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Influence of Microstructural Inhomogeneity on Fracture Behaviour in SSM-HPDC Al-Si-Cu-Fe Component with Low Si Content

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Abstract. In the current paper, a low-Si aluminium alloy (1.4-2.4% Si) was used to fabricate a complex shape telecom component using Semi-Solid High-Pressure Die Cast (SSM-HPDC), process. Microstructure and fracture characteristics were investigated. The cast material exhibited microstructural inhomogeneity, in particular macrosegregation in the form of liquid surface segregation bands in addition to sub-surface pore bands and gross centre porosity. Tensile specimens were taken from the cast components. Elongation and microstructural inhomogeneity were investigated and correlated. Fracture surfaces of the tensile specimen were examined under scanning electron microscope (SEM). The study showed that both near surface liquid segregation bands and subsurface porosity strongly affected the fracture behaviour. Dominant for loss of ductility was gross centre porosity. The centre porosity was found to be a combination of trapped gas and insufficient, irregular feeding patterns.

Introduction

Component manufacturing using Semi Solid Metal Casting integrated with High Pressure Die Casting (SSM-HPDC) is a promising alternative to manufacture complex shaped components by standard HPDC. In aluminium casting, the improvement in component characteristics is achievable due to the pre-solidified particles, primary α -phase in slurry (α_1 -Al) particles [1], which decrease the tendency of turbulent flow and lead to less porosity formation. In the SSM-HPDC, the use of alloys with low content of alloying elements is not very typical due to narrow freezing intervals that makes difficulties in slurry preparation process and increases inhomogeneity in the microstructure of the final product [2]. However, compared to the standard HPDC, SSM-HPDC can offer better castability for the alloys susceptible to shrinkage porosity, due to higher fraction of α_1 -Al phase with average shape factor, $SF = \pi A / p^2$ nearer to 1 (round shape) [3].

However, in the presence of both solid and liquid phase, during filling, inhomogeneous deformation in semi-solid state is expected in SSM-HPDC. This can lead to the separation of solid particles and liquid phase, which appears in the form of longitudinal and transverse macrosegregation in the cast component [4]. Consequently, in a cast component, there is likely a large variation in the properties, based on microstructural inhomogeneity. The mechanism of the longitudinal macrosegregation in HPDC was studied by Kaufman *et al.* [5] describing as sponge effect, where the liquid portion of the semisolid slurry is exuded by hydrostatic pressure. The transverse macrosegregation is related to three different phenomena; skin effect [6], migration of solid particle to the centre part of casting [7] and also dilatancy band in the form of porosity or positive macrosegregation (eutectic-rich) band [8]. The formation of either porosity bands or eutectic-rich phase bands have been attributed to localized shear bands depending on alloy composition [9, 10].

In the current paper, the microstructural inhomogeneity and the deterioration of mechanical properties in a thin-walled telecom component made by SSM-HPDC in a low Si-content aluminium alloy were investigated. In addition, the effect of inhomogeneity, such as longitudinal, transverse macrosegregation and defect band formation on the fracture behaviour of tensile bars was studied.

Experimental Procedure

Experiments were performed on an industrial scale, using a 400 ton HPDC machine equipped with a RheoMetal™ slurry generator [11]. Table 1 shows Alloy X composition as a low-Si containing aluminium alloy, used in this study. The shot weight was approximately 3 kg and the melt holding temperature was 665°C (15°C superheat). A standard cast iron ladle was used. The Enthalpy Exchange Material (EEM) was 6% of the shot weight and stirring was made at 900 rpm. The final slurry temperature was 645±1°C. The injection speed was varied from 50% to 90% of maximum plunger speed (4m/s) for the second phase filling. The temperature of the die was recorded and varied between 200°C to 255°C for the region near-to-gate and 230°C to 255°C for the region near-to-vent. First phase filling speed and phase switch point were fixed and regarded as optimized.

Table 1. Composition [wt%] and liquidus temperature [°C] of Alloy X used for experimental work

Alloy	Al	Si	Fe	Cu	Mn	Mg	Zn	T _L (°C)
X	Bal	1.4-2.4	<1	0.6-1.0	0.2-0.4	<0.3	<0.15	650

Figure 1. The Rheo-Cast component and three different tensile bars

The schematic of the rheo-cast component is shown in Fig. 1. In the runner, the maximum thickness was around 20 mm and for the gate, the thickness decreased to 4.5mm. Maximum thickness of the component was 2 mm. For tensile testing study, 200 components were manufactured in 20 different process conditions. One component was selected from each process condition and three tensile bars from different locations of the component were produced. A total of 60 samples were tested.

Results and Discussion

Macrosegregation. Fig. 2 shows the microstructure in the cross section of cast components for two different casting conditions in near-to-gate and near-to-vent regions. Primarily, the different fractions of α_1 -Al in the near-to-gate region (Fig. 2(a) and 2(c)) and near-to-vent region (Fig. 2(b) and 2(d)) indicates the separation of liquid phase and solid phase in the early stage of the filling process. This is similar to squeezing a sponge exuding melt from a high solid fraction slurry. The fraction of α_1 -Al in these regions of components was assessed using Olympus Stream™ image analysis system using contrast based recognition and a particle size discrimination as α_1 -Al particles are larger in size than primary precipitation in the die cavity. In the region, near-to-gate for the condition with the lowest die temperature (T_{tool}) and lowest plunger speed in second phase (V_2) (Fig. 2(a)), the material consisted of 82%±3 of total α_1 -Al particles.

For the process condition with the highest die temperature (T_{tool}) and highest second phase speed (V_2) (Fig. 2(c)), the fraction of α_1 -Al particles in the region near-to-gate decreased to 71%±3 of total α_1 -Al particles. The transverse macrosegregation in the form of fine equiaxed and coarse microstructure morphology were formed at the surface of die (skin effect) and centre of the samples. It is clear that the thickness of skin layer increased by increasing the liquid portion. Therefore, the thickness of this layer is larger for the near-to-vent region (Fig. 2(b) and 2(d)). In the case of different process conditions, higher temperature and speed decreased the skin thickness for the near-to-vent region. By measuring the area fraction of porosity in the samples from the near-to-gate and the near-to-vent region for ten different samples, an increase in the porosity were observed for the near-to-vent region compare to the near-to-gate region.

Figure 2. Sample with lowest V_2 and coldest T_{tool} ; (a) near-to-gate and (b) near-to-vent region. Sample with highest V_2 and hottest T_{tool} ; (c) near-to-gate and (d) near-to-vent region

Fig. 3 shows transverse macrosegregation in the form of higher fraction of eutectic phases and porosity band in the cast components, which are similar to shear bands found in HPDC castings. The eutectic bands were observed in the samples with higher amounts of alloying elements (2.3 % Si, 0.9 % Cu), whilst the sample with porosity bands had lower amounts of alloying elements (1.5 % Si, 0.6 % Cu). This can be explained by the fraction of liquid in the porous network available for feeding to compensate for the solidification shrinkage and volume expansion in the shear band [12,13]. Using JMatPro^{TM} software, it was calculated that the eutectic point of the alloy with the highest alloying content occurs when 83% of solid phase formed, whilst for the sample with lowest alloying content, 93% of solid fraction was formed at the eutectic point. Consequently, formation of either porosity band or eutectic-rich band is related to feeding possibility of the expanded volume in the shear band. So based on the JMatPro^{TM} results, in the samples with higher amounts of alloying elements, the existence of sufficient eutectic phase (liquid phase) to compensate for expanded volume leads to positive macrosegregation. In contrast, the formation of the porosity band in the samples with lower amounts of alloying elements is related to insufficient amount of remaining liquid. This type of inhomogeneity has also been found in HPDC of aluminium alloys with different Si content by Laukli *et al.* [14].

Figure 3. Two typical shear bands; (a), (b) eutectic rich band and (c) porosity band

Mechanical Properties. Tensile tests were performed at a strain rate of 10^{-4} /s in the as-cast condition. Strain was recorded by means of a Zwick^{TM} digital clip-on extensometer with a 20 mm gauge length. In this study, to investigate the effect of inhomogeneity on the mechanical properties and fracture behaviour in the cast compounds, three samples were taken from location 1, 3 and 5 of each component (Fig. 1). The tensile test results together with the 95% confidence interval are shown in Table 2. Increase in the yield stress value in the sample from location 5 with the finer microstructure due to higher liquid segregation (Fig. 2(b) and 2(d)), highlights the effect of microstructure morphology on the final mechanical properties. Moreover, lower average elongation value and very early fracture for samples from location 5 indicated that a different fracture mechanism governs the crack formation and propagation for these samples.

Table 2. Yield stress (YS), ultimate tensile stress (UTS) and elongation value of three samples

Location	YS (MPa)	UTS (MPa)	Elongation (%)
1	64.3±2.57	178.9±8.94	10.7±1.31
3	66.1±3.20	181.4±14.01	13.6±1.74
5	69.9±2.74	155.9±8.66	5.8±1.72

Fractographic examination. 12 fracture surfaces from four components with different elongation values (0.6-16%) were chosen to be investigated more in detail using optical microscopy and scanning electron microscopy (SEM) techniques. The SEM analysis using EDS measuring showed very few oxides in the fracture surface. The oxides did not interfere with the fracture propagation. Fig. 4 illustrates the different behaviour of main crack propagation in the core part and skin part of the samples. For the samples from near-to-gate shown in Fig. 4(a) and the sample from near-to-vent region with eutectic bands, Fig. 4(b), the secondary cracks were formed perpendicular to main crack line. In the samples from near-to-vent region with porosity band, Fig. 4 (c), the fracture surface was following porosity bands.

Figure 4. (a) Typical fracture of high α_1 -Al concentrated region, with secondary cracks, (b) fracture through a region with positive macrosegregation (c) fracture surface following porosity bands

Near-to-gate region. Closer examination of samples under SEM from near-to-gate region showed mix mode fracture surface with dimples and more brittle cleavage features, similar to river marks (Fig. 5(a)). Furthermore, the different shape and size of the dimples in the fracture surface revealed clearly the different α -aluminium phase sizes. These particles can be classified according to their size as α_1 -Al particles, in the range of 60 to 85 μ m and rapidly solidified particles (α_2 -Al particles) in the die cavity in the range of 5 to 15 μ m.

Fig. 5(a) also demonstrates shear and plastically deformed dimple due to tensile and bending stresses at this area. Additionally, the oval dimples elongated in the direction of the applied shear force. For the tensile tested samples with the highest value of elongation, there was clear evidence that the microvoids around the matrix had the main role of the material failure. On the other hand, presence of a pore on the fracture surface (Fig. 5(b)), clarified that this inhomogeneity can be involved in the early crack formation. This was verified by showing that the medium elongation values belong to the samples with pores on the fracture surface.

Figure 5. (a) Mixed mode fracture in the location near-to-gate with cleavage features, (b) presence of pore and severely sheared surface parallel to the tensile direction

Optical microscopy of fracture surface of samples from location 1 and 3 proved the importance of microstructure in the preferred path of fracture, strongly influenced by the fraction and morphology of α_1 -Al particles. Fig. 6(a) shows propagation of the main crack in the samples with very ductile core region. The severely sheared α -phase particles were noticeable. It also illustrated that α_1 -Al particles in the fracture subsurface microstructure were elongated in the direction of the external stress (Fig. 6(b)). The skin part that contained individual α_1 -Al particles exhibiting heavy shearing as well (Fig. 6(c)). The observation of shear deformation in the samples from location 1 and 3 and also the line of shear in fracture surface, (Fig. 4(a)), explicitly suggest that crack initiated in one end of the specimen and propagated toward another surface (mode II). This might be an explanation for the c-shape dimple observed in SEM.

Figure 6. Typical fracture profiles in location 1 and 3; (a) Severely sheared deformed grain in the core region of component (b) plastic deformation of α_1 -Al particles in the fracture subsurface (c) Skin part the same type of shearing deformation was observed

Near-to-vent region. By observing fracture surface of tensile tested samples in the specimens from location 5, significantly different mechanisms of fracture were found, Fig. 7(a) through 7(d). The presence of dimples specified that the ductile fracture mode in some regions of samples was the main fracture mode, Fig. 7(b). This is more obvious for the skin layer in which early solidification decreased the chance of shrinkage porosity formation. On the other hand, no visible and significant deformation of microstructure in the centre of samples (Fig. 7(c)), states the presence of the large area of shrinkage porosity probably due to feeding issue. In addition, interdendritic shrinkage in the form of secondary crack after tensile testing, perpendicular to main crack surface was apparent as shown in Fig. 7(d).

Figure 7. (a) Shrinkage porosity and dimples in sample from location 5 (b) presence of dimples shows ductile plastic behaviour (c) shrinkage porosity and (d) interdendritic shrinkage

The optical microscopic study of samples from location 5 verified the presence of plastic deformation and shrinkage porosity at the same time on the fracture surface, Fig. 8(a) through 8(c). The plastic deformation on fracture surface and fracture subsurface microstructure were less than tensile tested samples from location 1 and 3, Fig. 8(a). Slight shear deformation was observed specially in the presence of entrapped α_1 -Al particles, Fig. 8(b). By studying the core part and skin layer of these samples at the fracture surface, secondary cracks in the eutectic regions (Fig. 8(b)) and shrinkage microporosity in subsurface of fracture in isolated zones after tensile testing were evident, as shown in Fig. 8(c).

Figure 8. Typical fracture profiles samples from location 5; (a) plastic deformation of surface with elongated subsurface grains, (b) limited plastic deformation at the fracture surface, with secondary cracks in the eutectic regions, (c) centre region of the sample with deep the secondary cracks visible

The SEM analysis on the fracture surface of these specimens, Fig. 9(a), also showed the continuous interdendritic shrinkage in this area. These shrinkage porosities were observed in the tensile tested samples from location 5 that had the elongation value less than 1.5%. Fig. 9(b) similarly illustrates that porosity bands were presented in the form of continuous line located around 550 μ m to 650 μ m from surface of component. These bands were formed in the same level that secondary cracks on the fracture surface were observed. Therefore, shrinkage porosity, formed in the large area of fracture surface of the tensile tested samples and formation of secondary fracture because of the presence of porosity band can explain shorter elongation values compared to samples from location 5 taken from the near-to-gate region.

Figure 9. (a) The SEM image of defect band in the form of shrinkage porosity, (b) the pore bands were observed at the same distance from the surface as the secondary crack profile (white arrow)

Conclusions

The microstructural inhomogeneity on the different location of components for a low Si aluminium alloy produced by SSM-HPDC process were studied. In the case of longitudinal inhomogeneity of microstructure, a decrease in the amount of α_1 -Al particles and finer microstructure for samples from the near-to-vent region, due to sponge effect, were observed. The pore bands were formed when the amount of liquid was insufficient and which therefore could not compensate for both expansion in the shear band and the solidification shrinkage. This type of bands was more dominating in the sample from near-to-vent region in comparison to the sample from near-to-gate region. For cross sectional inhomogeneity of microstructure in SSM HPDC, the formation of a fine microstructure near to surface (skin layer) and coarse microstructure in the centre of component were observed.

Moreover, the nature of the fracture was investigated under SEM. Different microstructure in the skin layer and core part of the samples resulted in the different profile of crack in the tensile test bars in the final fracture surface. Considering the relation between elongation value and porosity, the samples can be categorized into four groups:

- Samples with the highest elongation (>10%); Formation of dimples after tensile testing were observed in these samples. The oval shape dimples indicates complex stress experienced by the fracture surface.
- Samples with elongation between 6% and 10%; The fracture was initiated at pores and formation of dimples were observed in these samples. This indicates fracture is more ductile after crack initiation.
- Samples with elongation less than 5%; Formation of dimples after tensile testing were observed in the skin part of these samples. No sign of fracture surfaces shows that a large

area of shrinkage porosity was formed during last step of solidification mostly in the core part of components.

- Samples with lowest elongation, less than 1%; Presence of porosity band in the region near to the cast component surface and also shrinkage porosity in the core part of samples were observed in these samples.

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