Fatigue crack growth behavior and mechanical properties of additively processed EN AW-7075 aluminium alloy

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Abstract

Selective Laser Melting (SLM\textsuperscript{®}), an additive manufacturing (AM) technology, allows manufacturing of geometrically complex metallic parts directly. In the SLM technology, a high energy laser beam is applied to melt a thin layer of the metallic powder according to the information provided by CAD files. This layer-wise manufacturing offers the opportunity to create complex parts for application areas e.g., aerospace and automotive industries where the lightweight design has been and still is a priority for material development in recent years. Therefore, the materials such as aluminium alloys come into focus due to their low density and high mechanical characteristics. In view of these aspects, previously unused high strength aluminium alloy EN AW-7075 powder was produced by gas atomization and processed by SLM\textsuperscript{®} as presented in this paper. Initially, specimens were produced to examine monotonic and fracture mechanical properties in different building directions. The tensile tests and the fracture examinations show an anisotropic material behaviour. The fatigue crack growth curves have the double S shape, which is typical of aluminium. Mechanical characteristics obtained from the experiments are lower in comparison to the conventionally manufactured aluminium alloy properties.

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Keywords: Additive manufacturing; selective laser melting (SLM\textsuperscript{®}); aluminium alloy EN AW-7075; mechanical properties; fatigue crack growth behaviour

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1. Introduction

Additive Manufacturing (AM) is a new innovative technique that allows the direct manufacturing of complex products based on its 3D data in a layer-wise technology without tools like moulds, see Gebhardt (2013) or Gibson et al. (2010). In the meantime, there are lots of materials available for AM, e.g. plastics or metals, Wohlers and Caffrey (2015). They are used in several areas of application like aerospace, aircraft, medical technology and in the automotive industry. In order to fulfil the high requirements of these industries, high-quality products are expected. Selective Laser Melting (SLM®) enables the production of finished parts, which can be mechanically and thermally stressed to a very high degree; the parts are made of metal powder with a density of nearly 100%, Leuders et al. (2013), Riemer et al. (2014) and Thöne et al. (2012). This new technology offers the opportunity to produce complex and delicate structures, e.g. undercuts, lattice structures or topology optimized parts, Gebhardt (2013) or Gibson et al. (2010) or Riemer (2015). An Yttrium-laser melts the metallic powder locally and in the cause of coating, exposure and lowering the structure is created layer by layer.

The titanium alloy TiAl6V4 is frequently used for different technologies in the medical field because of its lower density, very high strength and biocompatibility, Jackson and Ahmed (2007). In the aerospace, aircraft and automotive industry the lightweight design is of paramount importance. Consequently, in these industries materials with low density and high mechanical properties are used such as aluminium alloys. Therefore, previously unused high strength aluminium alloys like EN AW-7075 powder was produced by gas atomization and processed by SLM®, see Fig. 1.

Aluminium has a high potential for lightweight applications due to its low density (2.7 g/cm³), see Davis (1996) and FKM-Richtlinie (2012) and good mechanical properties, Ostermann (2014). To achieve high mechanical properties of pure, face-centered cubic aluminum, Davis (1996), alloying elements like Si, Mg, Mn, Cu, Zn are required, Ostermann (2014). One of the commonly used alloy in airspace and automotive application is the high strength aluminium alloy EN AW-7075 – AlZn5,5MgCu in which the main alloying agent is zinc. To increase the mechanical strength of this alloy further, a specific heat treatment can be carried out. The EN AW-7075 alloy in conditional solution annealing and subsequent aged treatment (T651) achieves 540 MPa tensile strength at 7 % elongation, see DIN EN 755-2 (2008).

The aim of this study is to investigate the applicability of the high strength aluminium alloy EN AW-7075 focused on the application in lightweight structures. In this context, the mechanical properties such as tensile strength and fatigue crack growth behaviour are determined experimentally and given a recommendation for reliable
processing on a selective laser melting manufacturing system. As the final result, complex aluminium structures were additively generated and provide an explanation for the current properties.

2. Experimental details

In the present research, several EN AW-7075 specimens with standardized geometries were additively manufactured and examined for example cubes for optical micrographs, cylindrical tensile specimens for investigating the mechanical properties and compact tension (CT) specimens for the determination of fatigue crack growth behaviour. These specimens were manufactured on a SLM® 280HL (SLM Solutions Group AG) system with a build chamber of 280 mm x 280 mm x 350 mm, a 400 W Yttrium laser and in inert gas atmosphere. The platform was not heated. Following SLM® processing the chamber was flooded with nitrogen and the oxygen content is reduced below 0.2 %. For the manufacturing of specimens, EN AW-7075 powder was produced by gas atomization. In Fig. 2 the particle size distribution and the particle shape of the powder are illustrated. The mean particle size is about 42.1 µm. The particle shape exposed several spherical as well as longitudinal particles. There are also adhesions at the main particles, which have an irregular form.

By using Energy-dispersive X-ray spectroscopy (EDX) a chemical analysis of a powder particle was performed. The chemical composition according to the norm values, DIN EN 573-3 (2009), cast by gas atomization (measured by supplier TLS Technik GmbH & Co. Spezialpulver KG according EN 10204) and powder particle of the aluminium alloy EN AW-7075 are shown in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm value, DIN EN 573-3 (2009)</td>
<td>0.40</td>
<td>0.50</td>
<td>1.2-2.0</td>
<td>0.30</td>
<td>2.1-2.9</td>
<td>0.18-0.28</td>
<td>5.1-6.1</td>
<td>0.20</td>
<td>Balance</td>
</tr>
<tr>
<td>Cast / melting</td>
<td>0.20</td>
<td>0.20</td>
<td>1.60</td>
<td>0.05</td>
<td>2.5</td>
<td>0.20</td>
<td>5.80</td>
<td>0.01</td>
<td>Balance</td>
</tr>
<tr>
<td>Powder particle</td>
<td>0.40</td>
<td>0.32</td>
<td>2.13</td>
<td>-</td>
<td>1.95</td>
<td>0.26</td>
<td>5.10</td>
<td>-</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Initially, several process parameters were varied in order to find the best set of process parameters for the best possible result. For the experiments of this work, the following process parameters are applied, see Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser beam power</td>
<td>350</td>
<td>W</td>
</tr>
<tr>
<td>Laser beam diameter</td>
<td>0.20</td>
<td>mm</td>
</tr>
<tr>
<td>Laser scanning speed</td>
<td>930</td>
<td>mm/s</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>0.05</td>
<td>mm</td>
</tr>
</tbody>
</table>
With this set of parameters, specimens like cubes (10 mm x 10 mm x 10 mm), tensile and CT specimens were produced to examine the mechanical and fracture mechanical properties. In order to investigate the influence of the building direction regarding possible anisotropic behaviour, specimens with different orientations were manufactured. The CT specimens with a crack growth perpendicular to the building direction and the tensile specimen with the load direction perpendicular to the building direction are figured in Fig. 3 a as well as parallel to the building direction, see Fig. 3 b.

Two different conditions were taken into account. The condition “as-built” corresponds to the state immediately after the SLM® manufacturing process without any heat treatment. In order to achieve a better mechanical performance, the other specimens were heat treated, see Holt et al. (2000). These specimens were solution annealed for 1.5 hours at 753.15 K following by rapid quenching in water (293.15 K) and then aged for 6 hours at 443.15 K.

For the optical micrographs, each specimen was mechanically polished and as appropriate etched. The micrographic observation was conducted by using an optical microscope. The scanning electron microscope (SEM) analyses were performed on the tensile specimens to characterize the fracture surface with varying specimen conditions.

An universal testing machine, INSTRON 5569, was used for the characterization of the quasi-static properties. The tensile tests were displacement controlled with a crosshead speed of 5 mm/min according to the DIN EN ISO 6892-1 (2009) standard. The specimen geometry (A 6 x 30) was based on the norm DIN 50125 (2008). A minimum of three specimens was tested for each condition. By the use of an optical extensometer the elongation was measured at room temperature (293.15 K).

Analysis of crack growth behaviour under sinusoidal loading at a stress ratio $R = 0.1$ were conducted at ambient conditions (293.15 K). The CT specimens were manufactured according to the ASTM 647-08 (2008). For the fatigue crack growth experiments an INSTRON testing machine, Electro Puls™ E10000, was chosen. For continuously monitoring the crack propagation the direct current potential drop method was utilized at the measurement system MATELECT DCPD. The determination of crack growth values was conducted by the system FAMControl, see Sander and Richard (2004). The thickness of the CT specimen was 3 mm and the width ($w$) amounted 40 mm. This specimen was equipped with a V-shaped notch at a length of 8 mm. For the fatigue crack growth analysis, a crack length ($a$) range from 8 mm to 32 mm was chosen. The $a/w$ ratio was ranging from 0.2 to 0.8. In order to avoid crack initiation effects, the experimental data were evaluated starting from a crack length of 10 mm. To characterize the threshold value of stress intensity factor ($\Delta K_{th}$) a low stress intensity factor range ($\Delta K$) an exponential decrease of $\Delta K$ at a constant $R$-ratio was imposed. 20 Hz was the test frequency which was applied to specimens.
3. Results and discussion

The tensile mechanical properties from literature are compared to additively manufactured EN AW-7075 alloy in Table 3. The ultimate tensile strength (UTS) and elongation values are clearly lower than the values of the conventionally produced aluminium alloy. The UTS-values for the specimens manufactured with a load direction parallel to the building direction (Fig. 3 b) are in as-built condition by 203 MPa with a standard deviation of ±12 MPa and in heat treated condition by 206 MPa with a standard deviation of ±25.7 MPa. The elongation for parallel load to the building direction specimens are in as-built condition by 0.5 % with a standard deviation of ±0.2 % and in heat treated condition by 0.56 % with a standard deviation of ±0.11 %. The heat treatment has no significant influence on the mechanical properties. The quasi-static properties for the specimens with load direction perpendicular to the building direction (Fig. 3 a) show a significant reduction in comparison to the other building direction. In the as-built condition, UTS decreases to 42 MPa with a standard deviation of ±7.5 MPa and in heat treated condition to 45 MPa ±0.5 MPa. These results indicate noticeable anisotropic behaviour related to the building direction. Findings of anisotropic behaviour for other additively manufactured materials can be found in Riemer (2015) and Gebhardt (2014). Furthermore, the mechanical properties of additively manufactured aluminium are significantly lower than the values from literature DIN EN 755-2 (2008) of conventionally produced aluminium alloy EN AW-7075 T651.

<table>
<thead>
<tr>
<th>Condition</th>
<th>load direction</th>
<th>ultimate tensile strength (MPa)</th>
<th>elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-built</td>
<td>parallel to building direction</td>
<td>203 ±12</td>
<td>0.50 ±0.2</td>
</tr>
<tr>
<td>as-built</td>
<td>perpendicular to building direction</td>
<td>42 ±7.5</td>
<td>0.51 ±0.25</td>
</tr>
<tr>
<td>heat treated</td>
<td>parallel to building direction</td>
<td>206 ±25.7</td>
<td>0.56 ±0.11</td>
</tr>
<tr>
<td>heat treated</td>
<td>perpendicular to building direction</td>
<td>45 ±0.5</td>
<td>0.2 ±0.05</td>
</tr>
<tr>
<td>literature (T651), DIN EN 755-2 (2008)</td>
<td>-</td>
<td>540</td>
<td>7</td>
</tr>
</tbody>
</table>

The measured results of the analysis of fatigue crack growth employing direct current potential drop technique are illustrated in Fig. 4. These fatigue crack growth curves are determined on CT-specimens with crack plane parallel to the building direction (Fig. 3 b) for as-built and heat treated conditions.

Fig. 4. Crack growth curves for SLM®-processed EN AW-7075 in different conditions. Crack plane and growth are parallel to the building direction. Data for conventionally processed reference material by Sander (2008) and Eberlein (2016) are displayed in black and gray color.
The fatigue crack growth curves for both conditions have double S shape, which is typical of aluminium, see also Richard and Sander (2012). The threshold value $\Delta K_{\text{th},I}$ for the as-built condition (blue curves in Fig. 4) is by 1.77 MPa$\cdot$m$^{1/2}$ with a standard deviation of $\pm$ 0.08 MPa$\cdot$m$^{1/2}$. The crack path of the as-built specimen with the building direction shown in Fig. 5 a is displayed in Fig. 5 b. For the heat treated condition (red curves in Fig. 4) the threshold value $\Delta K_{\text{th},I}$ is by 1.58 MPa$\cdot$m$^{1/2}$ with a standard deviation of $\pm$ 0.03 MPa$\cdot$m$^{1/2}$ and the associated crack path is illustrated in Fig. 5 c. These results show that the heat treatment has no significant influence on the crack growth behaviour. The crack growth curves of a conventional processed material, Sander (2008) and Eberlein (2016), in T651 condition shows better fracture mechanical properties and higher threshold value.

For the CT-specimens which were built with a crack plane perpendicular to the building direction (Fig. 6 a) it was not possible to initiate a crack by cyclic loading. Fig. 6 b and Fig. 6 c show the failed CT-specimens with the crack paths. The clamping or force transmission point was the area of the failure, see Fig. 6 b. In order to increase the stress intensity factor on the crack tip the crack length was lengthened by machine up to 22 mm. Despite the cyclic loaded Mode I situation the crack grows parallel to load direction respectively parallel to the building direction, shown in Fig 6 c. Similar to the results of the tensile tests the fracture mechanical characteristics demonstrate an anisotropic behaviour related to the building direction. In case of the crack orientation perpendicular to the building direction, the specimens failed after the strength criteria.

Fig. 5. (a) Crack plane of CT specimen parallel to the building direction; (b) crack path of as-built CT-specimen; (c) crack path of heat treated CT-specimen.

Fig. 6. (a) Crack plane of CT specimen perpendicular to the building direction; (b) crack path of failed CT-specimen at force transmission point; (c) crack path of failed CT-specimen with machine lengthened crack to 22 mm.
Fig. 7 shows optical micrographs of the aluminum alloy EN AW-7075 after SLM processing. Arch-shaped lines resulting from an equally shaped melt pool during processing are visible, see Fig. 7 a. Solidification cracks were observed due to the high crack sensitivity of the aluminum alloy, Figures 7 b and 7 c. Alloying elements such as magnesium and copper can lead to a relatively large range of solidification temperature compared with binary alloys and increase potential cracks which leads to an early crack initiation under loading.

Fig. 7. Optical micrographs of the aluminium alloy EN AW-7075 after SLM processing: (a) cube region (polished and etched) with arch-shaped lines; (b) cube region (polished and etched) with cracks; (c) cube region (polished) with cracks.

These cracks seem to be a reason for the weak mechanical properties in the presented work, cf. Table 3. Moreover, the process parameters i.e. laser power, hatch distance and scan speed play a major role in affecting the mechanical properties. Consequently, different process parameters on the EN AW-7075 powder and possible post-treatments for the improvement of the mechanical properties have to be investigated in future work.

Figures 8 a and 8 b show scanning electron microscope (SEM) images of the crack surfaces after tensile tests for heat treated specimens, which were built horizontally (Fig. 8 a) and vertically (Fig. 8 b) regarding to the building platform.

In Fig 8 a, a crack propagates nearly perpendicular to the direction of the applied load. This perpendicular fracture leads a relatively flat surface at the break. The crack grows through the grain of the material and chooses the path of the least resistance. Therefore, it seems to be transgranular brittle fracture. In addition, the vertically built specimen (Fig. 8 b) shows dimples area after tensile test in comparison to the horizontally built specimens, which
suggests a ductile fracture behaviour. It confirms the results shown in Table 3 that the vertically built specimen showed more ductility comparing to other specimen conditions. Besides, non-melted particles were observed in this specimen. According to these findings, a relationship between non-melted particles, cracks and SLM process parameters are a major subject of a follow-up study. Table 3 compares the tensile results of the specimens manufactured by SLM and conventional methods. The vertically SLMed specimen shows a higher ultimate tensile strength and elongation to failure than the horizontally build specimen. It is assumed that different microstructures after the SLM process may be a reason for the improvement of the tensile strength. Moreover, microstructural evolution after SLM process will be detailed in the future work.

4. Conclusions

The results of the current work show that gas atomized powder from the aluminium alloy EN AW-7075 can be used to manufacture complex structures by selective laser melting. This work shows that under the presented conditions additively build structures cannot be used for high performance applications due to the low ultimate tensile strength at low elongation as compared to conventionally manufactured parts. The fracture mechanical performance as well as the threshold values of the stress intensity factor are below the known material values for this aluminium alloy. The results of the tensile tests and the fatigue crack growth behaviour on as-built and heat treated specimens demonstrate an anisotropic behaviour related to the building direction. The reason for the low mechanical properties can be found by process-induced initial cracks parallel to the building direction. A relatively large range of solidification temperatures can be one explanation for this phenomenon. In order to improve the mechanical properties, additional investigation with different process parameters on the EN AW-7075 powder and possible post-treatments is essential.

References

