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# Microstructure and mechanical properties of as-processed scandium-modified aluminium using selective laser melting

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ABSTRACT

Additive manufacturing (AM) offers significant benefits towards optimized lightweight structures for aircraft and space applications. High-strength aluminium alloys are of special interest to reach a maximum mass reduction. The paper presents the development of appropriate selective laser melting (SLM) processing windows for a scandium modified aluminium alloy (Scalmalloy®), reaching densities >99%. The mechanical properties of as-processed material are analyzed, pointing out a comparably low anisotropy with regard to the build orientation. A fine-grained microstructure is observed next to regions of coarser, elongated grains. The paper discusses the observed microstructure, and concludes with suggestions for innovative material design for AM.

## 1. Introduction

Additive manufacturing technologies such as selective laser melting (SLM) are still on the threshold to industrial application. Especially in high-tech sectors the technologies offer benefits e.g. in terms of lightweight and functionally optimized parts and applications. Thereby the degree of an achievable mass reduction in lightweight applications depends not only on structural optimisations (e.g. the integration of lattice structures or topology optimization), but also on the mechanical properties of the lightweight material used. High-strength structural aluminium alloys are therefore of special interest for the SLM technology.

There is a basic need to develop aluminium alloys, designed specifically for additive manufacture, which will satisfy a broad range of industrial requirements. For lightweight applications, there are currently very few alternatives to AlSi10Mg. However, although AlSi10Mg can offer good mechanical properties, in both as-processed and heat treated condition, these properties can be influenced significantly by the selection of different SLM-processing parameters. This makes it more difficult for industry to use AM for real applications, and consequently every machine and processing window needs to be qualified separately. A potential solution to this problem is designing alloy systems being more suitable to the specific SLM process conditions, also with regard to variations of alloying elements,

### *1.1. State of the art*

To date, the most commonly used aluminium alloys for SLM are casting alloys from the 4XXXer series, containing silicon as the main alloying element. Examples are the AlSi12 and AlSi10Mg alloys, respectively. They were originally developed for casting processes, offering good castability and reduced shrinkage imparted by the presence of a relatively large volume fraction of Al–Si eutectic with a corresponding low melting temperature.

Mechanical properties of SLM-processed AlSi10Mg are shown in Table 1. Buchbinder [1,2] reports that changing the processing window (basically laser power $P_L$) influences the mechanical properties significantly, as for higher $P_L$ and consequently higher scan speed $v_s$ the cooling rate is increased, leading to a more fine grained material. Thijs [17] investigated how microstructures could be influenced by the implementation of different scan strategies and demonstrated that fine grain structures, which were developed as sub-micron cells, grew along ⟨100⟩ crystal directions from the melt pool border towards the centre of the melt pool, hence along the temperature gradient. Columnar grains are further growing at the centreline of the scan tracks along the build direction. It was also reported that due to the moving heat source and scan strategy applied, the thermal gradients and growth rate vary over the melt pool, and consequently the fineness of cells and possible textures changed over the cross-section of the melt pool. Hence anisotropic mechanical behaviour is a typical result for additively processed

**Table 1**
Mechanical properties for SLM-AlSi10Mg, serving as an age hardenable alloy for comparison to Scalmalloy®. Left column: Build orientation.

| | $\sigma_{0.2}$ (MPa) | $\sigma_{UTS}$ (MPa) | *A* (%) | Ref. |
|---|---|---|---|---|
| 0° | ≈240 | ≈420 | ≈5.9 ± 1 | (Buchbinder et al., 2011)[a] |
| 90° | ≈215 | ≈400 | ≈3.2 ± 0.5 | |
| 0° | 250 | 350 | 2.5 | [18] |
| 90° | 235 | 275 | 1.1 | |

[a] Without preheating of the build platform.

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aluminium, although reported property values are overcoming the requirements of EN-1706 for all build directions [2].

Siddique [13] investigated AlSi12, processed with different specific laser energy inputs, base plate heating and post-build stress relief combinations. He concluded that high strength can be achieved by developing a fine microstructure, but at the cost of fracture strain. Again changing the processing conditions significantly affected the mechanical properties, and a certain anisotropy is obvious.

Magnesium serves as the primary alloying element in 6XXX series alloys, with smaller additions of Si. These alloys are age hardenable. Jerrard et al. [6] showed the basic SLM-processability of an Al6061 alloy, and investigated the consolidation behaviour compared to pure Al. He found a better material density as Mg and Si significantly improved wetability; however, mechanical properties were not reported.

### *1.2. Scandium modified aluminium (Scalmalloy®)*

Scalmalloy® is a protected Sc- and Zr-modified aluminium alloy concept for AM procedures, developed by Airbus Group Innovations. The metallurgical origins can be traced back to materials developed, during the 1970s, in the US and former Soviet Union [7]. The addition of Sc to the Al alloy facilitates good levels of microstructural control, however, due to the high cost of Sc and high buy-to-fly ratios in conventional lightweight engineering, such alloys have not yet caught the attention of industry.

The effects of Sc on the properties of Al-alloys have been investigated by several researchers [4,9–11,20], and can be summarized as follows:

- The Al–Sc solid solution can decompose upon cooling, forming fine dispersed, fully coherent intermetallic $Al_3Sc$ precipitates of the cubic $LI_2$ crystal structure, acting as an age hardener and leading to high strength, with an strength increment of about 40 to 50 MPa per 0.1 wt.% Sc.
- The precipitation of $Al_3Sc$ takes place at higher temperatures (275–325 °C) compared to classical age hardening high strength Al-alloys (150–200 °C), leading to a high resistance against premature precipitates coarsening (e.g. strong heat affected zone occurrence).
- $Al_3Sc$ precipitates can prevent recrystallization even up to high temperatures.
- $Al_3Sc$ particles are known to be very effective for grain refinement, acting as seed crystals during solidification (heterogeneous nucleation).
- Sc is claimed to improve general weldability in Al alloys, e.g. for alloys which are susceptible to hot cracking and extended heat affected zone formation.

These effects are very welcome for AM where process-specific effects such as e.g. the formation of columnar grains and the corresponding anisotropic material behaviour is known for many alloys [14,19]. As in AM the fly-to-buy ratio is much closer to 1 and therefore the cost-influence of Sc is limited, Sc-containing alloys might be an interesting way to overcome some of these microstructure related properties. Schmidtke [12] proofed the basic SLM-processability of Scalmalloy®, and presented first mechanical properties in a post-built-up heat treated condition.

### *1.3. Concept of the paper*

The paper presents the development of an appropriate SLM processing window, and analyses the micro-structure in the as-processed condition. Static mechanical properties are presented and discussed. The paper concludes with assumptions on the formation mechanisms for the observed microstructure, which will serve as a basis for future alloy design for AM.

## 2. Materials and methods

### *2.1. SLM process*

The SLM-process is affected by many processing variables, including powder properties and machine setup. A ConceptLaser M2 machine was used equipped with a 200 W Nd-YAG laser operated in cw mode. The Gaussian beam focus diameter is ≈100 µm [3]. Next to a given powder the main parameters affecting the process are the laser power $P_L$, the layer thickness $t_L$, the scan velocity $v_s$ and the hatch distance $d$. Due to high reflectivity of aluminium, $P_L$ was set to the maximum of 200 W to optimize process productivity, and the layer thickness $t_L$ was 30 µm. The hatch distance $d$ was varied between 90 µm and 225 µm and scan velocities $v_s$ were varied to optimize material density. The volume specific energy density $E_V$ combines the parameters to a single main driving parameter for material density.

$$E_V = \frac{P_L}{v_s \cdot t_L \cdot d} \quad (\mathrm{J/mm^3}) \tag{1}$$

$10 \times 10 \times 10\ \mathrm{mm}^3$ test samples were produced using an alternating scan strategy from layer to layer, and bi-directional scanning within the layers as given in Fig. 1. To avoid over-heating effects in scan reversals, no "island-scanning" was applied, which would be the typical scan strategy used on ConcepLaser machines.

In total > 120 samples were produced, and for promising processing windows ≥3 samples were analyzed to assess the standard deviation of the material density.

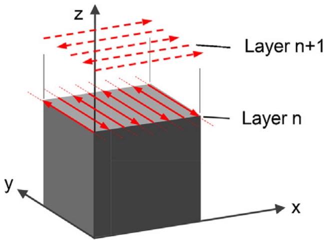

**Fig. 1.** Scan strategy for SLM test samples. *z*-direction indicates the build orientation.

### *2.2. Scalmalloy® powder raw material*

The chemical composition of the powder used during these trials is presented in Table 2. The particle size distribution was measured by optical particle analysis using PowderShape®. Thereby, the particles are filtered for an area-equivalent diameter < 120 µm; more details on the measurement principle are given by Spierings [16].

**Table 2**
Chemical composition (in wt.%) of the material according to supplier information. $D_{10}/D_{50}/D_{90}$ are the quantiles for number ($q_0$) and volume ($q_3$) weighted particles size distributions.

| Mg | Sc | Zr | Mn | Fe [12] | Others [12] | Al |
|---|---|---|---|---|---|---|
| 4.6 | 0.66 | 0.42 | 0.49 | ≈0.068 | ≈0.05 | Bal. |
| | $q_0$ $D_{10}$ | 3.9 µm | | $D_{50}$ 6.2 µm | $D_{90}$ 49.9 µm | |
| | $q_3$ $D_{10}$ | 38 µm | | $D_{50}$ 58 µm | $D_{90}$ 83 µm | |

### *2.3. Measurement techniques*

The density ($\rho$) of consolidated material was determined by the Archimedes method, using a theoretical maximum density of $2.67\ \mathrm{g/cm^3}$, as described by Spierings et al. [15]. Density measurements were corroborated by optical measurements showing minor residual porosity in the builds.

The microstructures of as-processed samples were analyzed using a FEI Helios dual beam FIB instrument equipped with an EDAX-EBSD system. Electro-polished surfaces were prepared using a Struers Tenupol 3 twin jet electro-polisher, a 5 vol.% perchloric acid in 95 vol.% methanol electrolyte, cooled to −50 °C, voltage of 25 V. High resolution EBSD maps were collected using a step size of 80 nm in areas of fine grained material (×10K magnification), and 250 nm steps were used to map large areas of coarse grained material at lower 750× magnification. All EBSD maps were recorded using beam conditions of 20 kV, 5.5 nA and a 12 mm working distance. The cutting plane orientations for SEM measurements are given in the respective figure captions, using the coordinate system shown in Fig. 1.