Effect of temperature and displacement rate on behaviour of as-cast AA5182 and Al–3.3%Cu alloys under tensile loading near solidus temperature

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Abstract. Hot cracking develops in the still semi-solid casting during the last stages of solidification. The micro-mechanism of its origin is not generally accepted. There exists considerable doubt whether it is initiated by a void or develops as an instantaneous crack. The aim of this work is to study the mechanism of fracture behaviour of aluminum alloys around solidus temperature. Tensile tests were performed on notched specimens of as-cast AA5182 and Al–3.3%Cu alloys using a Gleeble 3500[®] thermomechanical simulator. The effect of temperature and strain rate on the propagation of fracture in the semi-solid state has been studied to establish fracture mechanism. The transition from ductile to brittle mode of fracture has been observed around the solidus temperature. The fracture is intergranular and propagates through interdendritic channels.

Keywords. Fracture; AA5182; Al–3.3%Cu; solidus temperature.

1. Introduction

Hot cracking is a common casting defect occurring in the final product. This is initiated and maybe propagated in the still semi-solid casting (Eskin *et al* 2004). It is also known that it is influenced by casting parameters (Suyitno *et al* 2004).

Hot cracking has been studied by performing tensile test at semi-solid temperatures either by *in situ* solidification experiments (Lankford 1972; Forest and Bercovici 1983; Spittle and Cushway 1983; Ohm and Engler 1990; Nedreberg 1991; Magnin *et al* 1996; Instone *et al* 2000) or by reheating specimens from room temperature (Williams and Singer 1968; Fredriksson and Lehtinen 1979; Spittle *et al* 1997; Martin *et al* 1999; Haaften *et al* 2000). The structures obtained are different and so are the results of mechanical tests. The necessary condition for an alloy to be tested for mechanical properties is the ability to retain its shape and to transfer stress. In the lower part of the solidification range, so-called solid–liquid or semi-solid part, alloys satisfy that condition and therefore, can be mechanically tested.

It is observed that both strength and ductility strongly decline from just below the solidus temperature to the semi-solid state, while fracture surface gradually changes from rough, related to the ductile behaviour, to smooth, related to the presence of a liquid film.

Correlation between hot cracking susceptibility and composition of an alloy is well established (Eskin *et al* 2004). The link between the appearance of hot cracks and the mecha-

nical properties in the semi-solid state is obvious. This connection was explored for decades. Nevertheless, the micro-mechanism of its origin is not generally accepted. There are controversies regarding whether it is initiated by a void or develops as an instantaneous crack. Most literature which report this phenomenon only deal with sufficient condition for the possible occurrence of hot cracking (Braccini *et al* 2000; Farup *et al* 2001; Haaften *et al* 2002a, b; Martin *et al* 2002). Meanwhile, the mechanism of initiation and propagation of the hot tear is not concluded. A solute-rich (eutectic) path along grain boundaries ahead of the hot-crack tip was observed in billets with hot tears. The porosity is maximum in the centre of the billet and in the concentration range of low hot tearing susceptibility. A mechanism of crack initiation in liquid pockets and crack propagation along solid bridges is suggested (Suyitno *et al* 2006).

There have been no studies concerning the initiation and propagation of hot cracks. This is caused by the fact that *in situ* observation is difficult as the hot crack starts to develop.

The aim of this study is to investigate experimentally the behaviour of notched specimens of aluminum alloys around solidus temperature under tensile loading. Effects of temperature and strain rate on the progression of fracture in semi-solid state have been examined.

2. Experimental

Experiments were performed on AA5182 specimens drawn from the centre of 460 mm wide and 1440 mm thick slab and Al–3.3%Cu from the centre of 194 mm diameter

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Table 1. Chemical composition of AA5083 and Al-3.3%Cu.

Alloy	Mg	Mn	Si	Fe	Cu	Zn	Ti	Al
AA5182	3.60	0.16	0.21	0.26	<0.01	0.01	0.02	Balance
Al-3.3%Cu	<0.01	<0.01	0.08	0.20	3.26	0.02	<0.01	Balance

Figure 1. Schematic drawing of specimen: dimensions in mm and thickness 3 mm. **Figure 2.** Temperature profile during heating and tensile testing of sample.

billet in as-cast condition. The chemical compositions of the alloys are given in table 1.

The notched-tension test samples were 3 mm thick and 25 mm wide with V-notch on both sides. The complete geometry of the notched-tension test specimen is shown in figure 1. The loading direction was perpendicular to the thickness of the slab and cross-section of the billet. Tensile tests were carried out on a Gleeble 3500[®] thermomechanical simulator. The specimen was clamped between two water-cooled jaws and heated via Joule heating. Load and displacement were measured by sensors attached on the mouth of the notch. Temperature was measured with a chromel–alumel thermocouple which was spot-welded on the specimen. The tests were performed in stroke control mode and different loading histories. During the test, time, temperature, crack mouth opening, jaws movement and load were recorded.

Table 2. Parameters for experiment.

	Temperature (°C)	Deformation rate ($\mu\text{m s}^{-1}$)
AA5182	550	0.8 and 3.4
AA5182	540, 555 and 560	0.8
Al-3.3%Cu	580	0.8 and 3.4
Al-3.3%Cu	580, 585, 588 and 590	0.8

Figure 3. Microstructure images of AA5182 (a) and Al-3.3%Cu (b) at as-cast condition.

Figure 2 shows an example of a process chart which shows the temperature profile during heating and tensile testing of the sample. The specimen was heated rapidly till 450 °C, then it was heated slowly before reaching a testing temperature. The specimen moves freely due to the thermal expansion along the longitudinal direction during initial heating. The stroke was applied when the temperature reached testing temperature. The specimen was slightly compressed in the initial step of the stroke.

Two aspects influencing the fracture behaviours were investigated viz. strain rate and temperature. Two deformation rates of 0.8 and $3.4 \mu\text{m s}^{-1}$ were applied during tensile test at 550°C for AA5182 and 580°C for Al-3.3%Cu. The effects of temperature were investigated by performing tensile tests at various temperatures viz. 550 – 560°C (~ 4 – 5% of liquid fraction based on calculation using Scheil formula) for AA5182 and 580 – 590°C (~ 0 – 1% of liquid

fraction based on calculation using Scheil formula) for Al-3.3%Cu at a deformation rate of $0.8 \mu\text{m s}^{-1}$. The parameters used are compiled in table 2.

Another test was performed to investigate how the damage develops and propagates during tests on AA5182. The specimens were stretched at 555°C and deformation rate of $0.8 \mu\text{m s}^{-1}$, and then stopped at 10%, 25%, 35% and 50% of total crack mouth opening. The specimens were held under

Figure 4. Load–displacement curve of AA5182 at various temperatures. (Displacement rate: $0.8 \mu\text{m s}^{-1}$ and temperatures: (1) 540°C , (2) 555°C and (3) 560°C).

Figure 5. Load–displacement curve of Al-3.3%Cu at various temperatures. (Displacement rate: $0.8 \mu\text{m s}^{-1}$ and temperatures: (1) 580°C , (2) 585°C , (3) 588°C and (4) 590°C).

Figure 6. Load–displacement curve of AA5182 as an effect of displacement rate (Displacement rate: (1) $0.8 \mu\text{m s}^{-1}$ and (2) $3.4 \mu\text{m s}^{-1}$).

Figure 7. Load–displacement curve of Al-3.3%Cu as an effect of strain rate at temperature 590°C (Displacement rate: (1) $0.8 \mu\text{m s}^{-1}$, (2) $2.5 \mu\text{m s}^{-1}$ and (3) $7.6 \mu\text{m s}^{-1}$).

the condition till total fracture. On the completion of tests, the specimens were cooled rapidly from 555 °C to room temperature to keep the microstructure of that stage. The cracked area was cut from the specimen for metallographic observation. The specimens cut from the cracked area were mounted on the sample holder and then polished. Wet polishing paper was used to avoid adverse effect of temperature

on the sample and to prevent the particles of the polishing paper from getting embedded into the surface of the sample. The specimens were observed under an optical microscope in unetched condition. The fracture surface of AA5182 fractured at 550° and 560 °C, and Al-3.3%Cu fractured at 580° and 590 °C were investigated by using scanning electron microscope (SEM).

Figure 8. Fracture development of specimen at left notch, centre and right notch. Displacement: (a) 10%, (b) 25%, (c) 35% and (d) 50% of total displacement for fracture.

Figure 9. SEM images of fracture surface: (a) AA5182 cracked at 550 °C, (b) AA5182 cracked at 560 °C, (c) Al-3.3%Cu cracked at 580 °C and (d) Al-3.3%Cu cracked at 590 °C.

3. Results and discussion

Figure 3 shows microstructure of the sample at as-cast condition under polarized microscope. AA5182 has a mixed structure of dendritic and globular features and Al-3.3%Cu alloy has a dendritic structure. The microstructure shows clearly that the grain size of AA5182 is smaller than that of Al-3.3%Cu alloy. Grain sizes of AA5182 and Al-3.3%Cu alloys are ~ 90 and $210\ \mu\text{m}$, respectively.

The effect of testing temperature on the load–displacement curves is shown in figures 4 and 5 for AA5182 and Al-3.3%Cu, respectively. The results show that at temperatures between 585° and 588 °C, the load–displacement curve of Al-3.3%Cu exhibits transition from ductile to brittle mode. Such a transition is also observed for AA5182 at 555 °C. This, however, is not so prominent as in Al-3.3%Cu.

The effect of displacement rate on the load–displacement curves is shown in figures 6 and 7. AA5182 is fractured at 555 °C and Al-3.3%Cu is fractured at 590 °C. Increase in extension rate causes an increase in maximum load and decrease in extension where the load reaches a peak load.

Optical microscopic images of the left notch, the centre and the right notch of the sample where the cross head was stopped on reaching a strain of 10%, 25%, 35% and 50%

for AA5182 at 555 °C are shown in figure 8. The fracture appears to have been initiated around the notch by cavity formations just ahead of the notch (figure 8a). With further displacement, cavity coalescence develops into microcracks at the inter-granular sites. Later, this develops into a main crack. Cavity was observed in all the materials between both notches (figure 8(b–d)). SEM images of fracture surface of specimen fractured at 550° and 590 °C for AA5182 and at 580° and 590 °C for Al-3.3%Cu alloy are shown in figure 9. It is shown that the surface is smooth which indicates existence of liquid at the time of fracture. The inter-granular fracture is clearly seen in the figure. The fracture surfaces of AA5182 show dendritic features which is not so clear in Al-3.3%Cu.

The present study reveals that the strength and ductility of aluminum alloys decrease with increasing temperature and increasing strain rate. Decrease in ductility leads to brittle fracture. Brittleness is not only shown by decrease in ductility with temperature and strain, but also by the fracture surface (figure 9). The fracture appears to be initiated in the solidification range. This result is characteristic of intergranular fracture surface.

The load–displacement curve shows that the load increases rapidly even at a small displacement. After the load reaches a

maximum point, it decreases slowly or rapidly depending on whether it corresponds to a ductile or brittle process, respectively. The fracture propagates in a way that is dependent on the temperature and strain rate. The higher the temperature or strain rate, faster is the propagation. At a lower temperature or strain, the imposed deformation appears to be accommodated by crack propagation and sliding. Whereas at a higher temperature or strain rate, the imposed deformation is probably accommodated by crack propagation as the strength of liquid film being low, the time available is not enough for the grains to slide.

The load–displacement curve indicates the phenomenon of increasing strength with decreasing temperature of aluminum alloys in the solidification range. It also tends to a condition of the zero strength point at a particular temperature (Eskin *et al* 2004) and the brittle temperature range in which the lowest fracture strain is obtained at the solidification range. Although, the transition from ductile to brittle mode of fracture is not clearly defined, but the rapid decrease of fracture strain in the last stage of solidification could correspond to the transition (Novikov 1996).

The fracture surface shows that the grain is covered by liquid. The role of liquid grain boundary clearly affects the mechanical behaviour and mechanism of fracture is initiated by a cavity formation in the liquid phase mainly at the triple-junction as supported by Marion *et al* (1983) and Suyitno *et al* (2006). The extension of the cavity is shown on observation of the damage development and propagation (figure 8). The cracks propagate rapidly across the grain boundary facets.

This study reveals that the fracture is brittle in the semi-solid region, so that it can be a basis for prediction of the fracture in the semi-solid region such as hot cracking. Griffith's approach on fracture that is based on the assumption of brittle material might be applied to the problem (Suyitno 2005). However, the prediction of this fracture should also involve the permeability behaviour of the semi-solid state and the relation with porosity.

4. Conclusions

On the basis of the tensile tests performed on notched specimens of aluminum alloys around solidus temperature, the following conclusions can be drawn:

- (I) Brittle mode of fracture is promoted by increasing temperature and tensile strain rate.
- (II) The fracture process is initiated by cavity formation that subsequently develops into microcracks by coalescence of the cavity. Propagation of microcracks thus formed results in fracture.

- (III) The hot tear passes through the interdendritic channels so that the fracture surface is intergranular with interdendritic structure.

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