Microstructure and mechanical properties of selective laser melted AlSi7Mg

Liye Lianga, Xuexin Pamb, Guilan Wang*, Haiou Zhangc, Hao Zhangd

a. Huazhong University of Science and Technology, School of Materials Science and Engineering, Wuhan 430030;  
b. Chinese Academy of Sciences, Institute of Metal Research, Shenyang110016;  
c. Huazhong University of Science and Technology, School of Mechanical Science and Engineering, Wuhan 430030;  
d. Ningbo Institute of Materials, Chinese Academy of Sciences, Ningbo, 315201  
*Corresponding author: Guilan Wang: wglab@hust.edu.cn

Abstract: This paper focuses on researching the formation mechanism of mesh eutectic textures of AlSi7Mg manufactured by selective laser melting (SLM) and the relationship between the evolution of the eutectic Si structure and mechanical properties with ageing temperature. The microstructure of AlSi7Mg could be analyzed with the help of the scanning electron microscope (SEM), different thermal analysis (DTA), x-ray diffraction analysis (XRD). After a suitable heat treatment process, the strength of AlSi7Mg manufactured by SLM can surpass 440MPa. The article describes the relationship between microstructures and mechanical properties, which provides a basis for heat treatments for other researchers. The major outcome of this paper, it could help to formulate a heat treatment with high elongation or high strength for SLM AlSi7Mg. This article describes the reason for the formation of the mesh eutectic Si texture. It is believed that the fine mesh eutectic Si texture is the unique advantage of SLM technology over casting or forging technology.

1. Introduction

SLM Al alloy are currently widely used in the aerospace field and SLM can directly manufacture metal parts with complex structures according to the geometric data. Al alloy materials are known for having good thermal conductivity, and SLM Al alloy parts with complex structures, leading to a strong application prospect. AlSi7Mg is currently the most useful cast aluminum alloy material in the aerospace field and, together with AlSi10Mg can be used as the casing part of aviation engines or heat exchangers. Hypereutectic Al alloys, such as AlSi20, can be employed as the piston for the engine due to its low thermal expansion and great wear resistance [1]-[2].

The mechanical properties of SLM Al alloy are related to its microstructure [3]. The microstructure of Al-Si alloy, for instance, mainly includes eutectic Si texture, α-Al phase, and balanced and non-equilibrium Mg-Si phase. The density of AlSi10Mg aluminum alloy manufactured by SLM is directly proportional to the scanning speed and laser power, and inversely proportional to the scanning distance [4]. Regarding the microstructure of AlSi10Mg, it was observed that, when formed by SLM, it presents a mesh eutectic Si texture and fine α-Al phases. The Orowan dislocation loop can be structured when the dislocation cuts through the eutectic Si texture of the cell wall [5].
It is worth noting that both the building parameters and the heat treatment system affect the strength of the aluminum alloy manufactured by SLM. Building parameters such as scanning speed and laser power can directly affect the density of SLM parts [6]. The aims of this paper to discuss the formation process of eutectic Si texture and the relationship between microstructures and mechanical properties. All samples were built based on the same building parameters.

2. Experiment Work:
The powders of AlSi7Mg alloy were made by N2 gas atomization, and all the nominal composition of powders was listed in the Table 1. The specimens were manufactured by Conceptlaser Xline 1000R under the protection of N2 gas and their platform temperature was set at 120 °C. The manufacturing process is shown in Fig. 1. This way can save experiment costs. The respective aging temperatures were 140 °C, 180 °C, 220 °C and 260 °C, and the duration of aging treatment was 6 hours. When it comes to the tensile tests, all were carried out according to the GB/T228-2010 standard, and the dimension schematic of tensile test samples formed the dog bone shape represent in Fig. 2. The SLM building parameters were listed in Table 2. Metallographic samples were polished by 400#, 600#, 800#, 1000# sandpapers and etched with the solution (HF:HCl:HNO3:H2O=2:3:5:95, vol.%). It is worth out that all the observation surfaces of specimens were cross vertical sections. An optical microscope (OM) and FEI Inspect F50 SEM were used to analyze eutectic Si textures of AlSi7Mg powders while the microstructure of SLM AlSi7Mg specimens were observed by Zeiss MERLN Compact SEM. DTA assisted to analyze the phase transition process at a heating rate of 10 °C/min. XRD is used to analyze the phase of SLM AlSi7Mg. The coater forward direction is the X direction, and the vertical direction is the Z direction. The corresponding vertical direction is the Y direction.

| Si (wt.%) | Mg (wt.%) | Ti (wt.%) | Al (wt.%) |
|----------|----------|----------|----------|
| AlSi7Mg  | 7.0      | 0.3      | 0.1      | Balance  |

| Hatch parameters | Layer thickness(μm) | Laser power(W) | Scanning speed(mm per second) | Hatch space(mm) | Laser spot (μm) |
|------------------|---------------------|----------------|-------------------------------|-----------------|-----------------|
| Border parameters| 50                  | 990            | 2200                          | 0.2             | 200             |

Figure 1 Manufacturing process
3. Results and Discussion

3.1. AlSi7Mg powders
The AlSi7Mg powders represented in Fig. 3 are nearly and totally spherical. The size range of AlSi7Mg powders is 15-53 μm.

3.2. Microstructure of SLM AlSi7Mg
In Fig. 5, the XRD result shows the microstructure of AlSi7Mg is composed by eutectic Si texture, Mg2Si and α-Al phase. The eutectic Si texture surrounds α-Al phases. It can be seen in the XOY section that the size of α-Al phase is relatively close to each other, while in the XOZ section, the Al phase seems to form columnar crystal. The Eutectic Si texture is distributed at the boundary edge of the α-Al grain, and later on, the Mg2Si phase is precipitated inside of eutectic Si texture. Also, a small amount of Si particles are precipitated in the α-Al phase.

Comparing microstructure and energy spectrum analysis results in Fig. 6, it can be seen that the Si element is mainly distributed in the eutectic Si texture and a small amount Si is precipitated in the α-Al phase. The distribution of Al and Mg elements is more uniform than that of Si elements, a phenomenon that might be may be related to the nucleation of primary α-Al phase during the formation of eutectic Si texture.
The Mg2Si phase in both the powder and the as-shaped structure has undergone two divergent transformation processes. This may be related to the rapid cooling characteristics of the SLM forming process, and the structure is obtained as Mg-Si atomic clusters and GP zones at a great cooling rate. As the heat treatment temperature increases, it will transform to the equilibrium state to form a metastable β" phase, represented by the exothermal peak at 243 °C in Fig. 8(c). As the temperature further increases, the non-equilibrium Mg2Si phase gradually transforms into the non-equilibrium β' phase, and then into the equilibrium β phase [8]. When the temperature reaches 303°C, an exothermic peak is generated, and the eutectic silicon structure is now globalized. This may be related to the interdiffusion of Si element [7].

3.3. Diffusion and eutectic Si textures

Figure 6 Microstructure of (a) casted AlSi7Mg, (b) AlSi7Mg powders, (c) SLM AlSi7Mg and (d) SLM Al-Mg-Sc-Zr

Figure 7 Mechanical properties of as-built status
When the SLM process is characterized by fast heating and cooling processes and when AlSi7Mg is formed with significant diffusion coupling, the size of the primary α-Al phase and the eutectic Si texture is much smaller than that of the as-cast state. The melting temperature of vacuum atomized aluminum alloy is close to the casting temperature, and the cooling rate of vacuum atomized powder is higher than the casting process. In this case, the obtained α-Al phase and eutectic Si texture are also smaller than the casting process, as shown in Fig. 7. It has to be noted that the fine primary α-Al phase and eutectic Si texture obtained by SLM forming AlSi7Mg are not available in casting and forging processes. The microstructure of the Al-3.7%Mg-0.3%Sc-0.15%Zr alloy formed by SLM, no eutectic texture could be detected in Fig. 7(d). This fine mesh eutectic texture is unique to SLM Al-Si materials. Such fine mesh eutectic texture cannot be obtained by casting or forging technology. This can be considered a significant advantage of SLM over casting or forging processes.

3.4. Heat Treatment and Mechanical Properties
The strength of SLM AlSi7Mg first rises and then decreases, as the aging temperature gets higher (Fig.9). The Mechanical property of as-built status shows in the Fig.8. A higher aging temperature also brings an increased elongation. During this phase, the strength of AlSi7Mg formed by SLM is related to the microstructure, molding process, powders characteristics, heat treatment and other factors [9]. The DTA result shows that the non-equilibrium phase of Mg2Si precipitates in large quantities, whenever the heat treatment temperatures are increased. The non-equilibrium phase of Mg2Si is also responsible to surge the relative dislocation pinning effect and the strength of AlSi7Mg that increases slightly at 120 ℃-170 ℃. The eutectic texture of the AlSi7Mg mesh formed by SLM plays the role of grain boundaries, and the α-Al phase is responsible for the role of grains [10]. Also, the decomposition of the mesh eutectic texture reduces the strength of AlSi7Mg. Regarding the heat treatment at 120 ℃ to 260 ℃, the α-Al phase of AlSi7Mg did not undergo recrystallization and grain growth [11] and such phase increases as mesh eutectic texture transition into Si particles, thereby affecting the elongation of AlSi7Mg.

Figure 8 Mechanical properties at different aging temperatures

4. Conclusions
Through SEM, XRD, DTA and other inspection results, the microstructure of SLM AlSi7Mg mainly includes primary α-Al phase, mesh eutectic Si texture, and a small amount of non-equilibrium Mg2Si phase. The mesh eutectic texture is distributed between the columnar α-Al phases.

When it comes to the formation mechanism for mesh eutectic Si texture of SLM AlSi7Mg, it can be hypothesized that it is related to the rapid heating and cooling characteristics of SLM. The metal in the SLM molten pool is heated to an extremely high temperature, and then quickly cooled to complete solidification. This kind of mesh eutectic Si texture cannot be obtained by casting and forging processes, making this feature a key technological advantage of SLM.

SLM AlSi7Mg can obtain extremely high strength by aging treatment at 160 ℃-180 ℃. At this temperature, the eutectic structure did not decompose significantly, and a large amount of
non-equilibrium Mg$_2$Si phase was precipitated, which made the strength of SLM AlSi7Mg more than 440MPa.

As the aging temperature got higher, the yield strength and ultimate tensile strength first increases and then is lowered. Regarding the elongation process, it is also gradually strengthened. The mesh eutectic texture is finally decomposed into many eutectic particles. The non-equilibrium Mg$_2$Si phase is precipitated firstly, and then slowly transformed into the equilibrium Mg$_2$Si phase.

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