Original Article

Correlation between segregation behavior and wall thickness in a rheological high pressure die-casting AC46000 aluminum alloy

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\textbf{A B S T R A C T}

The segregation behavior of a rheological high pressure die-casting (Rheo-HPDC) AC46000 aluminum alloy at positions with different wall thicknesses was studied. The results reveal that positions with different wall thicknesses exhibit different cooling rates that can result in distinctly different segregation characteristics. Segregation results in varying microstructure, elemental distribution, and hardness along the thickness of an alloy. The segregation in a Rheo-HPDC AC46000 alloy can be categorized as: cross-sectional segregation along the thickness and center segregation. As the distance from the alloy surface increases, the volume fraction of the primary phase increases, and the hardness of the microstructure and content of the eutectic Al-Si, Al\textsubscript{2}Cu, and α-(FeMn)\textsubscript{3}Si\textsubscript{2}Al\textsubscript{15} phases decrease. As the alloy wall thickness increases, the differences in the volume fraction of the primary phase, elemental content, and hardness of the microstructure between the edge and center gradually decrease. Compared with the normal center microstructure, the volume fraction of the primary phase in the center segregation microstructure is lower, and the morphology is not round. The content of the eutectic Al-Si, Al\textsubscript{2}Cu, α-(FeMn)\textsubscript{3}Si\textsubscript{2}Al\textsubscript{15}, and Si phases is higher, and these phases are nonuniformly distributed. Center segregation is often accompanied by shrinkage cracks. As the alloy wall thickness increases, the center segregation area and crack size increase, and the more hard–brittle α-(FeMn)\textsubscript{3}Si\textsubscript{2}Al\textsubscript{15} particles accumulate the crack. The hardness of the center segregation structure is higher than that of the normal center structure. With increasing alloy wall thickness, the hardness of the center segregation microstructure first increases and then decreases.

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1. Introduction

Al-Si-Cu alloys are widely used in the automotive and communication fields due to their light weight, remarkable castability, high strength-to-weight ratio, and adequate corrosion resistance [1–3]. The production of complicated structural components made of Al-Si-Cu alloys is required to decrease vehicle weight and improve fuel economy [4]. High pressure die-casting (HPDC) is a conventional technology that is primarily used for producing aluminum alloy products owing to its low cost and high efficiency [5,6]. However, there are a large number of porosities in HPDC components caused by gas entrapment during high-speed filling, which generate local stress concentration and seriously deteriorate mechanical properties [5,7]. Therefore, the use of HPDC aluminum alloys in critical safety components is restricted owing to internal defects and corresponding reduction in material performance [7,8]. Improvement of the HPDC process to manufacture components with high quality and enhanced performance is thus highly worthwhile. In recent years, rheological HPDC (Rheo-HPDC) technology has acquired increasing attention as an effective process for improving the microstructure and properties of aluminum alloys [9–11]. Rheo-HPDC provides components with many advantages, such as low porosity, high mechanical properties, good corrosion resistance, and heat treatability [10–13].

Segregation exists extensively in components formed by molding technologies [14], such as gravity casting [15], HPDC [16], forging [17], and extrusion [18]. Similarly, segregation is also the major practical problem in semisolid processing, which results in heterogeneous microstructure and mechanical properties in the final products [19]. Until present, the studies on segregation behavior of aluminum alloy semisolid forming have been mainly focused on thixoforming [20–24]. There are few relevant studies on the segregation behavior of Rheo-HPDC aluminum alloys. Zhou et al. [25] studied the microstructure of A380 aluminum alloy automobile shock absorbers prepared by Rheo-HPDC. There were no evident differences of microstructures at different positions in the shock absorbers, which have marginally different wall thicknesses. Möller et al. [26] studied the surface liquid segregation (SLS) phenomenon in Rheo-HPDC plates (6 mm) of 7075, 2024, 6082, and A201 alloys. Results revealed that the SLS in the Rheo-HPDC plates caused significant differences in properties between the surface and center of these plates, and the SLS layer had higher hardness due to the presence of hard intermetallics. Masuku et al. [27] investigated the influence of SLS on the corrosion behavior of Rheo-HPDC 7075 and 2024 alloys. The electrochemical results revealed that SLS has no significant effect on the corrosion of the alloys. However, these reports mainly focused on the study of cross-sectional segregation of the alloys at positions with similar wall thickness. A study on the segregation of Rheo-HPDC aluminum alloy with different wall thicknesses and large wall-thickness differences is still lacking. It is therefore significant to investigate the segregation of alloys with different wall thicknesses and greater wall-thickness differences.

The object of the research described in this paper is the AC46000 aluminum alloy automobile boosters prepared by Rheo-HPDC. An automobile booster is a component that has various wall thicknesses at different positions and larger wall thickness differences. The segregation behavior of the booster in the cross-section along the thickness direction at different wall-thickness positions was studied.

2. Experimental procedures

The chemical compositions (wt.%) of the commercial AC46000 aluminum alloy used in this study were 9.58% Si, 2.62% Cu, 0.69% Fe, 0.56% Mn, 0.90% Zn, 0.06% Mg, and Al balance. Differential scanning calorimetry (DSC, NETZSCH STA-449F3) was employed to determine the liquidus and solidus temperatures of the alloy. A 35 mg sample was placed in the analyzer, heated to 700 °C at a rate of 10°C/min under Ar protection, and cooled to room temperature at the same rate. Fig. 1 presents the DSC curve of the alloy, depicting the solidus and liquidus temperatures of 524 °C and 603 °C, respectively.

The alloy was heated to 720 °C in a resistance furnace, and the melt was cooled to 660 °C after refining, drossing, and degassing. Approximately 1.5 kg of the melt was scooped and poured into a self-developed forced convection stirring (FCS) apparatus to prepare semisolid slurry; the detailed experimental procedure is available in Refs. [12,28]. In this experiment, the parameters of the slurry preparation were pouring temperature of 650 °C, stirring time of 25 s, stirring speed of 12.56 rad/s and graphite lining temperature of 570 °C. The slurry was then fed into the pressure chamber of the HPDC machine to produce the automobile booster immediately. The mold was preheated to 200 °C prior to processing; the injection speed was 2.8 m/s and the injection pressure was 65 MPa.

Fig. 2(a) shows a photograph of the AC46000 aluminum alloy booster produced by Rheo-HPDC. Samples with wall thicknesses of 3, 5, 8, and 10 mm were cut from positions A, B, C, and D of the booster, respectively, as shown in Fig. 2(b). Microstructural observation, elemental content test, and hardness test were performed on the edge, 1/2 radius, and center on the cross-section along the thickness direction of the sample, and the specific locations are shown in Fig. 2(c). For microstructural observation, after grinding and
polishing, the samples were etched using a 0.5 vol.% solution of hydrofluoric acid. Microstructural studies were accomplished using an optical microscope (OM, NEOPHOT 21) and scanning electron microscopy (SEM, ZEISS EVO18). Meanwhile, an energy-dispersive spectrometer (EDS) attached to the SEM instrument was carried out to test elemental content. Phase compositions were performed using X-ray diffraction (XRD; Cu Kα, XRD-6000). Hardness measurements were conducted using a Vickers hardness tester (DHV-1000) at a load of 100 gf and dwell time of 10 s. Image Tool 3.0 software was used for calculating the volume fraction of the primary phase.

3. Results

3.1. Microstructure

Fig. 3 shows the XRD pattern of the Rheo-HPDC AC46000 alloy. The alloy consists of five phases, i.e. Al, Si, Al2Cu, α-(FeMn)2Si2Al15 and β-Al5FeSi.

Fig. 4 shows the SEM and EDS results of the Rheo-HPDC AC46000 alloy. From Fig. 4(a) and (b), it is observed that the nearly-spherical primary α-Al (α2-Al) particles are surrounded by the eutectic phase, the punctate/sheet Al2Cu is
distributed around the α-Al phase, and the long-sized/blocky Si particles are distributed in the eutectic structure. According to the EDS results (Fig. 4(c) and (d)), the phases corresponding to points A and B in Fig. 4(b) are α-(FeMn)₃Si₂Al₁₅ and β-Al₃FeSi, respectively. Fe element exists predominately in the form of α-(FeMn)₃Si₂Al₁₅ rather than the detrimental β-Al₃FeSi phase in Al-Si-Cu alloy as reported by Ma et al. [29] and Li et al. [30]. This is because the higher Mn content in the AC46000 alloy promotes the conversion of the acicular β-Al₃FeSi phase into the granular α-(FeMn)₃Si₂Al₁₅ phase, thereby reducing the detrimental effects of Fe.

Fig. 3 – XRD pattern of Rheo-HPDC AC46000 alloy.

Fig. 4 – SEM morphologies of Rheo-HPDC AC46000 alloy at (a) low and (b) high magnifications; EDS analysis results at points (c) A and (d) B in (b).
Fig. 5 – (a) Solidification curves, and (b) relationship between wall thickness and cooling rate at positions with different thicknesses of Rheo-HPDC AC46000 alloy.

<table>
<thead>
<tr>
<th>Wall thickness (mm)</th>
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<tbody>
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<td>Edge</td>
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Fig. 6 – Microstructures at edge, 1/2 radius and center of Rheo-HPDC AC46000 alloy at positions with different wall thicknesses.
Fig. 7 – Volume fraction of primary phase from edge to center in the microstructure of Rheo-HPDC AC46000 alloy at positions with different wall thicknesses.

Fig. 8 – Elemental content at edge, 1/2 radius, and center of Rheo-HPDC AC46000 alloy at positions with wall thicknesses of (a) 3 mm, (b) 5 mm, (c) 8 mm, and (d) 10 mm.
3.2. Cross-sectional segregation along the thickness direction

The average cooling rate between the pouring temperature and solidus temperature exerts a significant effect on the microstructure [31]. The average cooling rate is calculated as follows:

\[ v = \frac{T_L - T_S}{t_{L-S}} \]  

where \( v \) is the average cooling rate, \( T_L \) and \( T_S \) are the pouring temperature and the solidus temperature, respectively, and \( t_{L-S} \) is the solidification time for the melt to cool from the pouring temperature to the solidus temperature. Flow-3D software was used to simulate the solidification process of the booster. Fig. 5(a) shows the solidification curves of positions with different wall thicknesses in the alloy. The average cooling rates of positions with wall thicknesses of 3, 5, 8, and 10 mm are 256, 211, 147, and 95 °C/s, respectively. Wall thickness and cooling rate exhibited a linear relationship, as shown in Fig. 5(b), and the larger the wall thickness was, the smaller was the cooling rate.

Fig. 6 shows the microstructure of the edge, 1/2 radius, and center of the Rheo-HPDC AC46000 alloy at positions with different wall thicknesses; the volume fraction of the primary phase was measured and is presented in Fig. 7. It is observed that for positions with different wall thicknesses, the volume fraction of the primary phase increases from the edge to the center. With increasing wall thickness, the volume fraction difference of the primary phase in the microstructure between the edge and the center gradually decreases. For the positions with wall thicknesses of 3, 5, 8, and 10 mm, the volume fraction differences of the primary phase are 64.41%, 42.40%, 11.03%, and 7.22%, respectively. When the wall thickness reaches 10 mm, the difference is almost eliminated.

Fig. 8 shows the elemental content from the edge to the center at the positions with different wall thicknesses of the Rheo-HPDC AC46000 alloy. With increasing distance from the surface of the alloy, the content of Al, Si, Cu, Fe, and Mn decreases, while the content of Mg and Zn does not change substantially. Fig. 9 shows the difference in the elemental content between the edge and the center on the cross-sections of the positions with different thicknesses. As the thickness increases from 3 mm to 10 mm, the difference in the elemental content between the edge and center gradually decreases, among which the difference in the Al content decreases from 6.78% to 0.86%, that of Si content decreases from 4.69% to 0.4%, that of Cu content decreases from 1.55% to 0.34%, that of Fe content decreases from 0.35% to 0.05%, and that of Mn content decreases from 0.12% to 0.02%.

Fig. 10 shows the elemental map of the Rheo-HPDC AC46000 alloy at the positions with wall thicknesses of 3 mm and 10 mm. It is evident that Si element is mainly distributed in the blocky Si particles and needlelike eutectic phase, Cu element is mainly in the form of a punctate/sheet Al2Cu phase, and Fe and Mn elements are mainly present in the granular (FeMn)3Si2Al15 particles. Mg and Zn elements are uniformly distributed in the matrix. When the wall thickness is 3 mm, the distributed areas of the eutectic Al-Si, Al2Cu and α-(FeMn)3Si2Al15 phases decrease continuously with increasing distance from the alloy surface. However, the element distribution from the edge to the center is similar when the wall thickness is 10 mm. Compared with the position with wall thickness of 3 mm, the elemental distribution becomes more homogenous regardless of the edge, 1/2 radius or center.

Fig. 11 presents the hardness from the edge to the center and average hardness of the Rheo-HPDC AC46000 alloy at the positions with different thicknesses. It is observed that for the positions with different wall thicknesses, the hardness decreases from the edge to the center, which is related to the composition segregation of the alloy [26,32], as shown in Figs. 8 and 10. The increase of Al content from the edge to the center increases the volume fraction of the primary phase and results in the decrease of hardness. The reduction of the Si content decreases the content of the Al-Si eutectic phase, which decreases the hardness of the alloy [33]. The Al2Cu phase provides a strengthening effect [6,34], such that the reduction of Cu content reduces the mechanical properties of the alloy. The decrease of the content of the hard–brittle phase (α-(FeMn)3Si2Al15 and β-Al5FeSi) formed by Fe also plays a role in reducing the hardness [29,30,35]. Additionally, as the wall thickness increases, the hardness difference between the edge and the center gradually decreases because of the more uniform distribution of the alloy elements (Figs. 8 and 9). For the positions with different wall thicknesses in the alloy, the average hardness does not differ significantly, and remains at the level of 106–110 HV.

3.3. Center segregation

As the thickness of the Rheo-HPDC alloy increases, the cross-sectional segregation phenomenon gradually weakens. However, segregation may be present in the central part of the alloy also, which is called center segregation.

Fig. 12 shows the microstructure of the center segregation at the positions with different wall thicknesses of the
Rheo-HPDC AC46000 alloy. It is clear that the structure of the center segregation is considerably different from the normal center structure. The nearly spherical $\alpha_1$-Al particles in the normal structure are uniformly distributed. However, the $\alpha_1$-Al in the center segregation structure is less in quantity and irregular in shape (marked by yellow arrows in Fig. 12), and the content of eutectic Al-Si and $\alpha-(FeMn)_3Si_2Al_{15}$ phases increases. Center segregation is generally accompanied by shrinkage cracks, as indicated by the red arrows in Fig. 12(b), (d), (f) and (h), and numerous hard–brittle $\alpha-(FeMn)_3Si_2Al_{15}$ particles aggregate in the vicinity of the cracks. As the wall thickness of the alloy increases, the center segregation area increases significantly. Taking the area shown in the pink frame in Fig. 12 as an example, when the wall thickness is 3, 5, 8, and 10 mm, the center segregation area is 0.051, 0.997, 0.136, and 0.171 mm$^2$, respectively. As the wall thickness increases, the crack size also increases. These cracks and the hard-brittle phase severely disperse the matrix, reducing the performance.

**Fig. 10** – Elemental distribution of Rheo-HPDC AC46000 alloy at positions with wall thicknesses of 3 mm and 10 mm.
of the alloy [35,36]. The large wall thickness of the alloy can straightforwardly cause an appreciable difference in the cooling rate of the section. Prior to the solidification of the center of the thick wall, the semisolid slurry surrounding it had solidified, so that the center cannot be replenished with the external slurry; this results in shrinkage cracking in the center. In contrast, when the wall is thin, the difference of cross-sectional solidification speed is small, and the center segregation is minor. Comparing the area of center segregation at the positions with different wall thicknesses, it can be concluded that the cooling rate exerts a significant influence on the center segregation. Increasing the cooling rate can effectively reduce or even eliminate center segregation.

Fig. 13 shows the elemental map of the center segregation structure of the alloy at the position with a wall thickness of 3 mm. Si, Fe, Mn, and Cu in the center segregation structure are more widely distributed than in the normal center of the 3-mm-thick alloy as shown in Fig. 10 owing to the aggregation of α-(FeMn)3Si2Al15, Al5Cu, and Si phases in the segregation structure. The Cu element overlaps with each other and exhibits nonuniform distribution, while the Mg and Zn elements are uniformly distributed in the matrix.

Fig. 14 shows the elemental content of the center segregation and normal center structures of the Rheo-HPDC AC46000 alloy at the positions with different wall thicknesses. Compared with the normal structure, the center segregation structure exhibits lower Al content and higher Si, Cu, Fe, and Mn content, while its Zn and Mg content changed negligibly. Therefore, while there are few primary particles, numerous eutectic and hard–brittle phases are present in the center segregation structure (Fig. 12). As the wall thickness increases, the content of Si, Cu, Fe, and Mn in the center segregation increases, and the content of Al, Zn, and Mg decreases. Furthermore, with the increase of wall thickness, the differences in Al and Si elemental content between the center segregation and normal center structures gradually decrease, while the differences in Cu, Fe, and Mn elemental content increase, as shown in Fig. 15. The difference in Al elemental content decreases from 5.30% to 4.61% and that of Si element decreases from 4.52% to 3.02%. The difference in Cu elemental content increases from 0.34% to 0.62%, that of Fe increases from 0.38% to 0.65%, and that of the Mn increases from 0.12% to 0.38%.

Fig. 16 shows the hardness of the center segregation and normal center structures of the Rheo-HPDC AC46000 alloy at the positions with different wall thicknesses. The hardness of the center segregation structure is higher than that of the normal center structure when the wall thickness is the same. As the wall thickness increases from 3 mm to 8 mm, the hardness of the center segregation and normal structures increases progressively, which is consistent with the differences in the chemical composition at the positions with different wall thicknesses as shown in Figs. 14 and 15. However, the hardness decreases at a wall thickness of 10 mm, which may be caused by the shrinkage porosities at the center [37].

### 4. Discussion

Segregation affects the microstructure and properties of casting alloys [19,38,39]. For positions with different wall thicknesses in Rheo-HPDC AC46000 alloy, the increase of Al content and decrease of Si content caused by segregation can increase the volume fraction of primary phase and refine the eutectic structure. The increase of Si, Fe, and Mn elemental content can generate more eutectic and α-(FeMn)3Si2Al15 phases, which can increase the hardness of the alloy. The cooling rate has a significant influence on the segregation [40], while the cooling rate is affected by factors such as pouring temperature [41], pressure [42], mold temperature [43], wall thickness [44], and distance from the runner [45]. A low cooling rate results in the growth and coarseness of primary phase and acicular eutectic phase [45]. However, a high cooling rate causes severe cross-sectional segregation in the Rheo-HPDC alloy (Fig. 6).
Fig. 12 – Center segregation structure of Rheo-HPDC AC46000 alloy at positions with wall thicknesses of (a) and (b) 3 mm, (c) and (d) 5 mm, (e) and (f) 8 mm, and (g) and (h) 10 mm. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)
Fig. 13 – Elemental map of center segregation structure of Rheo-HPDC AC46000 alloy at the position with wall thickness of 3 mm.

Fig. 14 – Elemental content of center segregation and normal center structures of Rheo-HPDC AC46000 alloy at positions with wall thicknesses of (a) 3 mm, (b) 5 mm, (c) 8 mm, and (d) 10 mm.

Therefore, it is feasible to reduce or eliminate segregation by regulating the initial mold temperature [47], designing alloys with small differences in wall thickness [48], and using the proper cooling method [49].

Segregation exists in the cross-section along the thickness direction of the Rheo-HPDC alloy (Figs. 6 and 8). Taking the position A with a wall thickness of 3 mm as an example, it is the thinnest part of the casting and the cross section at this position exhibits a distinctly different structure and hardness (Figs. 6, 10 and 11). The cross-sectional segregation model of the alloy can be divided into four zones, as shown in Fig. 17(a). Zone 1 is the position closest to the mold wall, which contains a small amount of primary phase and a large amount of eutectic Al-Si, granular $\alpha$-(FeMn)$_2$Si$_3$Al$_{15}$, and sheet/blocky Al$_3$Cu phases (Fig. 10). The content of Si, Fe, Cu, and Mn in zone 1 is high; thus, its hardness is high. Zone 2 has an increasing content of primary phase and decreasing eutectic Al-Si, $\alpha$-(FeMn)$_2$Si$_3$Al$_{15}$ and Al$_3$Cu phases. Zone 3 has a large number of uniform spherical $\alpha$-Al and eutectic phase, while the content of $\alpha$-(FeMn)$_2$Si$_3$Al$_{15}$ and Al$_3$Cu phases is low; thus, the hardness is low. Zone 3 is the major structure of the alloy, possessing the largest area. Zone 4 is the center segregation region, containing a small amount of irregular primary phase and a large number of eutectic Al-Si, Al$_3$Cu, and hard–brittle...
Fig. 15 – Differences in elemental content between the center segregation structure and normal center structure of Rheo-HPDC AC46000 alloy at positions with different wall thicknesses.

Fig. 16 – Hardness of the center segregation and normal center structures of Rheo-HPDC AC46000 alloy at positions with different wall thicknesses.

phases. In Zone 4, shrinkage cracks may exist. From zone 1 to zone 4, the cooling rate decreases continuously, as shown in Fig. 17(b). The volume fraction of primary phase increases linearly from zone 1 to zone 3, while the volume fraction of primary phase within zone 4 is very low, as shown in Fig. 17(c). While the hardness decreases continuously from zone 1 to zone 3; it increases in zone 4 owing to the high content of \( \alpha-(FeMn)_{3}Si_{2}Al_{15} \) and the low content of \( \alpha_{1}-Al \), as shown in Fig. 17(d).

The pouring temperature of the semisolid slurry prepared using the FCS process is generally higher than the liquidus temperature of the alloy by approximately 50 °C [12]. After the alloy melt is poured into the FCS equipment, the melt temperature is rapidly dropped to between the solidus and liquidus temperatures. According to previous studies [12,50,51], a large number of globular particles exist in the semisolid slurry. According to Stokes’ law [52,53], the particles suspended in an alloy melt exhibit a smaller filling speed due to the smaller diameter of the particles and the higher viscosity of the slurry. During the rapid filling, the slurry with high solute concentration and a small amount of globular \( \alpha_{1}-Al \) particles flows at the front and contacts the mold wall first [54]. Since the location near the mold wall has a higher cooling rate, at a thin section of the wall, the slurry in the vicinity of the mold wall solidifies before the subsequently flowing slurry that contains numerous \( \alpha_{1}-Al \) particles reaches the mold wall for replenishment; moreover, eutectic and intermetallics replace the \( \alpha_{1}-Al \) sites, forming zone 1. The remaining slurry is rapidly solidified from the exterior to the interior, and the volume fraction of the primary phase increases with increasing distance from the mold wall, forming zones 2 and 3. As the final solidification location of the slurry, zone 4 is an isolated area that is incapable of transferring pressure and exhibits a lower cooling rate, altering the solidification conditions; this results in the growth of eutectic structures (Fig. 12). In addition, shrinkage cracks can easily occur in
Fig. 17 – Cross-sectional segregation model of (a) microstructure, (b) cooling rate, (c) volume fraction of primary phase and (d) hardness in Rheo-HPDC AC46000 alloy.

zone 4 due to thermal shrinkage and solidification shrinkage [55]. The larger the wall thickness is, the larger is the center segregation area and crack size; moreover, the more accumulated the hard–brittle phases are, the more likely that the stress of the alloy will concentrate and the plasticity will decrease. Therefore, it is crucial to reduce or prevent the center segregation of the alloy. Designing a suitable mold cooling system to reduce the difference of the solidification time of the alloy is considered an effective method of suppressing the center segregation [48,56,57]. For example, spot cooling can be designed in the position that has large temperature gradient [58].

5. Conclusions

Positions with different wall thicknesses in a Rheo-HPDC AC46000 aluminum alloy exhibit different cooling rates, which results in significantly different segregation characteristics. Segregation can be divided into the following two categories.

(1) Cross-sectional segregation along the thickness direction: For positions in Rheo-HPDC AC46000 alloy with different wall thicknesses, the volume fraction of primary phase
increases and hardness decreases as the distance from the alloy surface increases. As the wall thickness increases, the differences in the volume fraction of the primary phase, hardness, and elemental content in the microstructure between the edge and the center gradually decrease.

(2) Center segregation: Compared with the normal center structure, the primary phase in the center segregation structure is present in low quantity and is not round, while the eutectic Al-Si, Al3Cu, and α-(FeMn)2SiAl15 phases have high quantity and are nonuniformly distributed. Center segregation structure is generally accompanied by shrinkage cracks, and a large number of α-(FeMn)2SiAl15 brittle particles aggregate in the vicinity of the cracks. As the wall thickness increases, the center segregation area and crack size increase, and the brittle phase accumulating near the crack increases. For positions with different wall thicknesses, the hardness of the center segregation structure is larger than that of normal center structure. With increasing wall thickness, the hardness of the center segregation structure first increases and then decreases.

Conflicts of interest

The authors declare no conflicts of interest.

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