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SLM-processed Sc- and Zr- modified Al-Mg alloy: Mechanical properties and microstructural effects of heat treatment

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ABSTRACT

Traditionally 4xxx casting alloys are used for the additive manufacturing of structurally optimised lightweight parts in space, aerospace and automotive. However, for such applications there is a need for hardenable high-strength Al-alloys exceeding the properties of the 4xxx alloys family. The study analyses the hardness response of different heat treatment temperatures and hold durations applied to a Sc- and Zr-modified Al-Mg (5xxx-) alloy (Scalmalloy®) processed by Selective Laser Melting, and compares the mechanical properties and microstructure in the as-processed and annealed condition, and these properties are clearly related to the very fine grained microstructure. The results show that the static mechanical properties are exceptionally good with R_m-values exceeding 500 MPa along with almost no build-orientation related anisotropic effects, and a high ductility even in the heat treated condition. These properties are clearly related to the very fine grained material, along with the good hardenability of the alloy. The stress-strain curves show the typical Portevin-Le-Chatelier (PLC) effect as known for other 5xxx alloys. Due to significant grain boundary pinning by different particles the very fine-grained bi-modal microstructure originating from the SLM-process can be maintained even in the heat treated condition, and only a HIP treatment leads to local grain growth only in coarser grained regions.

1. Introduction

In many industrial sectors like space, aerospace and automotive, the performance of (metal) products depends on their weight. Weight reduction can be achieved by structural optimization, and the use of lightweight alloys like aluminium or titanium. Thereby, the weight reduction potential depends on the ability to produce parts with high structural complexity, as it is achieved e.g. by topology optimization, and the specific mechanical strength of the alloys used.

Additive manufacturing (AM) is able to fulfil both requirements. The technological benefits of AM come into effect especially at the production of parts with a complexity exceeding the possibilities of conventional manufacturing technologies. On the other hand, lightweight alloys like titanium and aluminium are readily processed by metal additive manufacturing such as Selective Laser Melting (SLM) once the process window for the specific alloy has been found.

State-of-the-art in SLM of aluminium are mainly 4xxx alloys, e.g. AlSi12 [1–3], AlSi10Mg [4–7] or AlSi7Mg0.3 [8]. Their near-eutectic composition facilitates SLM-processing due to the short solidification range, and the associated lowered risk of cracking. Good mechanical performances are reported for such alloys especially in the heat treated condition [3,4,9], although microstructure-related anisotropic effects with regard to the additive build orientation are evident, as reported by e.g. by Tang [10], and need to be considered. However, for structural applications in above mentioned sectors, hardenable 2xxx, 6xxx or 7xxx alloys are preferred. The SLM-processing of such alloys on the other hand is more difficult due to their potential for hot once the process window for the specific alloy has been found. Therefore alloy modifications can be a possible route to overcome potential processing constraints, leading to 'alloys for AM (SLM)'. That such an approach can be successful has been proven by Montero Sistiaga [11], who added Si to an Al-7075 alloy to at least minimize its hot cracking potential during SLM.

A newer SLM-processable and heat treatable Sc- and Zr-modified 5xxx alloy with significant advantages is the Scalmalloy® alloy system. In [12] the microstructure and related formation mechanisms of Scalmalloy® during SLM-processing have been presented in detail. This alloy offers high strength and ductility already in the as-processed condition, combined with comparably low anisotropic mechanical behaviour e.g. in $R_{P0.2}$, as discussed by Schmidke [13] and Spierings [14].

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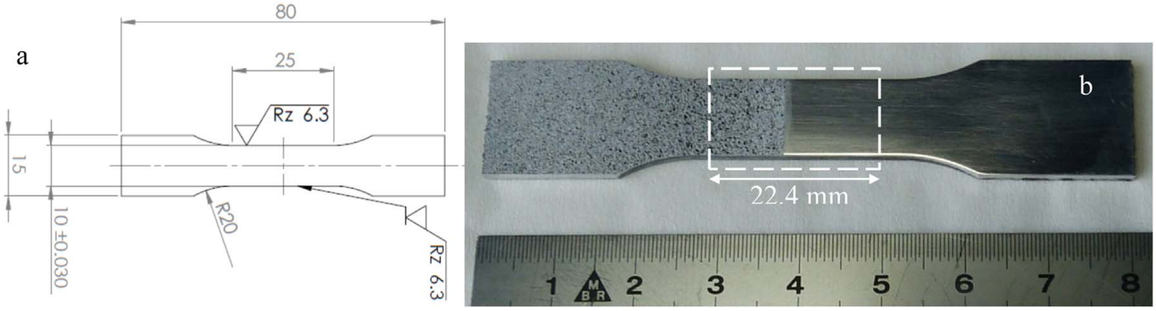

Fig. 1. a) Geometry of dog-bone like tensile test specimens. b) Image montage of the final prepared sample with left side coated surface, and right side as-peened surface. Dashed frame corresponds approximately to the measurement area with a length of 22.4 mm (Fig. 7).

By this the mechanical properties exceed reported values for traditional alloys like AlSi10Mg or AlSi12 [1–3,5,15]. Schmidke [13] discussed the static mechanical performance of heat treated samples in the 0°-, 45°- and 90° orientation, and found a very ductile fracture behaviour along the maximum shear stress orientation (fracture plane in 45° to the load direction). The tensile strength exceeded 520 MPa for all directions, having only a low anisotropy, which is consistent with initial findings discussed in [14]. The low anisotropy is related to the comparably fine grained microstructure with a high amount of equiaxed grains, and ageing improves the mechanical performance in Sc- and Zr-containing alloys due to the precipitation of (additional) $Al_3(Sc_x\ Zr_{1-x})$ particles from solid solution, as has been discussed for instance by Røyset [16] for a cast Al-0.2 wt%Sc alloy, or by Fuller et al. [17] for various Al-alloys with Sc weight-contents between 0.1% and 0.3%, and Zr weight-contents between 0% and 0.16%, respectively.

Literature reports about a wide range of ageing temperatures and times used for such alloys. Davydov et al. [18] analysed the micro-hardness evolution for temperatures between 300 °C and 500 °C for an AlSc0.4, and for an AlSc0.2 alloy at 400 °C and 450 °C, each with and without an addition of 0.15 wt% Zr. He found a very rapid hardening response of < 1 h for temperatures ≥ ≈ 350 °C, and much slower behaviour at 300 °C. Zr is reported to stabilize the microstructure, and to increase the strengthening remarkably. These findings are in good agreement with the ones from Fuller et al. [17], who used temperatures of 300 °C, 350 °C and 375 °C and ageing times up to ≈ 100 h. Røyset [16] investigated the fraction of transformed Al_3Sc at temperatures between 230 °C and 470 °C for hold durations up to ≈ 20 h, and constructed a time-temperature-transformation (TTT) diagram. He found a transformation time minimum at ≈ 310 °C (≈ 4 h for 95% transformation) for the coherent precipitation, and a time minimum at ≈ 410 °C where discontinuous precipitation dominates.

This paper discusses the development of a post-process heat treatment for a SLM-processed Sc- and Zr- modified 5xxx Al-alloy (Scalmalloy®), and presents the effects of a post-process heat treatment and HIP-processing on the static mechanical properties. The results are complemented with a microstructural comparison to the as-processed condition. Presented data provide an engineering starting point to design additively manufacture structural parts from that alloy.

2. Methods and materials

2.1. Sample production with SLM

The Scalmalloy® powder material with nominal composition of Al4.6Mg0.66Sc0.42Zr0.49Mn was used in a ConceptLaser M2 machine equipped with a 200W Gaussian Nd-YAG laser operated in cw mode. All samples were produced in a N_2 atmosphere using the maximum laser power available, and a 30 µm slice thickness. Details on the processing window development are discussed in Spierings [14]. $10\times10\times10mm^3$ cube samples were produced for the analysis of material hardness and microstructure, whereas static tensile test specimens were produced as cylinders with a length of 80 mm and a diameter of 7 mm in horizontal (90°) and vertical (0 °) build orientation to analyse mechanical properties using scan speeds of 170 mms^{-1} and 300;mms^{-1}.

For the heat treatment development, samples were produced at scan speeds of 170 mms^{-1} or 250 mms^{-1}. The energy density E_V used to produce the samples is calculated according to Eq. (1), with P the laser power, v_s the laser spot scan speed, d the hatch distance and t the slice thickness.

$$E_V = \frac{P}{v_s \bullet d \bullet t} \tag{1}$$

The tensile test samples were produced and analysed in different configurations: The E_V-levels were 135 Jmm^{-3} and 238 Jmm^{-3} corresponding to a scan speed of 300 mms^{-1} and 170 mms^{-1}, respectively, and surfaces were either in the as-built and peened condition, or the raw samples were machined to the final specimen geometry according to DIN-50′125-A5 with a surface roughness of N6 (R_a = 0.8 µm) or better, except for the HIPed samples which were turned according to DIN-50′125-B5 × 25. Samples were tested in the as-built and in different heat treated conditions, including hot isostatic pressure (HIP). For each configuration (build orientation, processing window, heat treatment) at least five specimens were prepared. Details on the sample configuration are indicated in the corresponding results section.

Additionally to the static testing of cylindrical tensile samples, flat dog-bone like specimens according to Fig. 1 with a thickness of 2.0 ± 0.02 mm were manufactured in a horizontal and vertical build orientation and HIPed (see below). These samples were used for optical space-resolved 2-dimensional strain monitoring by Digital Image Correlation, and the real Poisson constant of the alloy. The final samples were coated / sprayed with black-and-white dots in order to get optically traceable reference points.

2.2. Post-process heat treatment and HIP procedure

In order to promote controlled precipitation of $Al_3(Sc_1\ Zr_{1-x})$ particles a post-process ageing procedure was optimised for temperature and hold duration in two steps, using a ThermConcept KM/3 heat treatment oven and N_2 atmosphere.

In order to determine relevant heat temperature ranges where precipitation occurs, heat treatments at temperatures between 250 °C and 500 °C (at steps of 50 K) are applied for 4 h on samples processed at v_s = 170 mms^{-1}. This temperature range follows approximately the range used by Røyset [16] in the analysis of the Sc-fraction transformed to Al_3Sc particles, when he calculated the n-values for the Johnson-Mehl-Avrami-Kolmogorov (JMAK) relationship of transformation. This range also covers the aging times and temperatures used by Fuller [17] for different Al-Sc-Zr alloys. In addition the effects of hold duration was analysed on samples processed at v_S = 250 mms^{-1}. Hold durations of 0.5 h, 1 h, 2 h, 5 h, 10 h and 24 h were used for temperatures of 275 °C, 325 °C and 375 °C.

A HIP-process was performed at operating conditions over