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Thermal properties of selectively laser melted AlSi10Mg products with different densities

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Abstract

The thermal diffusivity and thermal conductivity of selectively laser melted AlSi10Mg samples with different target relative densities, 99 % and 99.5 %, have been studied in the temperature range 25 °C to 400 °C. The properties were measured in the build direction and orthogonal to the build direction, for the samples in the as-built and heat-treated conditions. The 99.5 % dense samples are characterized by a noticeably higher thermal diffusivity and higher thermal conductivity than the 99 % dense samples. For each sample, it is found that the applied heat treatment improves the thermal diffusivity and thermal conductivity of the as-built material, but also results in pronounced anisotropy, with greater thermal diffusivity and conductivity in the build direction, especially for the 99.5% dense sample. The anisotropy is attributed to the presence of Si particles along the grain boundaries of columnar grains. Since the columnar grains are elongated along the build direction, a smaller spacing between particle-decorated boundaries in the plane perpendicular to the build direction presents a higher resistance to the heat conduction.

Keywords: AlSi10Mg, additive manufacturing, selective laser melting, thermal properties, microstructure, electron microscopy

1. Introduction

Selective laser melting (SLM) is an additive manufacturing technique, in which the material feedstock is deposited layer by layer. In this technique, a laser melts part of the powder in each layer according to the design. Repeated melting and rapid solidification of the material occur during SLM, which results in characteristic microstructures and distinct mechanical properties [1, 2]. The principal advantage of additive manufacturing over conventional methods is the complete design freedom that allows fabricating very complex and intricate geometries. The advances in SLM make it possible to produce parts with reduced weight, increased functionality, or even reduce the number of parts in a component.

Aluminum alloys such as AlSi10Mg and similar compositions have been extensively used in the SLM process, where the major production challenges include porosity and cracking [3]. Nevertheless, AlSi10Mg and AlSi7Mg0.3 parts with a relative density of 99.8 % can be produced by SLM [4, 5]. Since aluminum alloys have a relatively low density, high thermal conductivity, and good corrosion resistance, among other properties, these alloys can be used in a wide range of applications, including heat exchangers and thermal management.

Despite advances in additive manufacturing, there are just a few experimental studies of SLM-manufactured metallic components for heat transfer applications. For example, Wong et al. [6] analyzed the heat transfer and loss characteristics of four different heat sinks produced using SLM: two pin-fin designs, one design with angled elliptical pins, and one design with diamond-shaped pins. The complexity

of the last two geometries made the parts difficult to manufacture using conventional methods. Comparing the different heat sinks, the diamond pin heat sink presented the highest heat transfer coefficient, whereas the angled elliptical pin heat sink exhibited the lowest pressure drops. Dede et al. applied topology optimization to design an optimized 3D heat sink for confined jet impingement air cooling [7]. The topology optimized heat sink was then fabricated by SLM using AlSi12 and experimentally tested to compare its performance with benchmark plate and pin-fin heat sinks. The results showed that the optimized heat sink performed better than the benchmark heat sinks. In a more recent study, Lazarov et al. [8] fabricated 3D topology optimized structures for passive cooling of light emitting diodes and compared the optimized structures to traditional designs, with the optimized structures showing performance advantages.

Clearly, thermal properties of the material are of key importance for SLM parts used in heat transfer applications. While the thermal properties of conventionally produced aluminum alloys have been extensively studied, e.g. [9–13], for SLM products such properties have been investigated only in a small number of papers. In particular, there are very few studies of the effect of porosity on thermal properties and the directional dependence of the thermal diffusivity (TD) and thermal conductivity (TC) in SLM parts. In one study, Kimura et al. [14] investigated the room-temperature TC along orthogonal directions of almost fully dense Al-Si samples produced by SLM and concluded that except for Al–1%Si, there was no anisotropy for the samples with a wide range of Si content. Yang et al. [15] studied the TD and TC before and after heat treatment of two SLM-fabricated AlSi10Mg samples having different densities. Some anisotropy was observed in one of the samples. However, the effect of porosity on thermal properties could not be evaluated since the samples had different thermal histories.

As reducing porosity often requires lower scan speeds and smaller hatch spacing [4], very low porosity parts will likely be more expensive to manufacture. Therefore, the effects of porosity on the TC are relevant for cost-effective production of heat sink and thermal management parts. The objective of the present paper is to study the thermal properties of selectively laser melted AlSi10Mg samples with target high relative densities of 99 % and 99.5 % both in the as-built and heat-treated conditions.

2. Materials and methods

2.1 As-built material and specimen preparation

The two AlSi10Mg samples were produced on an SLM 500 machine by Materialise in the form of rectangular prisms. The thickness of powder layers during SLM was ~30 µm. In order to reach high relative densities, proprietary hatch spacing and scan speeds were used. The samples were manufactured with two different target relative densities, 99 % and 99.5 %, and the different densities were achieved by varying the scanning parameters. Square specimens with a side length of 8 mm and a thickness of 1.5 mm were cut out from the samples in two planes: in the XZ plane parallel to the build direction (BD); and in the XY plane perpendicular to the BD. These specimens are designated as specimen XZ and specimen XY (see Fig. 1).

2.2 Measurement of the specimen density

The density of the specimens was determined at room temperature by Archimedes method using an analytical balance Mettler-Toledo XS205DU with a corresponding density determination kit. The density of the solid was determined with the aid of a liquid with a known density. The solid was weighed in air and then in the auxiliary liquid, water. The density ρ was calculated from the two weight measurements as follows:

$$\rho = \frac{A}{A - B}(\rho_0 - \rho_L) + \rho_L \quad (1)$$

where ρ is the density of the sample, A is the weight of the sample in air, B is the weight of the sample in the auxiliary liquid, ρ_0 is the density of the auxiliary liquid (water in this case), and ρ_L is the density of air (0.0012 g/cm^3). This method is commonly used to estimate the porosity of additive manufactured parts. Spierings et al. [16] experimentally tested the accuracy of density measurement using Archimedes method and microscopy and found that this method was accurate within 0.08 % for densities higher than 98 %.

2.3 Measurements and calculations of thermal properties

Laser-flash analysis was used to measure the TD of the specimens using a Netzsch LFA 457 MicroFlash instrument which has a manufacturer-stated error of 3 %. To give a reliable measurement of the diffusivity, the specimens were coated with graphite with known emissivity and absorptivity characteristics. The lower surface of the specimen was then heated by a laser pulse, and the temperature change at the opposite surface was measured with an infrared sensor (see Fig. 2). The temperature was increased from room temperature to 400 °C in steps of 50 °C at 2°C/min and held for ~10 min for each measurement (Fig. 3). After each test run the sample was cooled passively back to room temperature. The samples after the first heating sequence in the following are termed “heat-treated”, and TD was measured again for these heat-treated conditions applying the same heating sequence.

The thermal conductivity λ of a material can be calculated from the density ρ , thermal diffusivity α and the specific heat capacity c_p as shown in Eq. (2).

$$\lambda = \alpha \rho c_p \quad (2)$$

All specific heat properties were measured using a Netzsch DSC 200 F3 heat-flow differential scanning calorimeter, in an argon atmosphere at a constant heating/cooling rate of 2 °C /min. For each condition, the specific heat curves used in these calculations were for the heat-treated states, i.e. the curves for the as-built samples did not include peaks in the measured specific heat [17] that are generally associated with the formation or dissolution of precipitates. The error of the TC measurements was estimated from contributions of the density, diffusivity, and specific heat measurement errors (a 3 % error for the DSC measurements was used). This error is estimated to be 7 % for the equipment used, which is generally in agreement with an uncertainty of 8 % for a single TC measurement given by Ruoho et al. [18].

2.4 SEM and EBSD analysis

Scanning electron microscopy (SEM) and a Channel 5 electron backscatter diffraction (EBSD) system were used for analyzing the microstructure of the heat-treated 99.5 % dense sample in a Zeiss Supra 35 field emission gun electron microscope. Secondary electron images were taken from the polished surface at an accelerating voltage of 15 kV, while EBSD patterns were obtained at 21 kV. Both the XZ and XY planes were investigated using EBSD with a step size of 0.5 μm , covering at least 220000 μm^2 in each plane.

3. Results

3.1 Density

The measured densities were 2.649 g/cm^3 and 2.639 g/cm^3 for the 99.5 % relative density sample and the 99 % relative density sample, respectively. Using the target relative density, the full density can be calculated as 2.662 g/cm^3 for the 99.5 % relative density sample and 2.666 g/cm^3 for the 99 % relative

density sample, which are within 0.13 % of each other. If we assume that the true full density of the printed alloy is 2.666 g/cm³ then the relative densities are 99.4 % and 99.0 %.

3.2 Thermal properties

Figure 4 shows the TD and TC versus the temperature in both the as-built and heat-treated states, and there are differences in the TD and TC at elevated temperatures between the as-built XZ and XY specimens (solid lines in Fig. 4). These differences are much more pronounced for the XY specimens. The as-built 99.5 % dense XY specimen demonstrates a significant increase in the TD above 250°C as shown in Fig. 4(b), while changes in the TD for the other as-built specimens are smaller. Both the TD and TC of the heat-treated specimens (dashed lines in Fig. 4) are mostly higher than those of the as-built specimens, with similar values consistently achieved only at temperatures of 350°C and 400°C. For each condition, the TD and TC of the 99.5 % sample are higher than those of the 99 % sample. To enable easier comparison between the TC data of the different samples, TC values are presented Table 1 for 25 °C, 200 °C and 400 °C. Compared to the 99 % sample, the TC of the 99.5 % sample measured at 25 °C is 4–6 % higher in the as-built condition and 15–18 % higher in the heat-treated condition. However, the difference for the as-built condition is not considered significant due to the inaccuracy of the measurements. At higher temperatures, the differences in TC along the BD are significantly greater for the 99.5 % sample. Compared to the as-built 99 % sample, the as-built 99.5 % sample had a 23 % greater TC in the BD at 200 °C and a 33 % greater TC in the BD at 400 °C. For the heat-treated conditions the 99.5 % sample had a TC in the BD which was greater than that of the 99 % sample by the following values: 29 % at 200 °C and 34 % at 400 °C. In the case of the TC perpendicular to the BD, the TC is only ~3-4 % higher for the 99.5 % sample in both as-built and heat-treated conditions.

Comparing the different specimens of identical density, the TC is on average 19 % higher along the BD for the 99.5 % sample in the heat-treated state (dashed lines in Fig. 4(c,d)). In the case of the 99 % sample there is no significant difference in the TC between the two directions.

Table 1. Thermal conductivity for the as-built and heat-treated specimens at 25 °C, 200 °C and 400 °C

Sample	Temperature (°C)	Plane			
		XZ (measured $\perp$ BD)		XY (measured $\parallel$ BD)	
		As-built (W/m·K)	Heat-treated (W/m·K)	As-built (W/m·K)	Heat-treated (W/m·K)
99 % dense	25	115	119	115	132
	200	129	141	114	137
	400	144	144	141	141
99.5 % dense	25	120	140	122	152
	200	133	145	140	177
	400	150	149	187	189

3.3 Microstructure

The microstructure of the heat-treated 99.5 % sample in the XZ plane is shown in Fig. 5. A characteristic fish-scale pattern is observed in this SEM image, where bright features are Si particles. Although some particle-decorated boundaries can be distinguished in Fig. 5, quantitative analysis of grain

structures is rather difficult in such SEM images. In contrast, grains and their boundaries are accurately identified in orientation maps produced using the EBSD technique. In the EBSD data in Fig. 6, it is seen that in the XZ plane large columnar grains (up to $\sim 100\ \mu\text{m}$ in height) aligned close to the BD are combined with small grains observed in the vicinity of melt pool boundaries (Fig. 6(a)). Many of the columnar grains are characterized by orientations close to $\langle 100 \rangle // \text{BD}$ (red in Fig. 6). When viewed in the XY plane (Fig. 6(b)), the grains appear small and almost equiaxed, forming intersecting bands which reproduce the laser scanning pattern. The average grain size measured in the XY plane is $5\ \mu\text{m}$.

4. Discussion

The thermal properties of the SLM-manufactured AlSi10Mg alloy in the as-built samples do not appear to be appreciably different from those measured in this alloy produced by conventional die casting. For example, the thermal conductivity at room temperature of the as-built SLM samples studied in the present work is found to be 115 to 122 W/m-K (see Table 1), which is similar to the values reported for the die cast alloys with a similar chemical composition [10, 11]. Interestingly, whereas the TD values recorded for our material in the as-built condition are similar to those reported for AlSi10Mg by Yang et al. [15], the the temperature dependences for TD in the heat-treated conditions do not exhibit the same trend. For our heat-treated material, Fig. 4(a,b) shows an increase in TD at approximately 100°C as compared to those near 25°C and then the TD slowly decreases as temperature rises to 400°C . The trend in temperature is different than that reported by [15], which shows a monotonic decrease in TD as temperature increases in the heat-treated state. The cause of the differences in TD trends seen in the heat-treated SLM samples may be due to impurities in the commercial powders used to make the parts, different processing parameters and heating schedules (different heating rates and maximum temperatures). It is pertinent to mention that a range of TD values and trends have been reported for cast Al alloys as well [12].

Considering anisotropy in the TC, for the as-built conditions we observed only a small difference in the TC along two orthogonal directions at 25°C , which is similar to the findings of Kimura et al. [14]. The heat-treatment at temperatures below 250°C has a minor effect on the conductivity of the as-built SLM samples, However, above 250°C , the TC of the as-built samples increases significantly, especially for the XY specimens in the 99.5 % sample (see Fig. 4(c,d)). Apparently, this significant increase reflects changes taking place in the microstructure during the applied heat-treatment.

In the as-built condition, the microstructure of AlSi10Mg is typically described as a supersaturated α -Al phase of cellular morphology [17, 19–23], where cells are separated by finely spaced Si-rich boundaries containing Si particles with sizes in the nanometer range [21–23]. The number of scattering centers for electrons and phonons in the as-built material is high, and its thermal conductivity is therefore reduced. As the temperature increases, the spatial distribution of Si changes. Precipitation from the supersaturated solid solution can take place at ~ 230 – 260°C [19,20]. Furthermore, during annealing at $\sim 260^\circ\text{C}$ the average cell boundary spacing increases slightly as compared to that in the as-built condition [19], which suggests that at this temperature the cellular structure starts to decompose. At temperatures near and slightly above 300°C the cellular structure is broken up, and coarser Si particles are observed [19,20]. With increasing temperature and duration of the heat-treatment, the size of these Si particles increases further, while their number density decreases [5,17,19,20]. These changes in the microstructure improve the thermal conduction of the alloy and can explain the increased TC observed for our as-built samples between 250°C and 400°C .

In particular for the 99.5 % sample, the heat treatment increased the TD and TC for the XY specimens significantly more than for the XZ specimens, which results in increased anisotropy of the heat-treated

conditions, where a higher TC in the build direction was observed. The orientation dependence of the thermal properties observed in the present work can be rationalized taking into account the difference in the heat-treated microstructure in the XZ and XY planes. As is evident from Fig. 5 and Fig.6(a), the processing and heat-treatment applied results in the microstructure with comparatively coarse Si particles along the grain boundaries, where the boundary spacing along the BD is appreciably greater than the boundary spacing in the XY plane. Since the TC of Si is lower than that of aluminum, heat is conducted more easily along the columnar grains, i.e. along the BD. It is possible that the less pronounced anisotropy in the 99 % sample is due to the increased number of low TC pores that could dampen out higher TC of the solid matrix alone.

Our results emphasize the influence of porosity on the thermal properties of SLM-manufactured AlSi10Mg. The 99.5 % dense sample showed a noticeably higher TD and TC than the 99 % dense sample, which is important for critical thermal applications. These observations are consistent with an increase in electrical conductivity with increasing relative density observed in other SLM-manufactured Al alloys [24]. The observed anisotropy of the 99.5 % dense sample can be exploited for applications where direction-specific heat transfer is desired. It can also be taken into account in topology optimization or similar optimization techniques of SLM parts.

5 Concluding remarks

In this work, the thermal diffusivity and thermal conductivity of AlSi10Mg obtained by SLM with different relative densities, 99 %, and 99.5 %, were investigated in the temperature range 25 °C to 400 °C. It is found that thermal conductivity measured at 25°C increases by approximately 15–18% as the relative density of SLM-manufactured AlSi10Mg in the heat-treated state increased from 99 % to 99.5 %. The heat-treated material presents anisotropy in thermal conduction, with higher values measured along the build direction compared to those measured in the specimen sectioned orthogonal to the build direction. This anisotropy is significant in the 99.5% sample and less pronounced in the 99% sample. The anisotropy is attributed to the directionality of the microstructure, which contains columnar grains with particle-decorated boundaries. The columnar grains are elongated along the build direction in the XZ plane, while most grains are smaller and almost equiaxed in the XY plane. It is considered that the significantly smaller spacing between particle-decorated boundaries in the XY plane presents a higher resistance to the heat conduction.

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Figure captions

Figure 1. Specimens machined from XZ and XY planes of the as-built samples (all dimensions are in mm). Z is parallel to the build direction (BD).

Figure 2. Schematic illustration of the specimen orientation with respect to the laser pulse during the thermal diffusivity measurements: (a) laser pulse is perpendicular to the BD in the XZ specimen; (b) laser pulse is parallel to the BD in the XY specimen.

Figure 3. Heating sequence for the thermal diffusivity measurements. The temperature ramps at 2 °C/min between measurements and holds for approximately 10 min for each measurement. After the final heating, the samples were cooled passively back to room temperature.

Figure 4. Thermal properties in the as-built and heat-treated conditions of the XZ specimen (a,c) and XY specimen (b,d): (a,b) thermal diffusivity; (c,d) thermal conductivity.

Figure 5. A secondary electron image showing the microstructure in the XZ plane of the 99.5 % dense heat-treated sample.

Figure 6. Orientation maps obtained using EBSD showing the microstructure of the heat-treated 99.5 % dense AlSi10Mg sample in XZ plane (a) and XY plane (b). Different colors correspond to different crystallographic directions along the BD, as shown in the inset in (b). The build direction is vertical in (a) and normal to the image plane in (b). Black lines show high angle ($>15^\circ$) grain boundaries.