Selective Laser Melting of Aluminium Die-Cast Alloy

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Abstract

The additive manufacturing technology Selective Laser Melting (SLM) is used for direct fabrication of metal-based functional components. SLM is well established in serial production for dental restoration as well as for tooling. Main concern for industrial application remains the scope of processible materials and resulting mechanical properties. Towards processing of aluminium alloys commercially available systems exist with comparability in terms of applied process parameters and resulting mechanical properties remaining a challenge. Often no data are available concerning process parameters and mechanical properties. This holds especially for High-Power SLM systems with increased build rates as a result of extended laser powers of up to 1 kW. Especially when processing aluminium alloys the solidification conditions significantly affect the resulting microstructure in terms of size of dendrites and grains. Consequently, the present paper systematically investigates and correlates the process parameters (e.g. laser power, scan speed, layer orientation, preheating, etc.) on the microstructure and resultant mechanical properties for the die-cast alloy AlSi10Mg. At this, underlying phenomena for typically observed anisotropy of mechanical properties in dependence on layer orientation are further specified.

1 Introduction

Selective laser melting (SLM) is one of the powder-bed based additive manufacturing (AM) technologies. In order to manufacture a component with SLM the CAD model is sliced into layers (typically 30 µm). Layer-by-layer the component is built-up by melting the powder layer locally with a laser beam. Components manufactured with SLM offer a high geometrical flexibility and accuracy without almost any loss of material. This leads to resource savings and eco-design optimization. With regard to the state-of-the-art the suitability of SLM for small series production has already been established e.g. for steel.[1, 2] However, SLM's state-of-the-art process and cost efficiency of cast aluminum alloys is not yet suited for series-production. In order to improve this efficiency investigations were made to increase the build-up rate.[3-6] An increase of the laser power, layer thickness or laser beam diameter is mentioned to reduce the process time (The process-related build rate is determined by the product of hatch distance Δy_s, layer thickness D_s and scan speed v_S).

A widely studied material in SLM is cast-alloy AlSi10Mg. Buchbinder showed in [4, 7-11] that AlSi10Mg is a qualified material for SLM by producing components of nearly 100% density. Furthermore Buchbinder showed in [9, 11] that AlSi10Mg components have a wide range of mechanical properties depending on the solidification process. L. Thijs investigated that AlSi10Mg components manufactured by SLM have an extremely fine microstructure and hence a high hardness. [12] Kempen even observed in [13] higher mechanical properties of AlSi10Mg-components or at least comparable to the cast AlSi10Mg material. Further details of the investigations on aluminum alloys can be found elsewhere [11, 14].

However, the state-of-the-art process and cost efficiency is not yet suited for the production of higher lot sizes. To produce in series and for higher lot sizes using SLM, increased process productivity is necessary. For this reason first commercial SLM systems are available which are equipped with a 1 kW laser source. First investigations showed that the build rate is increased significantly (up to factor 5) using higher laser power for the processing of aluminium alloys.[3-6]

Despite all this progress there is still a big lack of knowledge and understanding about the correlations between process parameters (e.g. laser power, scan speed, layer orientation, preheating, etc.) and the resulting microstructure respectively mechanical properties. This holds especially for High-Power SLM systems with increased build rates as a result of extended laser powers of up to 1 kW. For the mechanical properties of aluminium alloys with 1 kW laser power are no data available for instance.

2 Experimental Design

The approach for the investigation of different influencing factors like laser power P_L, scan speed v_S, layer orientation or preheating on the static mechanical properties (R_m, $R_{p0.2}$, A_g) of SLM samples built out of AlSi10Mg is as follows:

- Influence of *laser power* and *scan speed* (build rate):

Tensile specimens were built with approx. 4 mm³/s (P_L = 240 W, v_S = 500 mm/s) and 20 mm³/s (P_L = 960 W, v_S > 1000 mm/s) build rate.

- Influence of *build-up direction*:

Tensile specimens were built in two build-up directions (0°, 90° layer orientation with reference to the applied load direction, Figure 1)

- Influence of *preheating*:

Tensile specimens were built without preheating and with preheating temperature (T_V = 220°C) for each build-up direction.

2.1 Machine Setup

The SLM process is carried out in an experimental machine in which an 1 kW Nd:YAG Single Mode laser from IPG with a wavelength of 1070 nm is used. The optical setup is designed regarding high laser beam intensities (e.g. components out of fused quartz glass) to minimize effects like thermal shifts or drifts. Using this setup the smallest possible laser beam is 50 µm (focus). In the following investigations the used beam diameter is approx. 200 µm (defocussed, Gaussian like intensity distribution) and the powder layer thickness is approx. 50 µm.

Parts were built under an argon protective atmosphere, with an oxygen amount below 1000 ppm. The SLM process chamber of the laboratory system is equipped with an integrated heating system for the substrate plate (up to 500°C). With the preheating system, the microstructure and mechanical properties can be influenced. Furthermore the residual stresses and distortion of the parts can be decreased [10, 15].

An nitrogen gas atomized AlSi10Mg powder with spherical morphology and a grain size distribution of 25-45 µm (d_{10} = 15,8 d_{50} = 21,1 d_{90} = 44,6 µm) was used. Its nominal chemical composition was measured and it lies inside the tolerances according to DIN EN 1706.

2.2 Tensile Specimens

The tensile specimens were built according to DIN 50125 (B4x20) and tested according to DIN EN 6892-1. The specimens are reworked by cutting means to assure a smooth surface conforming to the standards. The shown values of the mechanical properties are average values of 5 specimens each. The process parameters (scan speed and hatch distance) to achieve relative densities higher than 99% for the SLM samples were previously determined by test cubes (10x10x10 mm³) for 240 and 960 W laser power. The densities of the tensile specimens were measured by means of cross sections and light microscopy of one specimen for each batch and build-up direction (Figure 2). The hardness measurement is done according to DIN 50133 inside of the tensile specimens along the build-up direction (Figure 2). The values shown are the average values from at least 10 measurement points.

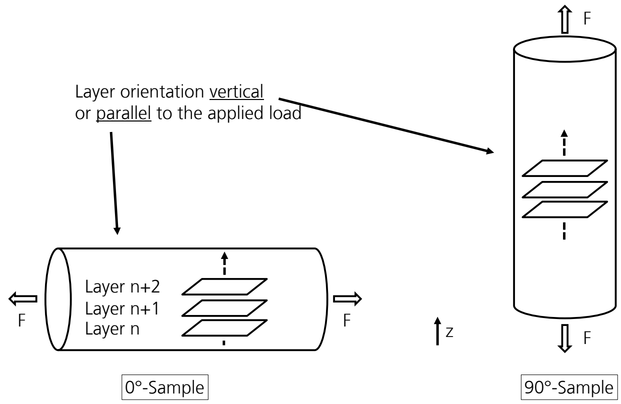

Figure 1: 0° and 90°-samples for tensile specimens, layer orientation depending on build-up direction (z)

3 Results

3.1 Density, Microstructures, Hardness

The primary objective during a material qualification for SLM is to obtain a component density approaching 100% without imperfections like cracks, fusion defects or pores. Thus a relative density above 99% is guaranteed for the tensile specimens (Figure 2, Figure 3).

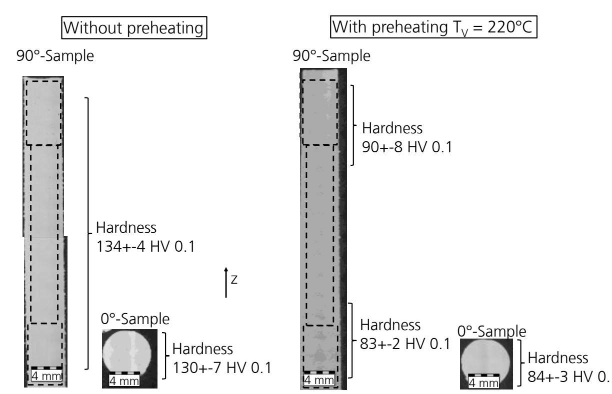

Figure 2: Cross section of samples for tensile tests, left: without preheating, right: with preheating (P_L = 960 W)

In Figure 3 and Figure 4 the density at different laser powers and scan speeds (build rates) is exemplified by means of cross sections. For both samples the density is higher than 99% and almost no imperfections are detectable except some little pores (< Ø20 µm). In general the microstructure (in Figure 3) for both samples built with different build rates are homogeneous and look similar although the laser power is by factor 4 different.

The SLM microstructure consists of cellular dendrites of the aluminum solid solution (white in Figure 3 & Figure 4) and interdentritic solidified eutectic Al+Si (grey in Figure 3 & Figure 4, see also [11, 12]).

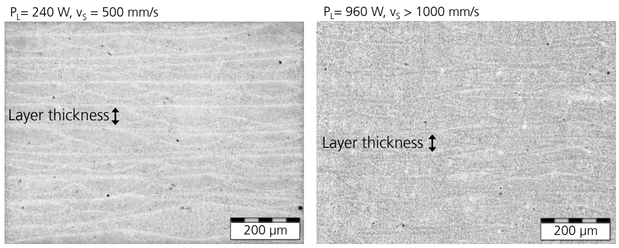

Figure 3: Microstructure of samples for tensile tests, left: P_L= 240 W, right: P_L= 960 W

The hardness of the tensile specimens built without preheating is for both parameter sets (different build rates) between 130 and 140 HV 0.1 high (Figure 2, left). During preheating significant coarsening of the dendrites (Figure 4) occurs from a temperature of 200°C, which is caused by a slower solidification (smaller cooling rate) [11]. In addition the grain size is increased due to preheating [11, 15].

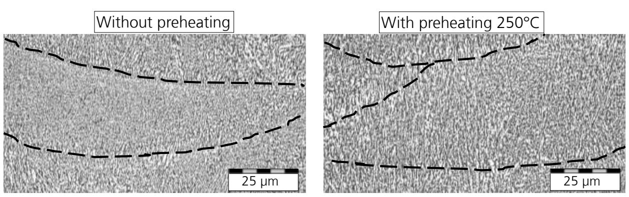

Figure 4: Microstructure of SLM samples built without (left) and with preheating (right) T_V = 250° [15]

These effects have an impact (influence), among others, on the hardness. The hardness falls to approx. 90 HV 0.1 at a preheating temperature of 220 (Figure 2, right). The reason for this is predominantly the microstructure coarsening (grain and dendrite size) [11, 15]. Thus, the hardness achieved, of all tensile specimens, still lies above the minimum value (75 HV 0.1) for the hardness of aluminum die-cast components out of AlSi10Mg (according to DIN EN 1706).

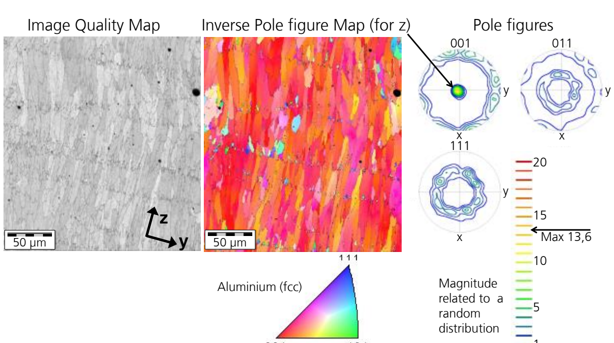

Figure 5: Exemplary EBSD results of one SLM sample (P_L = 960 W)

With the electron backscattering diffraction (EBSD) analysis the grain size, -orientation and texture in the SLM AlSi10Mg microstructure is investigated. In comparison to conventional cast microstructure the SLM microstructure is significantly finer and a distinct texture in direction of the build direction (z) exists (Figure 5), due to the highest thermal gradient in build-up direction.[11] The magnitude of the texture (factor 13, Figure 5) is predominantly depending on the solidification conditions. A faster solidification causes a grain refinement and the magnitude of the texture in direction of build-up direction increases (Figure 5).[11] Further analysis on microstructure dependent on different process parameters in correlation to the solidification conditions are discussed in [11]

3.2 Mechanical Properties

In general the static mechanical properties of AlSi10Mg tensile specimens show a strong correlation between the solidification conditions and the resulting properties. Slow solidification, e.g. due to low scan speed and/or preheating leads to a coarse microstructure (grains and dendrites) and thus to a more ductile behavior. This leads to lower hardness, lower static mechanical properties and higher breaking elongation (Hall-Petch-relation).

The tensile strength R_m and yield strength $R_{p0.2}$ of specimens built with 240 and 960 W independent of the build-up direction are in the same value range (R_m = 400-450 MPa, $R_{p0.2}$ = 210-240 MPa, Figure 6 & Figure 7).

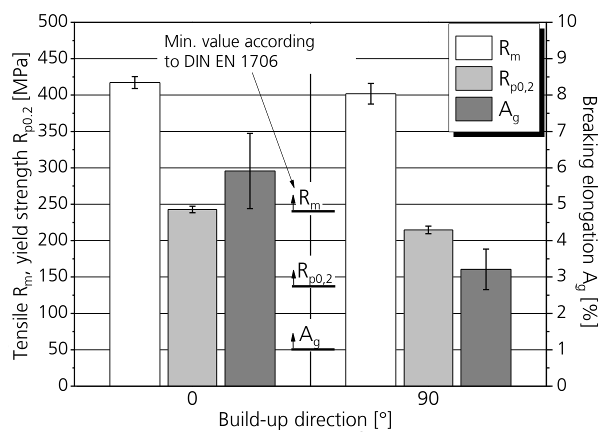

Figure 6: Mechanical properties for tensile specimens built with P_L = 240 W, v_S = 500 mm/s

The breaking elongation A_g of specimens built with 960 W is approx. 2-percentage points higher than of specimens built with 240 W. The grain size morphologies for both samples are not that much different, that the difference between the breaking elongations is explicable. One possible reason could be the higher intensity in the laser beam focus using 960 W and therefore more brittle elements are evaporated in comparison to the process with 240 W.

The breaking elongation A_g for specimens built with 240 W and 960 W is significantly depending on the build-up direction. Specimens with vertical layer orientation (90° build-up direction, Figure 1) to the applied load have almost by factor 2 smaller breaking elongations in comparison to specimens with a parallel layer orientation with reference to the applied load.

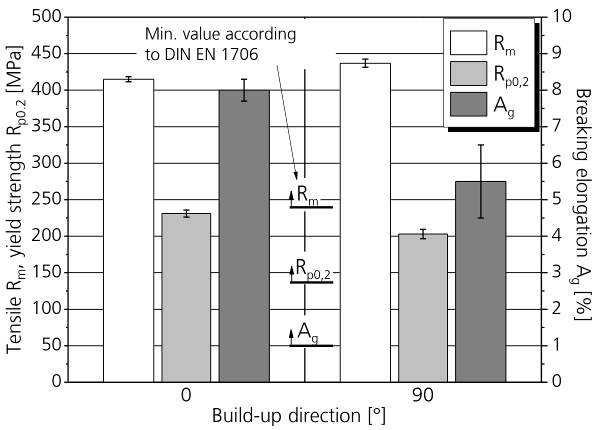

Figure 7: Mechanical properties for tensile specimens built with P_L = 960 W, v_S > 1000 mm/s

In the literature it is already shown that the static mechanical properties of AlSi10Mg specimens built with preheating and a laser power of approx. 200 W are decreased and the breaking elongation is increased [9, 11]. Regarding the tensile and yield strengths of specimens built with 960 W the same behavior appears (Figure 8). Due to the preheating respectively slower solidification the microstructure (dendrites) is coarser and therefore the mechanical properties decrease down to R_m = 300-250 MPa and $R_{p0.2}$ = 150-130 MPa. In contrast to the breaking elongation A_g of specimens built with 200 W and preheating [9] the breaking elongation A_g is decreased (Figure 8) in comparison to the breaking elongation of specimens built without preheating (Figure 7). The investigation of the grain sizes by means of the EBSD analysis of the microstructures of specimens (P_L = 960 W) built without preheating showed, that the grains are growing epitaxic over more than one layer (grain height 52+-27 µm, width 7+-2.5 µm). The fast solidification by using a high scan speed (v_S > 1000 mm/s) leads to this epitaxic grain growth over one layer [11]. In general the grain size increases due to slower solidification (preheating). Additionally at this point with preheating the epitaxic grain growth over one layer is decreased due to slower solidification. This leads in total to smaller grains and therefore to more grain boundaries in comparison to the specimens built without preheating. In general more grain boundaries decrease the breaking elongation. This could be one explanation for the decrease of the breaking elongation of specimens built with preheating and 960 W and a scan speed v_S > 1000 mm/s.[11]

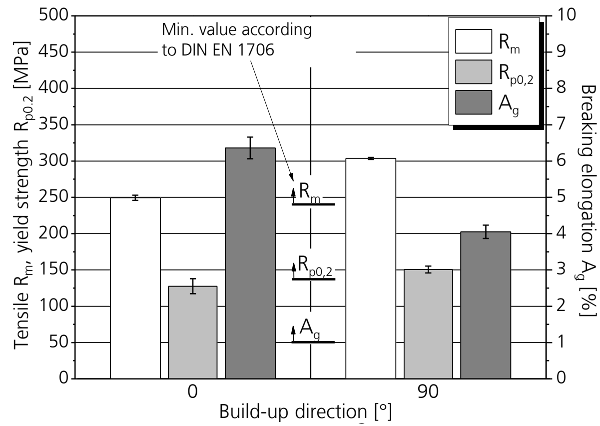

Figure 8: Mechanical properties for tensile specimens built with P_L = 960 W, v_S > 1000 mm/s and T_V = 220°C

Overall the static mechanical properties of the SLM AlSi10Mg specimens obtain at least the mechanical properties of die-cast AlSi10Mg components according to DIN EN 1706 specifications.

3.3 Discussion about the Anisotropy

Typically in the literature layer-based materials are known as anisotrop. Regarding SLM the general statement is that vertical layer orientation with regard to the applied load results in lower mechanical properties in comparison to parallel layer orientation [2, 16-22]. Mainly voids like fusion defects and pores are mentioned and of course the grain morphology. It is worth to look in more detail into the underlying phenomena regarding the anisotropy of SLM aluminium alloys. It is obvious that especially the breaking elongation independent of the process parameter is influenced by the layer orientation related to the applied load. At least three main influences are to be taken into account (Figure 9):

1. Voids (shape, size) like fusion defects and pores
2. Grain orientation (boundaries) and the magnitude of main texture orientation
3. Interfaces between melt tracks and layers

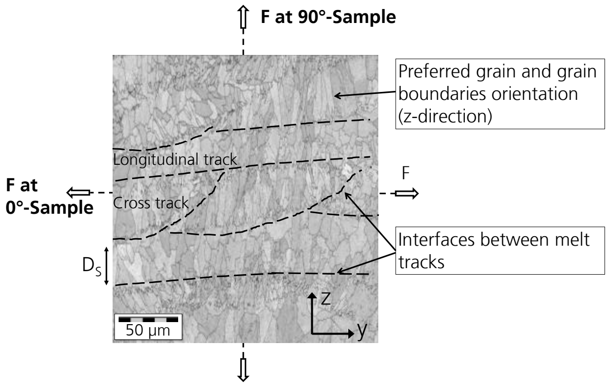

Figure 9: EBSD, Image Quality MAP of a SLM sample P_L = 240 W, v_S = 500 mm/s

Regarding the voids, the density measurement of the specimens showed almost no defects, therefore this influence can be neglected. The grain boundary orientations and the main texture orientation are both influencing factors which support the anisotropy. But the main influence is the orientation of the interfaces between melt tracks and layers. At the interfaces respectively melt boundaries the microstructure is due to different local solidification condition coarser.[11] Inside of these boundaries the silicium-rich phases are bigger in comparison to the phases inside of the melt track. These Si-phases are brittle in comparison to the Al-phases. In combination with the orientation of these Si-phases related to the applied load, they act as brittle elements which decrease the breaking elongation. This influence is higher for the vertical layer orientation than for the parallel layer orientation related to the applied load. To sum up even the local solidification conditions inside of one melt track influences the mechanical properties. Therefore a deep understanding of the solidification condition during rapid solidification is indispensable.

4 Summary

The results of the tensile tests demonstrate that the mechanical properties of the SLM AlSi10Mg specimens manufactured with High-Power SLM (1 kW) obtain values which are almost similar to the specimens built with 240 W laser power respectively lower build rate. Both, the mechanical properties of the specimens built with 240 W and 960 W laser power fulfill at least the mechanical properties of die-cast AlSi10Mg components according to DIN EN 1706 specifications. The microstructure (dendrites, grains and texture) investigation showed that the local solidification conditions inside of one melt track influences the mechanical properties significantly. Due to local solidification differences the anisotropy of the breaking elongation depending on the build-up direction is explained.

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