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Microstructural and textural gradients in SLM-manufactured AlSi10Mg after low-draught cold-rolling and heat treatment

Z Liao¹, L Zhang¹,², X Huang¹,² and D Juul Jensen³

¹ International Joint Laboratory for Light Alloys (MOE), College of Materials Science and Engineering, Chongqing University, Chongqing 400045, China
² Shenyang National Laboratory for Materials Science, Chongqing University, Chongqing 400044, China
³ Department of Civil and Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

E-mail: xiaoxuhuang@cqu.edu.cn, doje@dtu.dk

Abstract. Additively manufactured AlSi10Mg is often subject to a two-stage heat treatment, namely solid solution treatment followed by artificial aging, to achieve optimal properties. Before such heat treatments, slight surface plastic deformation may be applied to modify the surface quality and properties. However, gradients in microstructure and texture near the surface introduced by the plastic deformation may cause undesired microstructural and textural evolutions during subsequent heat treatment. In this work, we introduce plastic deformation in the surface layer in an SLM-manufactured AlSi10Mg sample by relatively low-draught cold rolling and we investigate the through-thickness variations in microstructure and texture in the deformed state and after heat treatment. The SLM-manufactured AlSi10Mg sample has a fine-scale microstructure and a weak texture, and is rather thermally stable during subsequent heat treatments. Applying 10% low-draught cold rolling to the SLM-manufactured AlSi10Mg sample is found to introduce a near Goss texture in the surface layer, while little change is observed in the center layer. After subsequent solution treatment and aging, abnormal grain growth occurred in the surface layer resulting in remarkable through thickness gradients in microstructure and texture.

1. Introduction
The AlSi10Mg alloy is by far the most commonly used aluminium alloy in selective laser melting (SLM)-manufacturing [1]. Due to the high cooling rate and large temperature gradient in the
manufacturing process, SLM manufactured samples exhibit structures and properties very different from those of AlSi10Mg prepared by conventional methods [2-5]. For SLM-manufactured AlSi10Mg samples, a T6 heat treatment is usually performed to achieve balanced mechanical properties [6-8]. An interesting aspect is that the surface of SLM-manufactured samples often exhibit metallurgical defects such as balling and oxidation, which can affect the subsequent heat treatment and reduce the performance of the finished component [9]. The aim of the present work is to investigate effects of surface plastic deformation prior to the T6 heat treatment and thus evaluate if surface deformation may be a route to optimize the surface quality and thereby avoid negative consequences of these defects. We use 10% low draught cold rolling as a straightforward method of surface deformation. We characterize the structure and texture of the surface and center layers of such samples and compare the results with those in samples heat treated without the additional surface deformation. Finally we discuss effects of the through-thickness microstructure and texture variations, introduced by the additional rolling, on the evolution during the heat treatment.

2. Method
Cylindrical AlSi10Mg samples with a diameter of 14 mm was printed using a conceptlaser xline1000r facility. The SLM machine is equipped with a 990 W Gaussian beam fiber laser having a focal laser beam diameter of 200 μm. A power of 900 W and scanning speed of 1500 mm/s were used for preparing all the samples. In the present work, four samples were prepared as shown in table 1. Samples C and D were cold-rolled to 10% thickness reduction with relatively low draught i.e. with roll-gap geometries l/h lower than one, where l refers to the contact length between the rolls and the specimen and h refers to the sample thickness [10-13]. While rolling, the sample transverse direction (TD) was parallel to the building direction (BD). After rolling, sample D was subjected to the same heat treatment as sample B. Figure 1 displays the complete post-processing of sample D. Through-thickness microstructure and texture variations of the four samples were characterized by electron backscatter diffraction in a JEOL JEM-7800F scanning electron microscope. Small as well as large areas were characterized using a step size of 0.8 μm and 8 μm respectively. This characterization was some at about the middle along RD of the rolled sample, where the rolling reduction is 10%.

Table 1. Sample designation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>State</th>
<th>Roll-gap geometry (l/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>As-SLM-manufactured</td>
<td>/</td>
</tr>
<tr>
<td>B</td>
<td>A + T6 heat treatment (see figure 1)</td>
<td>/</td>
</tr>
<tr>
<td>C</td>
<td>A + 10% cold rolling (see figure 1)</td>
<td>0.57-0.76</td>
</tr>
<tr>
<td>D</td>
<td>C + T6 heat treatment (see figure 1)</td>
<td>0.57-0.76</td>
</tr>
</tbody>
</table>
3. Results and discussion

Figure 2 shows the local microstructures and textures of samples A and B. Throughout the melt pool, three zones can be distinguished in the transverse cross section (perpendicular to BD) by the morphology and size of the eutectic Al-Si network: fine zones (FZ), coarse zones (CZ) and heat affected zones (HAZ). The as-SLM-manufactured sample has a fine microstructure with an average grain size of 7 μm (see figure 2b) and a weak texture (see figure 2c). When heat treated, Si particles precipitate (see figure 2d), but apart from that, no significant changes in grain size was detected and the texture change is small. This agrees with what is reported in the literature, namely that good thermal stability is caused by fine eutectic silicon particles pinning the migration of grain boundaries [14].

Figure 2. SEM images showing samples A (top row) and B (bottom row). (a) and (d) reveal the Si. (b)
and (e) are inverse pole figure coloring orientation maps (of the building direction (BD)) of small selected areas, while (c) and (f) are \{111\} pole figures of large areas obtained with a coarse step size. The FZ, CZ and HAZ in (a) represent the fine zones, coarse zones and heat affected zones respectively. In the orientation maps, black and white lines mark high and low angle boundaries, respectively.

Figure 3 shows the through-thickness microstructures and textures of sample C. From figure 3(a), it is obvious that there is a deformed zone extending from the surface layer to a depth of 200 µm, and in particular in the subsurface layer of this deformed zone, the melt pools are elongated along the rolling direction. These elongated melt pools are also seen in figure 3(b). This deformed zone is composed of grains which may be slightly larger than those seen after printing, as seen in Fig. 3b. The \{111\} pole figure calculated from the area within the white box in figure 3c reveals the formation of near-Goss texture components in the surface layer after 10% low-draught cold-rolling, while the center layer showed little change in microstructure and texture.

**Figure 3.** (a) SEM image showing the variations in microstructure through the thickness of sample C. Please note it is only the top half of the sample which is shown here. (b) and (d) Inverse pole figure coloring orientation maps (TD) of small areas at the surface and of the center layer, respectively. (c) and (e) Inverse pole figure coloring orientation maps (TD) of large areas at the surface and the center layer, respectively, and the corresponding \{111\} pole figures.

The through-thickness microstructures and textures of sample D are depicted in figure 4. Similar to sample B, Si particles precipitated during the heat treatment. The surface layer featured some very large Si particles, but the difference in average size is marginal (see the inserts in figure 4a). At the
surface layer, some huge grains, tens or even hundreds of times larger than the original grains, have appeared (see figure 4b). When the texture is measured by area, it is clear that these few abnormal grains dominate the texture (see figure 4c). Table 2 provides a summary of the grain sizes, and orientations of the six abnormal grains seen in figure 4. They all have different orientations. The center region is rather similar to the as SLM-manufactured sample after annealing (without rolling). This makes sense as these sample layers are not affected by the surface deformation.

These results clearly reveal that the thermal stability of the surface layer of SLM-manufactured AlSi10Mg is destroyed by the light cold rolling. The abnormal grains in the surface region may have a large effect on the properties, as has been suggested in [15-17]. Irrespective of how the present microstructures and textures in the surface of the deformed samples affect properties – improve or reduce, the present work has shown that even a light surface deformation has very significant effects on the microstructural response upon heat treatments. This opens new avenues toward microstructural engineering of additive manufactured AlSi10Mg.

Figure 4. (a) SEM image of sample D, the inserts show the Si particle size distributions at the surface and the center. (b) and (d) Inverse pole figure coloring orientation maps (TD) of small areas at the surface and of the center layer, respectively. (c) and (e) Inverse pole figure coloring orientation maps (TD) of large areas at the surface and of the center layer, respectively, and the corresponding {111} pole figures.
Table 2. Information about the extremely large grains.

<table>
<thead>
<tr>
<th>Grain</th>
<th>Grain size/μm</th>
<th>Euler angle</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>202.1</td>
<td>(62.3°, 30.9°, 27.5°)</td>
<td>{216}&lt;221&gt;</td>
</tr>
<tr>
<td>2</td>
<td>433.4</td>
<td>(8.5°, 41.5°, 35.6°)</td>
<td>{102}&lt;21T&gt;</td>
</tr>
<tr>
<td>3</td>
<td>150.5</td>
<td>(47.7°, 48.7°, 44.3°)</td>
<td>{112}&lt;11T&gt;</td>
</tr>
<tr>
<td>4</td>
<td>260.1</td>
<td>(270.3°, 35.0°, 39.8°)</td>
<td>{111}&lt;021&gt;</td>
</tr>
<tr>
<td>5</td>
<td>178.3</td>
<td>(248.1°, 27.1°, 80.4°)</td>
<td>{112}&lt;110&gt;</td>
</tr>
<tr>
<td>6</td>
<td>&gt;989.9</td>
<td>(79.0°, 19.2°, 62.7°)</td>
<td>{124}&lt;021&gt;</td>
</tr>
</tbody>
</table>

4. Conclusion
In the present study, it has been investigated what effects a slight surface deformation, here by 10% low draught cold-rolling, and a subsequent T6 heat treatment have on the microstructure and texture of the SLM-manufactured AlSi10Mg alloy. The following conclusions can be drawn:

1) SLM-manufactured AlSi10Mg sample exhibits a weak texture and fine microstructure that is rather thermally stable when subjected to solution treatment and aging.

2) While the center layer experience minimal change in microstructure and texture by the imposed light rolling, significant structural alterations are found in the surface layer together with the appearance of near-Goss texture components.

3) After heat treatment of SLM manufactured AlSi10Mg cold rolled 10%, abnormal grain growth is observed in the surface layer, while the microstructure and texture at the center layer are essentially identical to those of the non-rolled sample.

The present results illustrate how much even simple changes in the mechanical processing may affect the textures and microstructures and thus resulting the mechanical and physical properties of SLM samples. This is of relevance both for microstructural engineering while manufacturing SLM components, and for understanding possible changes in properties which may occur while a SLM component is in use.

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139-46


