Cross-section Effect on Mechanical Properties of Al A356 Alloy Tensile Specimens

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Abstract. Tensile testing is an effective method to evaluate the mechanical property of aluminum alloys. In the present work, two types of standard tensile specimens with round (RD) and rectangular (RT) cross-sections were cast in the same permanent die and their solidification characteristics, microstructures, and mechanical performances were studied. The equilibrium solidification and Scheil solidification models of the studied A350 alloy were calculated by Pandat software. The experimental solidification and cooling temperature analysis revealed that the solidification platform and supercooling of the RD sample were 3 seconds wider and 1.2 °C bigger than those of the RT one. The microstructural analysis expressed that the mean grain diameter and secondary dendrite space of RD were 1.52 and 0.75 μm smaller than those of RT; hence, the strength and elongation of RD were better than those of RT. Brinell hardness tests and differential scanning calorimetry were also carried out. According to the obtained data, the round specimen was selected for tensile test because of its superior performance.

1. Introduction

Tensile testing is an effective method to evaluate the mechanical properties of cast aluminum alloys [1]. According to the ISO international FDIS6892-1 standard and the Chinese GB/T 228.1 standard, rectangular, circular, square, and hexagonal cross-sections are used for cast metal samples. According to the Chinese GB/T13822 standard and the American ASTM E8 standard, round and rectangular cross-sections are used for high-pressure die-cast Al alloys. Moreover, according to the ISO2378-1972 standard and the Chinese GB 1173/T standard, the round cross-section is used for permanent die-cast Al alloys. Round specimens have better workability than rectangular ones; thus, they are more widely used in industrial applications. Generally, the round cross-section is preferred for cast tensile specimens; however, in some cases, rectangular one is also used. An actual casting often has a certain wall thickness, and in structural design, the wall thickness should be designed as evenly as possible. When the casting is supposed to be partially flattened, in most cases, it eventually becomes a plate with a certain wall thickness, implying that a cast specimen with a rectangular cross-section is closer to actual casting conditions than the one with a round cross-section.

Tocci et al. [2] studied the tensile properties of Si and Cr-containing cast Al-Si-Mg alloy at high temperatures using RD specimens according to the UNI EN ISO 6892-1 standard. Beroual et al. [3], using RT specimens, investigated the microstructure and hardness of AISi10.6CuMg alloy produced by sand casting and high-pressure die casting according to the JIS Z2201 standard. Song et al. [4] studied the microstructure and mechanical properties of die-cast ADC12 alloy with La and Yb additives using RD and RT specimens. Gunasegaram et al. [5] used RD and RT specimens to study the
melt flow velocity, microstructure, and mechanical properties of an Al-Si alloy produced by high-pressure die casting; however, no attention was paid to different characteristics of RD and RT specimens and their cross-sectional effect. In the current study, a permanent die with two different cavities was designed to manufacture tensile test specimens with round (RD) and rectangular cross-sections (RT) simultaneously. The solidification characteristics, mechanical properties, and microstructures of these two specimens were compared and analyzed.

2. Experimental Procedure
Commercial Al A356 alloy provided by Shandong Tailai Aluminum Foundry Tech. Co. Ltd. was selected as the raw material, and its chemical composition was 6.5-7.5 wt% Si, 0.30-0.45 wt% Mg, and Al balanced. After melting and refining, the liquid Al alloy was poured into a permanent die with a preheating temperature of 270°C. The casting system of the die and the specimens is displayed in Figure 1. The die temperature was controlled by a die temperature controller [6]. The temperatures of the specimens were recorded by a LR6012XSR/PD temperature recorder after every 0.1 s. A commercial A356 ingot was melted in a graphite crucible in a resistance furnace with a power of 5 kW, and the melting temperature was set to 750°C. After degassing and refining, when the temperature decreased to 650°C, the liquid alloy was poured into the permanent die cavity. After cooling, die opening, and cleaning, both RD and RT tensile test specimens were obtained.

Figure 1. Tensile test specimens with round and rectangular cross-sections and their casting system.

Tensile tests were conducted on a CHT4605 universal testing machine at room temperature to obtain the ultimate tensile strength (UTS) and elongation (El) of the samples. Samples for optical microscopy (OM), scanning electron microscopy (SEM), and hardness tests were cut from fractured specimens. To avoid the effects of tensile tests on the microstructure, samples were cut at least 5 mm away from the fracture. Samples for OM and SEM observations were etched by the Keller reagent (95 ml H₂O + 2.5 ml HNO₃ + 1.5 ml HCl + 1.0 ml HF) for 30 seconds. A Leica DM2700M OM was used to observe the microstructures of the samples. The secondary dendrite spacing (SDAS) and the mean grain size were calculated with the help of an image processing software. SEM images were captured by a SUPRA™ 55 thermal field-emission scanning electron microscopy. Brinell hardness tests were conducted on a XHB-3000 hardness tester with a cemented carbide ball of 5 mm diameter under a load of 1250 N for 30 s. Differential scanning calorimetry (DSC; NETZSCH DSC 404 F3) was conducted under a continuous flow of pure argon gas with a heating rate of 10 °C/min.
3. Results and Discussion

3.1. Solidification Temperature Curves
The typical cooling curves of the RT and RD specimens after casting are displayed in Fig. 2(a). A solidification platform was present in each curve, indicating the release of the latent heat of solidification. Two dashed double-dotted lines were drawn to mark the liquidus temperature ($T_L$) and solidus temperature ($T_S$) of the alloy. The cooling rates of the RD and RT specimens are presented in Figs. 2(b) and 2(c), respectively. The cooling rate ($R$) was calculated according to equation (1).

$$R = \frac{-\Delta T}{\Delta t} = \frac{(T_{i+1} - T_i)}{(t_{i+1} - t_i)}$$

where $T$ is the alloy temperature and $t$ is time. After pouring without an external heat source, the alloy cooled down when $R>0$ and was heated by the latent heat of melting when $R<0$.

It is noticeable from Fig. 2(a) that the temperature jumped suddenly after pouring and then gradually decreased, and eventually, about 170 s after pouring, the two curves gradually converged. It is also evident from Figs. 2(b) and 2(c) that the cooling rate fluctuated around zero after pouring and most of the time, the two curves were above zero. To compare the cooling rates of the two specimens, the rectangular zone marked in Fig. 2 was enlarged, and the corresponding result is shown in Fig. 3. In both curves, the eutectic reaction ($L\rightarrow\alpha\text{Al} + \beta\text{Si}$) began at the initial $R = 0$ time and ended at the second $R = 0$ time. After the second $R = 0$ time, the liquid was completely solidified. Owing to different cooling rates and total amounts of emitted heat, the widths of the solidification platform on the two curves were different. The RD curve was found to be wider than the RT curve. For the RD curve, the initial $R = 0$ time was about 12 s with a temperature of 557.3°C, and for the RT curve, that was about 7 s with a temperature of 558.5°C (1.2°C higher than that of the RD curve). Hence, the undercooling rate ($R$) of the RD sample was higher than that of the RT one, and the maximum $R$ values of the RD and RT specimens were calculated as 18.5 °C/s and 22 °C/s, respectively.

Figure 2. (a) Cooling curves of the round (RD) and rectangular (RT) specimens and (b, c) cooling rates of hypoeutectic A350 alloy with RD and RT cross-sections before and after pouring, respectively.
Figure 3. (a) Enlarged view of the rectangular zone marked in Fig. 2, (b, c) cooling rate of the round (RD) and rectangular (RT) specimens, respectively.

The Al-Si-Mg ternary phase diagram with the Mg content of 0.3 wt% is exhibited in Fig. 4. For the given Al-7%Si-0.3%Mg alloy, the composition line intersected the diagram lines at Points 1, 2, 3, and 4. When the temperature dropped to Point 1 (T_L = 615.4°C), α_Al with the FCC_Al structure precipitated from the liquid alloy (L→α_Al). When the temperature dropped to the range between Point 2 (574.66°C) and Point 3 (569.16°C), α_Al and β_Si with the Diamond_A4 structure precipitated from the liquid alloy (L→α_Al + β_Si); thus the eutectic reaction occurred in this temperature range, and Point 3 was the end of solidification (T_S). The four-phase equilibrium eutectic reaction (L→α_Al + β_Si + γ_Mg2Si) occurred at 555.91°C, and the composition of the alloy in the Al-Si-Mg system was 81.2580% Al, 5.5915% Mg, and 13.1505% Si. When the temperature dropped to Point 4 (440.4°C), γ_Mg2Si precipitated from supersaturated β_Si [7,8].

Figure 4. Phase diagram of Al-Si-0.3Mg alloy (wt%).

The equilibrium solidification and Scheil solidification models of the studied A350 alloy were simulated in Pandat software, and the obtained results are presented in Fig. 5. In the equilibrium solidification model, it was assumed that complete diffusion occurred in both liquid and solid phases and the compositions of the solid and the liquid always followed the phase boundaries defined by the equilibrium phase diagram. The fractions of the liquid and the solid were calculated by the lever rule. Three key points (1, 2, and 3) corresponding to Point 1, 2, and 3 in Fig. 4, respectively, are marked on the solidification curve in Fig. 5.
In contrast, in the Scheil solidification model, it was assumed that no diffusion occurred in the solid phase, the liquid had infinite diffusivity, and the local equilibrium at the solid-liquid interface was always maintained. The solid fraction \( (f_s) \) at any temperature \( T \) in the solidification range was calculated by the Scheil equation (2).

\[
 f_s = 1 - \left( \frac{T_m - T}{T_m - T_L} \right)^{1/(1 - K_0)}
\]

where \( T_m \) is the melting temperature of the pure metal, \( T_L \) is the liquidus temperature of the alloy, and \( K_0 \) is the equilibrium distribution coefficient. It is noticeable that the curve of the Scheil model existed below that of the equilibrium model. The lowest temperature in the equilibrium model was 569.16°C, which corresponds to the temperature of Point 3 in Fig. 4, and the lowest temperature in the Scheil model was 555.91°C, which corresponds to the temperature of the four-phase equilibrium eutectic reaction (TE).

3.2. DSC Analysis

The DSC curves of the RD and RT specimens are displayed in Fig. 6. Two prominent exothermic peaks were detected in the curves — the first P1 peaks corresponding to the \( L \rightleftharpoons \alpha_{Al} + \beta_{Si} \) reaction were sharp and the second P2 peaks corresponding to the \( L \rightleftharpoons \alpha_{Al} \) reaction were blunt. A gentle bulge was noticed before 450°C on the baselines, indicating the occurrence of solid-phase transformation, such as dissolution transformation. Owing to the slow heating rate, the P1 peak was detected at around 580°C, which is higher than the temperatures corresponding to Points 2 and 3 in Fig. 4. The temperature of the P1 peak on the RD curve was 579.8°C, which is 1.4°C lower than that of the RT curve.

![Figure 5](image1.png)

**Figure 5.** Comparison of the solidification simulations by the Scheil model and the equilibrium model.

![Figure 6](image2.png)

**Figure 6.** Differential scanning calorimetry (DSC) curves of the round (RD) and rectangular (RT) specimens at a heating rate of 10 °C/min.
3.3. Microstructures
Figs. 7(a) and 7(b) present the typical OM images of the RD and RT specimens, respectively. The SDAS ($\lambda_2$) is obtained by calculation according to equation (3).

$$SDAS = \frac{\sum_{i=1}^{n} L_i}{\sum_{j=1}^{m} N_j}$$

where $L_i$ is the length of a counting line ($i=1,2,3,...$) and $N_j$ is the number of dendrites which the counting line pass across ($j=1,2,3,...$), and the typical graphical calculating parameters are also shown in Fig. 7. The mean grain size of $\alpha_{Al}$ and $\lambda_2$ for the RD sample were 23.36 $\mu$m and 18.99 $\mu$m, respectively, and those for the RT specimen were 24.88 $\mu$m and 19.74 $\mu$m, respectively.

![Figure 7. Optical microscopy images of the (a) round and (b) rectangular specimens.](image)

3.4. Mechanical Property
Fig. 8 displays two sets of representative stress-strain curves of the RD and RT specimens. In the experiment, RD UTS and El% were 183.0±4.6MPa and 6.4±1.4%, while RT UTS and El% were 161.3±5.4MPa and 3.4±0.7%, respectively. It is clear that both of the UTS and elongation of RD were better than those of RT. The Brinell hardness test results of the specimens are presented in Table 1. For each specimen, hardness tests were carried out at five different points (labeled as HB1, HB2, HB3, HB4, HB5), and the corresponding mean standard deviation was denoted as $HB \pm \Delta$. It is obvious that the RD sample was harder than the RT one.

![Figure 8. Stress-strain curves of the round (RD) and rectangular (RT).](image)
Table 1. Brinell hardness test results of the round (RD) and rectangular (RT) specimens.

|       | HB1 | HB2 | HB3 | HB4 | HB5 | HB ± Δ |
|-------|-----|-----|-----|-----|-----|--------|
| RD1   | 73.0| 74.0| 76.2| 78.4| 78.4| 76.0±2.5 |
| RT1   | 70.0| 72.0| 72.0| 74.0| 73.0| 72.2±1.5 |

The strength and hardness of an alloy are closely related to its microstructure. The microstructural characteristics of an alloy are mainly determined by its undercooling and cooling rates during solidification. It is well known that the higher the cooling rate, the smaller the grain size. The mechanical properties of an alloy are greatly influenced by the grain diameter and $\lambda_2$ in the light of equations (4) and (5).

$$\sigma = \sigma_0 + Kd^{-1/2} \tag{4}$$

where $\sigma$ denotes strength, $\sigma_0$ and $K$ are constants, and $d$ is the mean grain diameter,

$$\lambda_2 = K_1(GR)^{-\alpha} \tag{5}$$

where $\lambda_2$ represents SDAS, $G$ is the temperature gradient, $R$ is the cooling rate during solidification, $K_1$ and $\alpha$ are constants. The theoretical liquidus temperature of the studied alloy was calculated as 569.16°C. The undercooling of RD was estimated as (569.16 - 557.3 =) 11.86°C, and that of RT was (569.16 - 558.5 =) 10.66°C, 1.2°C lower than that of RD. The DSC analysis reveals that the P1 peak on the RT curve appeared 1.4°C later than that on the RD curve; thus, the undercooling analysis is consistent with the DSC results. The cooling rate of RD was slightly slower than that of RT; however, the $\lambda_2$ of RD was slightly bigger than that of RT due to the formation of the temperature gradient $G$ during solidification (Fig. 3). Moreover, it is clear from Fig. 2(a) that the solidification time of RT was shorter than that of RD and the holding time for RT after solidification at high temperatures was longer than that of RD; hence, grains in RT grew bigger than those in RD.

For most Al-alloy castings, the performance data of RT specimens are closer to actual solidification conditions; thus, they are generally recommended for industrial applications. Nevertheless, RT specimens are easy to deform, and leveling can be applied to them afterward. The mechanical performances of RT specimens are generally affected to some extent by the Bauschinger effect and anisotropy [9]. However, in the present study, the UTS, elongation, grain refinement, and Brinell hardness of RD were superior to those of RT; thereby, the RD specimen was easier to be machined after casting than RT. Therefore, the RD specimen was selected for casting due to its superior performance.

4. Conclusion

In the present work, two types of standard tensile specimens with round (RD) and rectangular (RT) cross-sections were cast in the same permanent die and their solidification characteristics, microstructures, and mechanical performances were studied. The main conclusions are presented below.

1) The RT sample solidified earlier than RD. Two R = 0 times existed on the cooling curves of RD and RT specimens. The cooling rate and solidification platform of RD were larger and wider than those of RT. The undercooling of RD was 1.2°C bigger than that of RT, in turn, the temperature of RD corresponding to the $\alpha_{Al} + \beta_{Si}\rightarrow L$ reaction was 1.4°C lower than that of RT.

2) The cooling rate of RD was slightly slower than that of RT. The $\lambda_2$ of RD was slightly thinner than that of RT. Moreover, the holding time of RD at high temperatures was shorter than that of RT. The ultimate tensile strength, elongation, grain refinement, and Brinell hardness of RD were superior to those of RT. The casting round specimen was selected for tensile test due to its superior performance.
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