase the build rate significantly. Thus, aluminum is qualified for high build rate applications using a new prototype machine tool including a 1 kW laser and a multi-beam system.

Keywords: Selective Laser Melting (SLM); Aluminum; Direct Photonic Production; Series Production

1. Motivation / State of the Art

Europe and the rest of the world share the common objectives of providing abundant, clean, secure and affordable energy, whilst simultaneously achieving substantial reductions in greenhouse gas emissions to mitigate the potentially serious consequences of climate change. To achieve these aims a cleaner and more resource-efficient production in manufacturing, e.g. in the field of power generation, the aircraft and automotive industry as well as in other energy-consuming industrial branches, is inevitable.

From a production point of view Additive Manufacturing technologies like Selective Laser Melting represent one of the areas of greatest potential. Some of most outstanding ecological performance indicators are:

- *Resource savings* - The production of e.g. aero engine components traditionally creates a massive amount of waste, e.g. through machining from solid blocks. ('Buy to fly' ratios of 10 to 1 are not uncommon). AM techniques have the potential to approach zero wastage through the use of recycling within the processes. This also results in a reduction in emissions because fewer raw materials need to be produced. Considering moulding processes, e.g. die casting, lots of energy and resources are consumed to produce tools like dies and moulds. By contrast AM techniques provide an almost unchallenged freedom of design without the need for part-specific tooling.
- *Eco-Design optimization* - AM is a key enabler for the design and topology optimization because the additive nature of the techniques allows very complex parts to be created monolithically. This includes the design for light-weight structuring with a weight reduction by typically up to 50% e.g. in the case of automotive power train

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or turbine components as well as the “design for performance” rather than “design for manufacturing” see Figure 1).

- *Toxic chemicals reduction* - In comparison to conventional manufacturing technologies AM techniques do not directly use toxic chemicals like lubricant or coolant in any measurable amount.

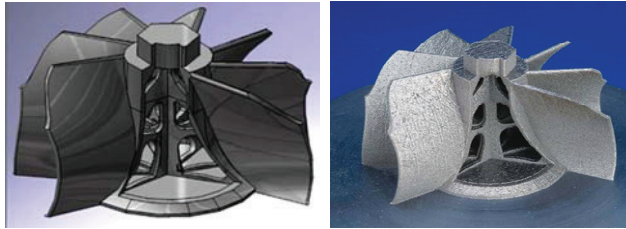


Figure 1. CAD image of a part created with an internal structure designed to reduce weight (left), component made out of IN718 by means of AM with a weight saving internal structure (right)

Yet, these AM technologies are mainly applied in design and product development rather than production since the build speed is too low. Hence, for the exploitation of sustainable AM techniques like SLM it is inevitable to enhance the performance and thus the build rate of currently available SLM machines. However, only little, if any research concerning SLM's performance and therefore its build rate has been conducted yet.[1] In order to come to a better understanding of the SLM process efficiency, the SLM process cycle time is divided into primary and auxiliary process time. The main process time only consists of the time that is needed to melt each single layer of a component whereas operations like substrate lowering and powder deposition are part of the auxiliary process time. With regard to this work the focus is on the primary process time because for a large volume that shall be additively manufactured this part of the total manufacturing time amounts to more than 80%. Large volumes can either consist of one large volume part or several low volume parts which are placed on a single substrate plate and manufactured simultaneously.

The main influencing variables of the primary process time are layer thickness (D_s), scanning velocity (v_s) and scanline spacing (Δy_s). The process related build rate is calculated according to the following equation:

$$\dot{V}_{process} = D_s \cdot v_s \cdot \Delta y_s \quad (1)$$

Scanning velocity and layer thickness are limited by the laser power available whilst scanline spacing is limited by the focus diameter ($\Delta y_{s,max}$ typically equals approx. 0.7 times the beam diameter). [2]

Among other topics, the Fraunhofer Institute for Laser Technology (ILT) has been qualifying aluminum alloys for SLM [4-7]. The primary objective during a material qualification for SLM is to obtain a component density approaching 100% without cracks and fusion defects. This requires evaluating the suited process parameters, especially scanning velocity and laser power. First investigations in [4] concerning the SLM-fabrication of aluminum gave evidence that it is possible to achieve approximately 100% density concerning the aluminum alloys AlMg3, AlMgSi0.5, AlSi12 and AlSi10Mg. The high reflectivity and thermal conductivity of aluminum compared to e.g. stainless steel require a laser power of at least 150 W at a scanning velocity of 50 mm/s to achieve densities of approx. 100% for a layer thickness of 50 μm . At a laser power of 250 W the scanning velocity can be increased which consequently increases the build rate [5-7].

In [4] first mechanical results for AlSi10Mg specimen (0° with reference to the applied load direction) with a layer orientation parallel to the tensile direction were determined for a layer thickness of 30 μm . A tensile strength R_m of 400 MPa and a yield strength $R_{p0.2}$ of 220 MPa with a breaking elongation of 11% were achieved. To evaluate the influence of different build-up directions [8] on tensile, yield strength and breaking elongation, tensile specimens according to DIN 50125 were built at 500 mm/s in three different directions (0° , 45° , 90° with reference to the applied load direction) and tested according to DIN EN 10002. Independent from the build-up direction the measured values for the tensile strength reach (Maximum $R_m = 355$ MPa) at least the minimum value (240 MPa) written in branch specific standards (Aluminiumschlüssel) for the die-cast material AlSi10Mg. Concerning the yield

strength the build-up direction shows no significant influence. The value of approx. $R_{p0,2} = 250$ MPa at all build-up directions exceeds considerably the minimum value of 140 MPa as specified in the branch specific standard (Aluminiumschlüssel). Additionally, all specimens exceed the appropriate standard value of 1% breaking elongation. In order to commercialize these results different companies like ConceptLaser, MTT-Technologies, EOS, Realizer, SLM Solutions and Phoenix Systems provide systems which are able to fabricate aluminum parts. Yet, the range of SLM-aluminum alloys is small. Only two aluminum alloys, AlSi10Mg and AlSi12, are provided. Furthermore, the build rate for the production of aluminum parts is not exceeding $5 \text{ mm}^3/\text{s}$.

Concerning materials with low thermal conductivity, e.g. tool steel, the experiments conducted to date indicate that there is only limited scope to increase the build rate based on higher laser power and a corresponding increase in the scanning velocity at a constant beam diameter. [3] Increasing the laser power while maintaining a constant beam diameter has the effect of increasing the intensity at the point of processing. This in turn leads to a higher evaporation rate resulting in a higher incidence of spattering which has a negative effect on the process as a whole. To avoid this, the beam diameter has to be enlarged. [3] By contrast, materials showing a high thermal conductivity, e.g. Cu and Al alloys, can be processed with increased laser power while maintaining a constant beam diameter. Hence, this work focuses on the increase of SLM's performance by increased laser power and scanning velocity with a special regard to the fabrication of aluminum parts. This will enable the exploitation of AM technologies' potential in light weight structuring and eco design.

2. Experimental Setup

Since currently available SLM machines provide laser power only up to 200 W (400 W) a new SLM machine is newly designed, both in terms of hardware and software, to contribute to an increased process efficiency. In order to increase the process related build rate significantly beyond $5 \text{ mm}^3/\text{s}$ the maximum laser power is extended to 1 kW.

The laser source used within this setup is a fibre coupled disk laser. The beam profile is Gaussian shaped. The flanks of the beam profile are steeper than those of a pure fundamental mode, whereas the top intensity is less complanate than a top hat beam profile. The focus radius measures $97.7 \text{ }\mu\text{m}$ and M^2 is calculated to 6.17 (see Figure 2).

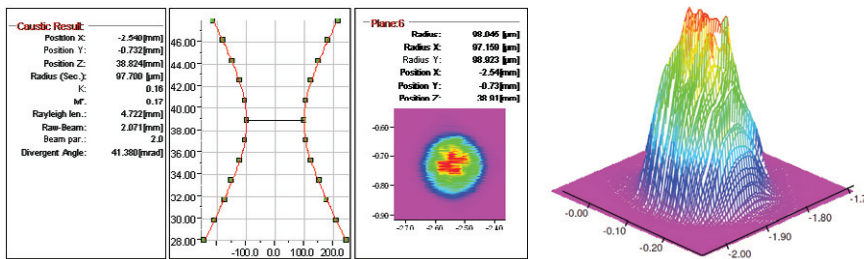


Figure 2. Caustic and beam intensity distribution measurement

For the manufacturing of multi-layer components each single layer is melted according to the 3-D CAD model. In order to smooth the component's outer surface, the contour of each layer is remelted before or after the hatchure (sum of the scan vectors of a single layer) is completed (see Figure 3, left).

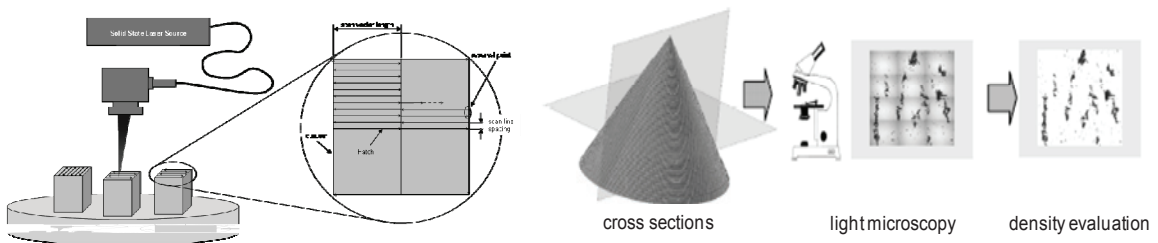


Figure 3. Schematic representation of layer wise building technique (left); Fabrication of cross sections and evaluation of density (right)

The prerequisite for manufacturing dense components are suitable sets of parameter values that can be identified on the basis of the smoothness of the generated layers, which permit an even application of powder. The density of the additively fabricated components is a crucial factor for their mechanical properties. Hence, an increase of the build rate without maintaining the density and thus the mechanical properties would cause serious problems for the industrial application of additive manufactured components. For the determination of the density, cross sections of the components are investigated by means of light microscopy, see Figure 3, left. The resulting pictures are statically filtered to suppress noise and segmented afterwards into molten material (white) and pores along with sinkholes, etc. (black), see Figure 3, right.

3. Results and Discussion

3.1. Density and Microstructure

In order to build dense components, it is important that the melt pool does not consist of different subareas but is cohesive and self-contained. [2] On the one hand the energy per unit length decreases with an increase of the scanning velocity. On the other hand the productivity of the SLM process is positively influenced by the scanning velocity. Hence, the laser power has to be increased if the scanning velocity increases. However, the augmentation of the laser power at a constant beam diameter increases the intensity at the point of processing which causes superheating and thus spattering and process instabilities.

The high reflectivity and thermal conductivity of aluminum require a laser power of at least 300 W at a scanning velocity of 500 mm/s (build rate amounts to approx. 4 mm³/s) to achieve densities approaching 100% for a layer thickness of 50 μm (Figure 4).

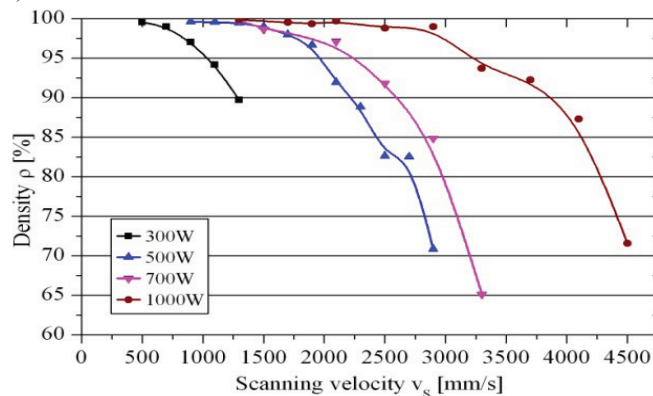


Figure 4. Density depending on scanning velocity and laser power with $D_s = 50 \mu\text{m}$, $\Delta y_s = 0.15 \text{ mm}$

Considering a laser power of 500 W the production of components with a density of approx. 100% is possible at a scanning velocity up to 1200 mm/s. With regard to the current state of the art for 50 μm layers, i.e. 500 mm/s (see section 3.1), an increase of around 200% (9 mm³/s) can be achieved. If the scanning velocity is further increased the energy per unit length is not sufficient anymore to fabricate dense components. Regarding a laser power of 700 W dense components can be manufactured at a scanning velocity up to 1600 mm/s. Hence, the build rate can be augmented by more than 300% (12 mm³/s) considering the current state of the art. At a laser power of 1000 W, the scanning velocity can be increased to approx. 2200 mm/s which consequently increases the build rate (approx. 16 mm³/s).

In Figure 5 the density at different scanning velocities and laser powers is exemplified by means of cross sections. The cross sections confirm the results shown in Figure 4. If the energy per unit length is too low e.g. at 2100 mm/s and 500 W the amount of imperfections increases therefore the density decreases. At 900 W (for 1300, 1700 and 2100 mm/s) the energy per unit is high enough to avoid imperfections and to reach densities above 99.5% but still small pores are detectable in the microstructure.

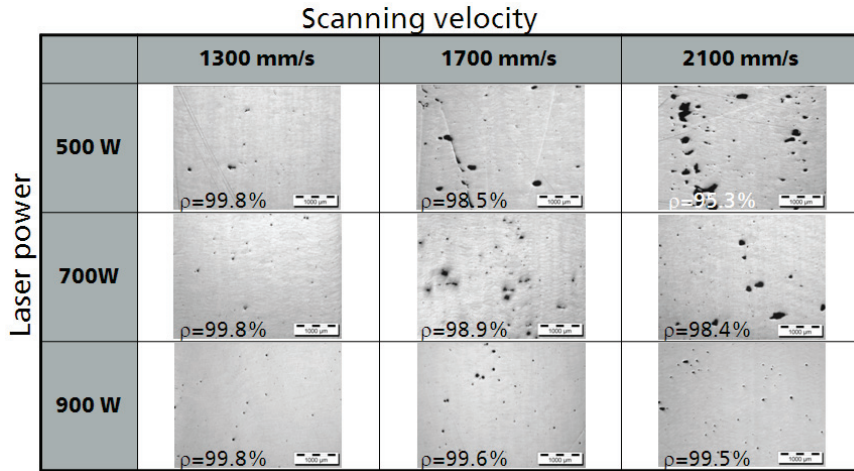


Figure 5. Densities by means of cross sections of SLM samples dep. on scanning velocity and laser power

The interaction time between the laser radiation and powder is approximately between 4×10^{-3} and 4×10^{-4} s. A higher cooling rate (approx. 7×10^6 K/s) appears compared to conventional processes like die-casting. Scanning velocity and preheating temperature offer the opportunity to influence the cooling rate [9]. For instance, the cooling rate can be augmented by increased scanning velocities resulting in a finer microstructure [7,8]. The microstructure illustrated in Figure 6 shows a dendritic solidification. The brighter areas are aluminum solid solutions and the darker are silicon or Al-Si-eutectics. Generally, SLM samples show a finer microstructure than e.g. die-cast parts due to the faster solidification.

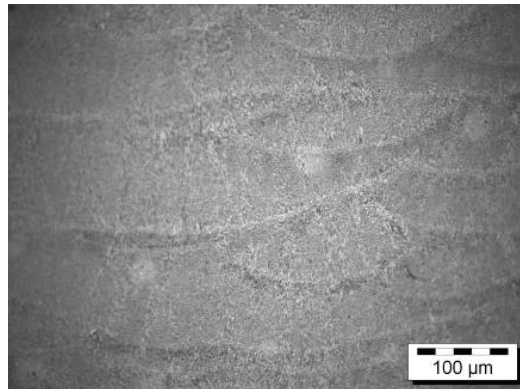


Figure 6. Microstructure of SLM sample built with $d_s = 0.2$ mm, $\Delta y_s = 0,15$ mm, $P_L = 900$ W $v_s = 2100$ mm/s, $D_s = 50$ μm

Besides scanning velocity, scanline spacing plays a major role in achieving higher build rates (see equation 1). In order to improve the build rate the increase of scanline spacing has been enlarged. The results shown in Figure 7 (left) shows that densities of approx. 99.5% are still reached with a scanline spacing of 0.2 mm (\approx beam diameter) for 900 and 1000 W laser power. For a scanline spacing of 0.25 mm ($>$ beam diameter) the density of samples produced with 900 W remains at approx. 99.5% as well. The lower density (approx. 96.8%) of samples produced with 1000 W and a scanline spacing of 0.25 mm is caused by spattering and process instabilities, which create imperfections. The amount of imperfections increases, because the area of remelting decreases, with increased scanline spacing. For a scanline spacing of 0.3 mm samples with a density higher 99.5% could not be built.

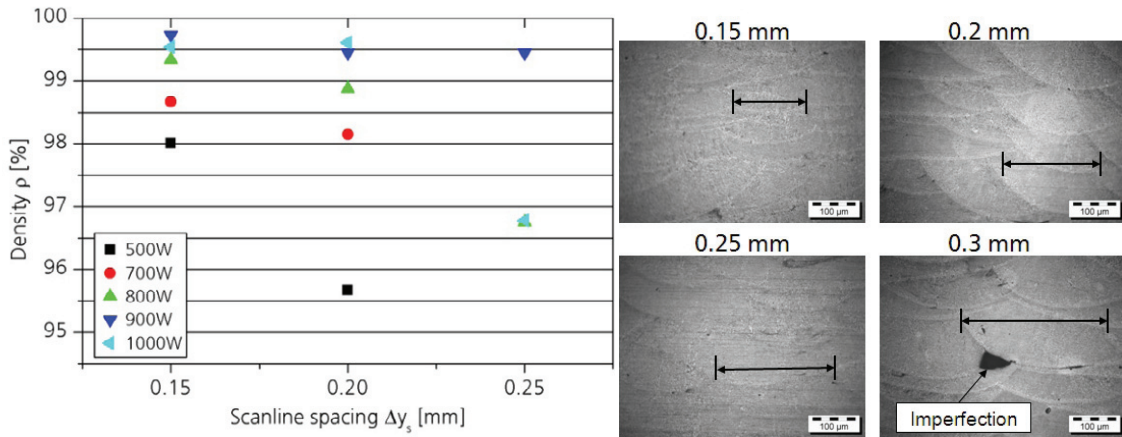


Figure 7. Density depending on scanline spacing, $P_L = 900\text{ W}$, $v_s = 1700\text{ mm/s}$, $D_s = 50\text{ }\mu\text{m}$ (left), Cross sections of SLM samples built with different scanline spacings (right)

This increase of scanline spacing from 0.15 to 0.25 mm raises the build rate by approx. 60%, while a density of at least 99.5% is achieved ($P_L = 900\text{ W}$, $v_s = 1700\text{ mm/s}$, $D_s = 50\text{ }\mu\text{m}$, build rate of approx. $21\text{ mm}^3/\text{s}$). This investigation demonstrates that the material AlSi10Mg, showing a high thermal conductivity, can be processed with a scanline spacing higher than the beam diameter. Hence the relation found in [2] ($\Delta y_{s,max}$ typically equals approx. 0.7 times the beam diameter) is not applicable for the material AlSi10Mg.

3.2. Mechanical Properties

Hardness is a first indication for the mechanical properties. Therefore, the hardness has been investigated for different process parameters. Figure 8 (left) shows the resulting hardness of SLM samples at different scanning velocities and different laser power. The hardness of samples built with scanning velocities between 1000 and 4000 mm/s is approx. 145 HV 0.1. (The hardness is not depending on the density. The density for samples scanned with 4000 mm/s is approx. 90%). The hardness is not influenced by using 500 or 900 W. In comparison to previous investigations [6,7], where an increase of hardness with higher scanning velocity has been demonstrated, the resulting hardness for this range of scanning velocity is not increased with higher scanning velocity. It seems that the hardness of the microstructure reaches a sort of maximum at approx. 145 HV0.1 and this already for scanning velocities of approx. 500 mm/s.

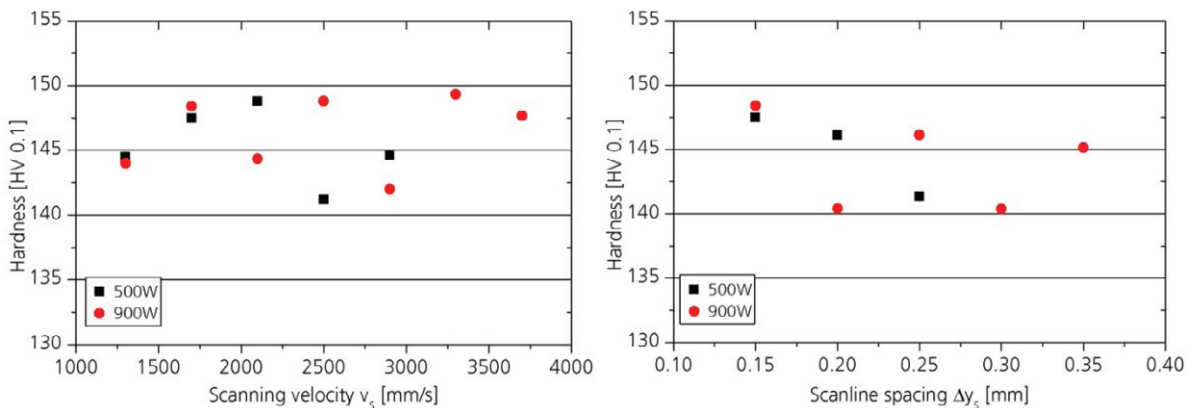


Figure 8. Hardness depending on scanning velocity (left), Hardness depending on scanline spacing (right)

Figure 8 (right) shows the hardness measured for samples built with different scanline spacings. The hardness is

not depending on the scanline spacing and reaches approx. 145 HV 0.1. As a result of the high scanning velocities and consequently high solidification rates the hardness of the SLM-made specimens is significantly increased by approx. 200% in comparison to the e.g. die casted parts. (According to EN 1706, Minimum hardness for AlSi10Mg is 74 HV). High hardness values indicate high tensile strength as well. In order to evaluate the mechanical properties tensile specimens were built according to DIN 50125 in three build-up directions (0° , 45° , 90° with reference to the applied load direction).

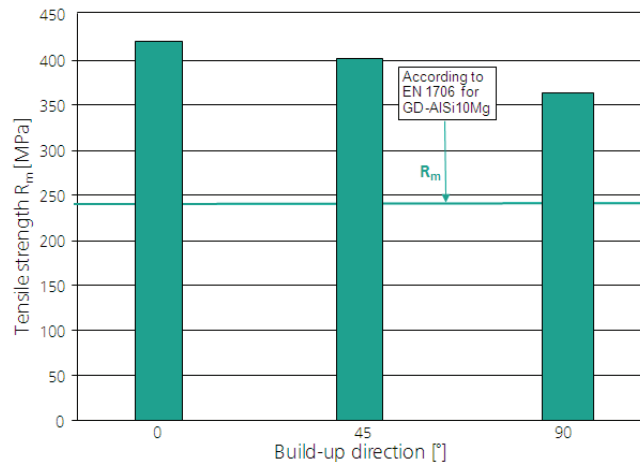


Figure 9. Tensile strength depending on build up direction

As shown in Figure 9, samples with a layer orientation parallel to the tensile direction (0°) show the highest tensile strength ($R_m = 420$ MPa), those built with a layer orientation perpendicular to the applied load (90°) show the lowest strength ($R_m = 360$ MPa). Independent from the build-up direction the measured values for the tensile strength outreach the minimum value ($R_m = 240$ MPa) according to EN 1706 for the die-cast material AlSi10Mg. The results of static tests so far demonstrate that the mechanical properties of the SLM AlSi10Mg specimens obtain at least the mechanical properties of serial-produced die-cast AlSi10Mg.

4. Summary

Additive Manufacturing technologies like Selective Laser Melting represent one of the areas of greatest potential to achieve a cleaner and more resource-efficient production in manufacturing. Yet, to date AM technologies are mainly applied in design and product development rather than production since the build speed is too low. Hence, for the exploitation of sustainable AM techniques like SLM it is inevitable to enhance the performance and thus the build rate of current process.

The results of the investigation demonstrate that the build rate for the production of AlSi10Mg parts can be increased by using a 1 kW laser. Due to the higher laser power the scanning velocity and scanline spacing have been enlarged while reaching densities above 99.5%. The state of the art build rate of approx. $5 \text{ mm}^3/\text{s}$ [6,7] can be increased to approx. $21 \text{ mm}^3/\text{s}$. This result is of major importance to future industrial applications of the technology, especially in the field of eco-designed products where high degrees in freedom of design are mandatory. Furthermore, first investigations of the mechanical properties, e.g. hardness of approx. 145 HV 0.1 and tensile strength of around 400 MPa promises sufficient mechanical properties which have to be analysed in detail in the future. The combination of high power selective laser melting with its unchallenged freedom of design and the use of the widely employed aluminum alloy AlSi10Mg is promising for the creation of newly eco-designed components in various industries.

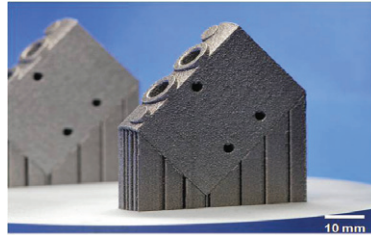


Figure 10. Produced Al-part with 1 kW laser power with a build rate of approx. 21 mm³/s, Courtesy of Festo AG & Co. KG

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