Effect of Solidification Cooling Rate on Mechanical Properties and Microstructure of Al-Si-Mn-Mg Alloy

Eunkyung Lee and Brajendra Mishra*

Metal Processing Institute, Worcester Polytechnic Institute, 100 Institute Rd., Worcester, 01609, MA, USA

Al-Si-Mn-Mg alloy, AA365 (Silafont-36), has been recently developed for automotive parts produced by the high-pressure die-casting process. During the die-casting process, differences in section thickness cause uneven cooling, which results in different mechanical properties and cause the build-up of residual stresses and defects in the part. In the present study, we have attempted to identify the microstructural changes of α-aluminum dendritic phase and eutectic region, and the mechanical property changes in AA365 alloy at different cooling rates during solidification. The alloy cooled at 9000 K/min (water quenching) acquired a secondary dendrite arm spacing (SDAS) of 3.4 µm and contained over 75% of dendritic α-aluminum phase, whereas the alloy having a cooling rate of 77 K/min (air cooling) showed 12 µm SDAS and 65.5% of α-aluminum phase. The ultimate tensile stress and the elongation of AA365 cooled at 9000 K/min went up to 262.3 MPa and 4.4%, respectively, when compared with the alloy cooled at 77 K/min, which had 192.3 MPa tensile strength and an elongation of 2.9%. The water quenching increases the hardness of dendritic α-aluminum phase by about 130% compared to that of the air-cooling, and it was confirmed that the fast cooling rate could increase the solubility of the elements that can be dissolved in the α-aluminum phase. The hardness of the alloy increased with an increase in the cooling rate during solidification due to uniform and fine size of the silicon bearing intermetallic phases in the eutectic region, caused by fast solidification.

Keywords: silicon aluminum alloy, microstructure, eutectic phase, alpha aluminum phase, cooling rate, mechanical property

1. Introduction

Aluminum-silicon alloys are widely used in automotive and aerospace industries for weight reduction owing to their superior lightweight properties. Among the many manufacturing processes, the production of thin-walled complex components with a large surface area, places high demands on die-casting design and production1). During the die-casting process, aluminum alloy cast components experience considerable changes in their mechanical properties, dimensions, residual stresses, and their metallurgical phase compositions. Particularly, the complex component causes a range of cooling rates due to the various local wall thicknesses. Therefore, the solidification microstructure, consisting of primary α-aluminum dendrite, eutectic region including silicon, Fe-based intermetallic phases, and solidification defects such as porosity and shrinkage, varies in different zones, thus resulting in the wide variety of mechanical properties in the component2). These changes place significant demands on additional processes, such as additional heat treatment, straightening, and replacement of non-heat treatable alloys with alloys that require heat treatment. However, excessive heat treatment of the parts causes surface blistering and mechanical treatment and can build severe residual stresses on the parts. These factors are required delicate considerations in process development3).

Among the changes in casting properties, mechanical properties of the cast alloy are strongly influenced by local microstructural features that form during solidification. The features, such as grain size, secondary dendritic arm spacing, precipitates, and phase fraction, are dependent on differential rates of cooling, caused by differences in section thickness of the cast part. Therefore, the relationship between the changes in microstructures and mechanical properties of the alloy are an important consideration in order to understand and predict the behavior of the materials3–6).

AA365, called Silafont-36, is made for high-pressure die-casting, and it contains 9.5–11.5% of silicon. This alloy was also known as the first successful application of a low iron die-casting alloy for the automotive field. This silicon content enables an excellent die filling capability, and thus, an excellent castability7). The microstructure of the alloy consists of eutectic region including silicon phase, primary α-aluminum dendrite, Fe-based intermetallic phase (Al, Fe, Si, etc.), and other precipitate phases.

Recently, the correlation with the mechanical properties and microstructure of this alloy have been studied, limedly focusing on intermetallic phases, such as α-Fe and β (or β′) phases formed due to the addition of elements such as Sr, Mn, O, etc.8) In addition, some researchers commented on the eutectic solidification of aluminum-silicon alloys showing uncertainties in the features that may form9–11). To better understand AA365 - one of the most widely used aluminum silicon material in die casting markets - it is necessary to get the information on the microstructural changes and the mechanical properties of the alloy as a function of the different cooling rate. For the α-aluminum phase, the microstructural behavior needs to be considered. The secondary dendrite arm spacing (SDAS) and the amount of α-aluminum phase resulting from different cooling rates during solidification affect the mechanical properties of the alloy due to solid solution strengthening. In the present study, tensile properties and the microstructure of AA365 in a mold casting process, with different cooling media, were investigated to understand the correlations.

2. Experimental Procedure

This study was performed on Al-Si-Mn-Mg AA 365 alloy. The chemical composition of the alloy was measured using
SpectroMaxX Spark Spectrometer. Prior to pouring, the melt temperature was maintained at 740°C and was degassed with pure argon injected for 30 minutes. After the dross was removed from the melt surface, alloy was poured into a copper mold designed for a sub-size tensile standard specimen. After the molten metal solidified, the specimens were cooled at three different cooling media, i.e. water, forced air (fan), and air (static). The cooling rates of the alloy with different cooling media were measured using temperature data acquisition. The collected data were analyzed with cooling rate (slope) from the initial temperature of 500°C.

For mechanical properties measurement, tensile testing was performed according to ASTM E812) using three replicates for each condition. The values of ultimate tensile strength (UTS), yield stress (YS), and elongation (E) of the alloy under different cooling conditions were recorded with an average value and standard deviation. The microstructure of AA365 for each cooling condition was investigated using optical microscopy. All the specimens were ground and polished up to 1 µm diamond step and analyzed at x100 magnification. Phase quantification of the alloy was carried out using ImageJ software. Nanoindentation grids were made on polished samples to measure the nanohardness of the α-aluminum dendrite and eutectic region using an Agilent G200 Nanoindenter and diamond tip, set to a depth of 500 nm. The measured values were recorded using five replicates.

3. Results and Discussions

The chemical composition of AA365 was measured to be Al-10.6mass%Si-0.7mass%Mn-0.28mass%Mg-0.1mass%Fe-0.08mass%Ti whereas the contents of other elements were less than 0.03 mass%(Ni, Cr, Ga, Sr, V). The cooling rates of AA365 with different cooling media were measured and the values are listed in Table 1. It confirms that forced-air with the fan had a large influence on the cooling rate. The cooling rate with water quenching was at 9000 K/min. The results support a previous study where cooling rates of water quenching and air cooling were >1 K/s (>60 K/min) and >130 K/s (>7800 K/min), respectively13).

The mechanical properties of AA365 with different cooling conditions are presented in Table 1. The values of UTS

<table>
<thead>
<tr>
<th>Cooling media</th>
<th>Cooling rate (K/min)</th>
<th>Ultimate tensile stress (MPa)</th>
<th>Yield stress (MPa)</th>
<th>Tensile strain (%)</th>
<th>Fraction of α-Al (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>77</td>
<td>192.3 (24.0°)</td>
<td>110.9 (14.6°)</td>
<td>2.9 (1.1°)</td>
<td>65.5</td>
</tr>
<tr>
<td>Forced air</td>
<td>168</td>
<td>187.3 (12.7°)</td>
<td>121.9 (7.5°)</td>
<td>2.0 (0.7°)</td>
<td>67.2</td>
</tr>
<tr>
<td>Water</td>
<td>9000</td>
<td>262.3 (32.8°)</td>
<td>141.8 (18.5°)</td>
<td>4.4 (0.9°)</td>
<td>75.1</td>
</tr>
</tbody>
</table>

Fig. 1 (a) Ultimate tensile stress (Y-axis, MPa); (b) yield stress (Y-axis, MPa); and (c) elongation (Y-axis, %) of AA365, according to the cooling conditions (X-axis: Cooling rate, CR/K·min⁻¹), such as air-cooling (77 K/min), forced air-cooling (168 K/min), and water (9000 K/min).

Fig. 2 The microstructure and SDAS of α-aluminum dendrite of AA365 (a) cooled in air (static, 12 µm), (b) cooled by forced air (with a fan, 6.5 µm), and (c) water-quenched (3.4 µm), at X100.
(262.3 MPa) and YS (141.8 MPa) of the alloy are markedly increased by water quenching. Particularly, the elongation of water-quenched alloy is 4.4%, which is significantly higher than the force-air cooled material. Results shown in Table 1 and Fig. 1 indicate enhanced strength and ductility of AA365 by water quenching.

Figure 2 shows the microstructures of AA365 cooled in three different cooling media after casting. Microstructural analysis reveals the presence of \(\alpha\)-aluminum dendrites, a eutectic region including silicon phase, and precipitates. The SDAS in the air and forced-air cooled conditions is over 12 and 6.5 \(\mu\)m (blue arrows in Fig. 2 (a) and (b)) respectively, while that of water-quenched is only 3.4 \(\mu\)m (Fig. 2 (c)). The smaller the SDAS, the smaller the repulsion stress felt by a dendrite boundary dislocation and the higher the applied stress needed to propagate dislocations through the material.

Many investigators have found that the cooling rate determines the SDAS and it affects significantly the mechanical properties of Al-Si (A356/357) alloys because the structure directly controls the size and distribution of eutectic silicon phases\(^{2,14,15}\). Likewise, it is confirmed in this study that the SDAS of primary \(\alpha\)-aluminum gets smaller as the cooling rate increases, which increases the mechanical properties of AA365 in terms of strength.

Phase quantification analysis of AA365 was carried out using image analysis software to divide constituent phases. The measured fractions of primary \(\alpha\)-aluminum dendrite phase are listed in Table 1. The fraction of \(\alpha\)-aluminum phase of the water-quenched alloy (75%) is higher than the air-cooled alloy (65.5%). This increase is attributed to the formation of secondary phases that get suppressed by fast cooling due to insufficient time for formation\(^{16-19}\).

In the present study, we found that the UTS and YS of the alloy were improved with an increase in cooling rate and it is attributed to the decrease of the SDAS of \(\alpha\)-aluminum phase. Some researchers have found that an increased strength of a material due to a finer grain size may reduce ductility\(^{20,21}\). However, in this study, along with the increases of UTS and YS due to water quenching, the elongation of the water-quenched alloy also has increased compared with that of the air-cooled alloy. The \(\alpha\)-aluminum phase exists as solid solution in the matrix of aluminum-silicon. It crystallizes in the form of non-faceted dendrites and has an fcc lattice. The metallic bonds are characterized by isotropy and relatively low bonding energy. For these reasons, the \(\alpha\)-aluminum phase is considered to have the highest ductility in Al-Si alloys\(^{22,23}\). In the present study, since there is a SDAS reduction of \(\alpha\)-aluminum and its ductile characteristic, it is concluded that a fast cooling not only increases the strength of the alloy but also increases the ductility.

Another mechanism for enhancing mechanical properties is the effect of solid solution strengthening. In this alloy system, it is known that Mn, Fe and Si can exist as solute elements and, therefore, have a considerable effect on the strength though their solubility is limited. It has also been mentioned that, under certain processing conditions, a super-saturated solid solution may be produced\(^{24,25}\). However, we have very limited information on how some strengthening effects affect bulk mechanical properties and how they change with cooling rate. Thus, we investigated the hardness of each phase and attempted to understand the strengthening mechanism in AA365. The results of hardness of \(\alpha\)-aluminum dendrite and eutectic region with different cooling rates are shown in Fig. 3 (a), and the measured areas are indicated in Fig. 3 (b). The hardness value of water-quenched eutectic regions containing Si particles, which are known to be brittle and possess high strength, were 0.57 GPa higher than that of \(\alpha\)-aluminum dendrite. Likewise, the hardness of the eutectic region cooled with forced-air and static air showed 0.36 and 0.59 GPa higher values than that of \(\alpha\)-aluminum dendrites, respectively. Additionally, the hardness of water-quenched \(\alpha\)-aluminum dendrite showed the highest value (1.61 GPa) compared with forced-air (1.49 GPa) and air cooled (1.23 GPa) specimen. Therefore, it is expected that a fast cooling rate can increase the solubility of the elements in the \(\alpha\)-aluminum phase\(^{24}\).

The eutectic region of the water-quenched alloy indicated the highest value (2.16 GPa) in the present study compared to that of forced-air (1.85 GPa) and air-cooled (1.82 GPa) alloy. The eutectic regions of the water-quenched alloy in Fig. 4 (c) indicate that Si particles in the region are much finer and have smaller features than that of the forced-air and the air-cooled alloys (Fig. 4 (a), (b)). In contrast, the microstructural features of the static air and forced-air cooled eutectic region show aggregate shapes. Therefore, it is con-
cluded that the dispersion and the size of the silicon particle have a large influence on the hardness of the eutectic region. This understanding will be a very important baseline in studying the effects of intermetallic phases or other precipitations and silicon phases on the strengthening of the alloy.

4. Conclusion

The microstructure and the mechanical properties of Al-Si-Mn-Mg alloy, AA365, with different cooling rates were investigated. The value of UTS and YS of the alloy markedly improved by water quenching. The ultimate tensile stress and elongation of the water-quenched AA365 were measured as 262.3 MPa and 4.4%, respectively. In the microstructural analysis, the water-quenched alloy acquired 3.4 µm SDAS and 75% α-aluminum phase, whereas the slow air-cooled material has 12 µm SDAS and 65.5% α-phase. The hardness of the water quenched α-aluminum dendrite had 130% higher value (1.61 GPa) than that of air-cooled AA365. It was confirmed that the fast cooling not only increases the strength of the alloy due to the reduction of SDAS of α-aluminum phase but also that the ductility of the alloy increases due to an increase in the amount of α-aluminum phase. The eutectic region of each condition showed a higher hardness than that of the α-aluminum dendrite. The microstructure of eutectic region with different cooling rates was compared and the smallest size and uniform distribution of the particles was observed in the water-quenched material.

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REFERENCES