# Constitutive Behaviour and Hot Tearing during Aluminium DC Casting

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#### Abstract

The prediction of hot tears during DC casting is complicated because of the complex cooling conditions and subsequent development of thermal stresses. Models developed for this purpose require a detailed knowledge of the process conditions and hot tearing mechanisms. Therefore, a micro structural investigation of hot tearing in commercial alloys was carried out in two ways: tensile specimens were deformed at various temperatures above the solidus, which conditions led to fracture. Further, crack propagation was studied in-situ at semi-solid temperatures. In both cases, the fracture surfaces of the specimens were investigated by SEM. Microstructural investigations of these cracks show that they initiate at any weak spot such as a pore or partially liquid grain boundary and occur by a combination of fluid film separation and rupture of solid bridges along grain boundaries. This leads to brittle behaviour on the large scale although local deformation can be very ductile. Similarities between hot tears in industrial ingots and cracked specimens indicate that important aspects of hot tearing during casting can be simulated by tensile experiments at semi-solid temperatures.

#### 1. Introduction

In the direct chill (DC) casting process of aluminium alloys, the cooling imposes strong thermal gradients on the ingot. Stresses and strains caused by both solidification shrinkage and thermal contraction may lead to distortion of the ingot shape (e.g. butt curl, butt swell, rolling face pull-in) and/or to hot tearing and cold cracking. From many studies [1,2,3,4,5,6,7,8,9,10], it appears that hot tears initiate above the solidus temperature and propagate in the interdendritic liquid film. This results in a bumpy crack surface covered with a smooth layer and sometimes with solid bridges which connect both sides of the crack [8,9,11,12,13,14,15,16,17]. During solidification, the liquid flow through the mushy zone decreases until it becomes insufficient to fill initiated cavities. Apart from these intrinsic factors, the solidification shrinkage and thermal contraction impose strains and stresses on the solid network, which are required for hot tearing. It is argued that it is mainly the strain and the strain rate, which are critical for hot tearing [2,9]. Crack propagation was studied in-situ at 500°C and fracture surfaces of the specimens were investigated by SEM. The results of the tests were compared with a hot tearing surface in an industrial AA5182 ingot and current hot tearing criteria were evaluated.

# 2. Experimental

# 2.1 Material

The materials investigated is an AA5182 alloy with the composition in wt%: Mg 3.6, Mn 0.16, Si 0.21, Fe 0.26, Al balance. The slab did not receive any additional heat treatment after casting.

# 2.2 Mechanical Testing

Tensile tests were carried out with a Gleeble  $3500^{\text{®}}$  thermomechanical simulator. The specimens were taken from the slices with the tensile direction parallel to the casting direction. The specimen is heated at  $50^{\circ}$ C/s via Joule heating during which it is kept at zero force. The test temperatures are from  $50^{\circ}$ C up to  $620^{\circ}$ C. The tensile tests were carried out at low strain rates (<  $3 \times 10^{-3}$  s<sup>-1</sup>), which are comparable to values in the DC casting process. At the moment the force was seen to decrease, which was interpreted as crack initiation, the specimen was quenched with water to preserve the microstructure at the time of fracture. Non-fractured specimens were quenched immediately after the tensile test. After the tests, selected non-fractured specimens were cut parallel to the tensile direction and studied by optical microscopy. The grain size was determined with the line interception method. Fractured specimens were studied by SEM.

2.3 In-situ Cracking Observation

In a SEM equipped with a hot stage, polished flat specimens with a V-notch were heated and deformed in tension. The specimen was mounted on a heating element and heated to 500°C in two minutes. The specimen was then deformed at a speed of 0.2 :m/s and crack propagation was studied. The tensile direction was normal to the casting direction and parallel to the rolling face of the slab.

2.4 Observation of Hot Tear Surface in an Industrial Ingot

Samples from casting experiments with AA5182 at an industrial research facility were selected and hot tears were investigated by SEM. The location of the samples was in the steady state part of the ingot at circa 10 cm from the crack initiation point. The samples were etched to remove the oxide layer on the hot tearing surface.

## 3. Results

## 3.1 Tensile Tests and Microstructural Observations

The resulting strain rate and strain of the tensile tests are summarised in Table 1. Also indicated is the liquid fraction  $f_{\rm L}$  and whether or not the specimen fractured. Optical microscopy on the uncracked specimens and on an as-cast specimen showed that all specimens had a similar grain size (110-120 :m), had Al<sub>6</sub>(Mn,Fe) and Al<sub>3</sub>Mg<sub>2</sub> as constituent particles and contained some porosity. No crack initiation phenomena were observed in the strained specimens. So, no major differences between the strained specimens themselves or with the as-cast specimen were observed.

SEM observations were made of the fracture surface of the specimen fractured at  $560^{\circ}$ C and , = 0.005. Figure 1 shows grains, which are covered with a smooth layer, which was

liquid at the time of fracture. Where the gap between two grains became too large, holes developed in the liquid film. In some parts, the two crack sides were still connected by solid bridges, which are solid connections between dendrite arms. Evidence for this is seen in the rough surface in Figure 1 at location SB1 where solid-state rupture has taken place. Solid bridges still in place are also present as can be seen at location SB2. Figure1b shows in detail one of the many side cracks in its final stage before decohesion. It is partly filled with solidified liquid. Figure 1c shows two separated grains with some remaining liquid. In this case, the liquid metal pressure was not high enough to feed the entire crack and a capillary meniscus remains.

T (°C)	fL	$\Phi$ (MPa)	<b>♥</b> (s <sup>-1</sup> )	,	Remark
500	0	8	2.7A10 <sup>-4</sup>	0.005	
500	0	8	3.3A10 <sup>-4</sup>	0.016	
510	0	4	4.4A10 <sup>-5</sup>	0.007	
510	0	8	2.1A10 <sup>-4</sup>	0.020	
520	0.01	6	1.5A10 <sup>-4</sup>	0.004	
520	0.01	3	8.2A10 <sup>-5</sup>	0.006	
530	0.02	3	4.8A10 <sup>-5</sup>	0.006	
540	0.02	4	1.9A10 <sup>-4</sup>	0.004	
540	0.02	4	2.5A10 <sup>-4</sup>	0.004	
540	0.02	2	5.2A10 <sup>-5</sup>	0.006	
540	0.02	10	2.5A10 <sup>-3</sup>	0.013	Cracked
540	0.02	10	2.7A10 <sup>-3</sup>	0.014	
550	0.03	1	3.3A10 <sup>-5</sup>	0.004	
550	0.03	3	1.6A10 <sup>-4</sup>	0.004	
550	0.03	5	8.0A10 <sup>-4</sup>	0.008	Cracked
556	0.04	3	1.5A10 <sup>-4</sup>	0.002	
560	0.04	2	9.0A10 <sup>-4</sup>	0.001	Cracked
560	0.04	2	6.5A10 <sup>-4</sup>	0.005	Cracked
580	0.07	0.8	5.0A10 <sup>-4</sup>	0.003	Cracked
580	0.07	0.8	3.3A10 <sup>-4</sup>	0.005	Cracked
580	0.07	0.9	4.0A10 <sup>-4</sup>	0.010	Cracked

Table 1: Experimental parameters for the hot tearing simulations with AA5182 and resulting strain rate and strain.



Figure 1: SEM micrograph of fracture surface of tensile specimen, fractured at 560°C. a: grains covered with a (solidified) liquid film. SB1: remains of fractured solid bridges, SB2: solid bridge still intact. b: side crack, not fully separated. c: separated grains with some remaining liquid which forms a capillary meniscus (C).

## 3.2 In-situ Cracking Observation:

Figure 2 shows stills from a video of the in-situ deformation in the SEM at 500°C. The crack started at the notch of the specimen but after some deformation cracks also initiated at grain boundaries and pores. These separate cracks grew to each other to form the final crack.

They mainly followed the grain boundaries and due to the different crack initiation locations, the final crack has a meandering form. Although the grain boundaries were clearly the weakest part of the structure, the occurrence of slip lines (Figure 2c) indicated that the grains themselves also deformed. Side cracks were also formed but they stopped growing when the stress was relieved by propagation of the main crack. No liquid is present at 500°C, but when a crack is formed solid bridges initially form the connection between the sides of the crack and they flow in a ductile manner during separation (Figure 2b).



Figure 2: Tensile deformation (direction: ) in SEM at 500°C. Left: cracks initiate at different locations and grow towards each other. Square: detail shown in Middle. Right: slip lines (SL).3.3 Observation of hot tears in an industrial ingot

The cracking surface of hot tears in one of the AA5182 ingots of the industrial casting experiments was investigated by SEM. The grain size is approx. 135:m. Many side cracks are present and hot tear follow the grain boundaries (Figure 3). Part of the grain boundary surface was liquid at the time of fracture as indicated by the smooth dendrite arms although the grain boundary surface was not completely covered by a liquid film. The irregular marks on the grains show evidence of solid-state deformation in places where the grains were still connected.

There are large similarities between the fracture surface of the tensile specimens (Figure 1) and the ingot hot tears (Figure 3). Both have a similar grain size and show intergranular fracture, solid bridges and dendrite arms covered with a liquid layer. There are also similarities between the in-situ specimens and the ingot hot tears, since both show intergranular fracture and solid bridges.



Figure 3: SEM micrograph of the hot tear surface (in plane of paper). Left: marks (M) on surface indicate solid-state rupture. Right: side crack with marks and capillary meniscus (C) of remaining film.

## 4.1 Hot tearing observations

In the tensile tests, apart from liquid film separation, ductile failure occurred locally where solid material formed bridges across the liquid film (Figure1). Therefore, the material behaves brittle on the large scale whereas locally it behaves in a ductile manner. Further, the data summarised in Table 1, although too limited to make a complete ductility curve, give the general picture of a steeply decreasing ductility just above the solidus temperature, a minimum around a fraction liquid of 0.04 (560°C) and a slight increase again at higher temperatures. This is consistent with literature data [12,14,15,18].

The in-situ SEM observations are especially suited to study crack propagation. They show intergranular cracking and the development of solid bridges (Figure 2). They further show that grain boundary separation occurs in three stages. Where grain boundaries are perpendicular to the tensile direction, the crack grows by opening the grain boundary as a wedge. Upon reaching a grain boundary more or less parallel to the tensile direction, the crack arrests briefly and then continues along one of the grain boundaries by a sliding motion.

Observations on the hot tear surface of the industrial ingot show that many features such as side cracks, liquid films, solid bridges and grain size are similar to features observed on the fracture surfaces of the tensile specimens and the in-situ SEM specimens. This indicates that tensile experiments at semi-solid state such as carried out in this study can be used to study hot tearing and to evaluate existing hot tearing criteria.

## 4.2 Hot tearing criteria

Figure 4 shows the strain vs. strain rate of the specimens tested in semi-solid state. It indicates that tendency for cracking is mainly a function of strain rate. A recent hot tearing model of Rappaz et al recognises this. [19]. The model is further developed by Braccini *et al.* [20] to include crack growth and deformation of the solid network. This modification makes it possible to calculate directly the strain rates at which nucleation or growth of a cavity occurs, which allows comparison with the experimental data. The minimum strain rates for both nucleation and growth are given in Figure 5.

Except for the highest solid fractions, the result is dominated by the liquid flow part. The critical strain rate for growth is higher than for nucleation, which means that the first is of importance for hot tearing.



Figure 4: Strain vs. Strain Rate



Figure 5: Minimum Strain rates for both nucleation and growth

The critical strain rate increases with increasing liquid fraction because of the higher permeability of the mush [21,22]. The experimental data from Table 1 are also shown in Figure 5. It is observed that there is a one to four orders of magnitude difference between the model and the experimental data.

Further, in contrast to the model, the experimental data show a decreasing strain rate with increasing liquid fraction. Despite the difficulties to link the existing models with the experimental data, both give information relevant to hot tearing during DC casting. The model indicates the importance of fluid flow, while the experiments illustrate the role of solid bridges. It is concluded that with the current knowledge it is possible to rank alloys with respect to their tendency for hot tearing but there is still no constitutive description of the hot tearing mechanism.

#### 5. Conclusions

Microstructural investigations of cracking induced in the semi-solid temperature range indicate that cracking in AA5182 starts at any weak spot such as a pore or partially liquid grain boundary follows almost exclusively the grain boundaries and occurs by a combination of fluid film separation and rupture of solid bridges. This leads to brittle behaviour on the large scale although locally deformation can be very ductile. Similarities between hot tears in the industrial ingot and cracked specimens indicate that important aspects of hot tearing during casting can be simulated by tensile experiments at semi-solid temperatures.

The validity of the current hot tearing models is restricted to relatively high liquid fractions ( $f_L > 0.1$ ) because the models do not take into account the presence of solid bridges. Experiments indicate that hot tearing occurs at a strain rate of about  $10^{-3}$  s<sup>-1</sup>. This value should be regarded as a minimum value for hot tearing, as during casting afterfeeding will (partly) compensate the straining of the mush.

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