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HOT TEARING IN ALUMINIUM – COPPER ALLOYS

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Abstract

For many aluminium alloys, hot tearing susceptibility follows a lambda curve relationship when hot tearing severity is plotted as a function of solute content. In the past, there has been some difficulty quantifying hot tearing. Traditional methods rely upon measuring electrical resistivity or the number and/or length of cracks in tests such as the ring test. In this experimental program, a hot tear test rig was used to investigate a series of binary Al-Cu alloys. This device measures the load imposed on the mushy zone during solidification. Hot tearing susceptibility was quantified in two ways. The first method involved measuring the load at the solidus temperature (548°C). The second method was to radiograph the hot spot and measure the image density of the cracks. Both methods had advantages and disadvantages. It was found that the results from the hot tear rig correlates with other published data using different experimental methods.

Introduction

Hot tearing along the centreline of DC castings is a major source of rejects limiting both the productivity of the process and its viability for casting a wide variety of alloys and ingot size combinations. Hot tears are generally thought to originate at temperatures between the liquidus and the bulk solidus of the alloy being cast. They occur when the restriction of solidification shrinkage and thermal contraction generate stresses which exceed the strength of the partially solidified metal. It is a problem commonly encountered during the casting of long freezing range alloys.

While the general mechanisms of hot tearing are understood i.e. the inability of liquid to feed imposed strain on the mushy material, work continues on improving the understanding of the mechanisms at play. Theories have focused on freezing range, microstructure development, feeding and imposed stress by the casting process, with relative success. The aspect least understood is the role of mechanical deformation of the semisolid microstructure on the hot tearing susceptibility of an alloy.

There are many factors that affect the level of stress in DC casting. The most important are the casting speed, mould size and alloy composition. As the casting speed increases, heat input increases which then results in increased temperature gradients and higher stress in the centre of the ingot. Similarly, increasing the mould size also increases the heat input and creates a longer diffusion path. In practice, casting speed is reduced as the ingot diameter increases [1]. As the alloy content increases, thermal conductivity decreases which results in deeper sump depths and higher temperature gradients.

It is known that hot tearing depends on alloy composition and study of the behaviour of binary alloy systems assists in understanding the role of alloy chemistry. It has been shown that hot tearing susceptibility tends to follow a lambda curve which is developed by plotting hot tearing severity as a function of solute content. For example hot tear severity is often a measure of total crack length or electrical resistivity [2, 3]. Pure metals and high solute alloys tend not to hot tear under similar testing conditions. The most susceptible alloys are low solute alloys such as 1 wt% Si and 1 wt% Cu alloys.

Hot Tear Test Rig Development

A hot tear test rig developed by Instone [4], and specifically designed to simulate the casting conditions found in DC casting was used. In particular, the rig simulates the tensile stress field found in the centre of the casting whilst still providing an ample supply of feed liquid. A detailed description of the equipment and the development considerations that went into its design are contained in references [4] and [5].

A schematic plan view of the mould and picture of the casting are displayed in Figures 1 and 2 respectively. The steel mould has a combined center pouring reservoir and riser (not shown) that feeds the centers of two cast bar cavities. This not only creates a hot spot but also ensures that feeding remains available to the centre region during solidification thus reproducing the feeding conditions found in DC casting. Tensile stresses encountered in

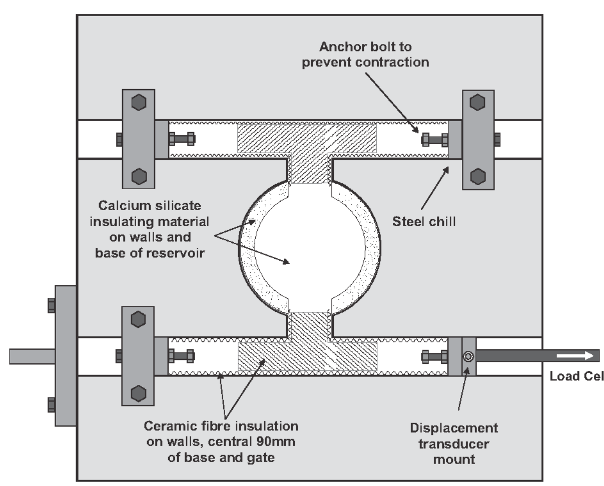


Figure 1. Plan view of the mould.

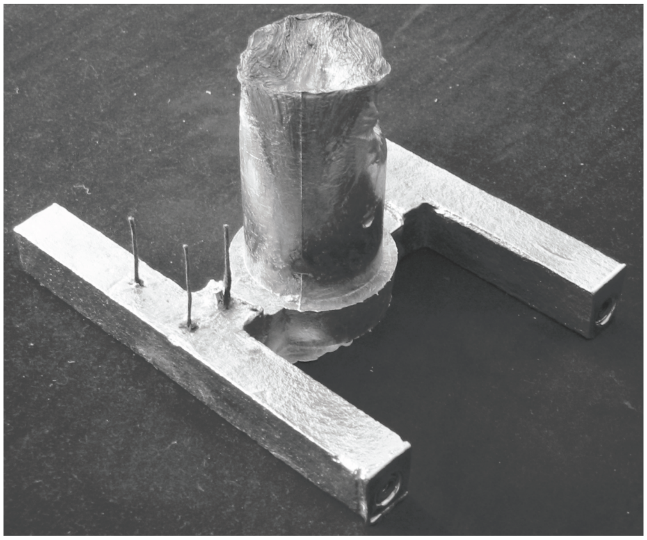


Figure 2. Photograph of a casting with embedded thermocouples.

the centre of an ingot can be reproduced in the cast bar by anchoring the ends. One cast bar is fully restrained and is used for microstructural examination and direct measurement of hot tears. The other cast bar is used for data collection (temperature, load, and displacement) and is restrained at one end while the other end is attached to a load cell. Temperature is measured via three type K thermocouples located in the gate, hot spot, and in the cast bar 30 mm from the hot spot (see Figure 2). The thermocouples are inserted through holes drilled in the mold cover plate and are positioned 4 mm below the surface. Ceramic fibre insulation was used to line the mould in specified areas to assist in producing the desired directional solidification. 3 mm ceramic fibre paper was used on the top surface of the mould.

The riser was a two-piece cylinder made from calcium silicate insulating material (N17). It also served as a convenient sprue through which metal was poured. The riser provided a metalostatic head to assist in mould filling and to supply feed material to the cast bars during solidification.

A schematic diagram of the hot tear test rig is displayed in Figure 3. The basis of the hot tear test rig is a modified tensile testing machine with a 5kN load cell which was laid on its side to allow the crosshead to operate horizontally.

Experimental

Hot tearing experiments were performed on a range of compositions within a binary alloy system and compare the results with other published data. The aluminium – copper binary system was chosen since it is known to be particularly sensitive to hot tearing and there are published data available for comparison. Alloy compositions from pure Al to Al – 5 wt% Cu with and without grain refiner added (0.05 wt% Ti in the form of Al5TiB master alloy) were cast in the hot tear rig. Data generated from the tests were analysed and compared with published data.

The pouring temperature for all tests was maintained at 755°C which gave a superheat of approximately 100°C. The mold preheat was maintained at 200°C. After casting both cast bars were separated from the riser and visually examined. The top and bottom of fully restrained cast bar was scalped to produce an even surface and then radiographed to reveal the extent of hot tearing. After radiography, the fully restrained cast bars were sectioned through the center of the hot spot region and were ground, polished, and anodized to reveal the grain structure.

Results and discussion

Table I compares the target compositions to the measured chemical analysis as well as the measured grain size for all the castings. As expected, the grain size of the grain refined (GR) and non grain refined (NGR) groups of castings decreases as the solute content increases.

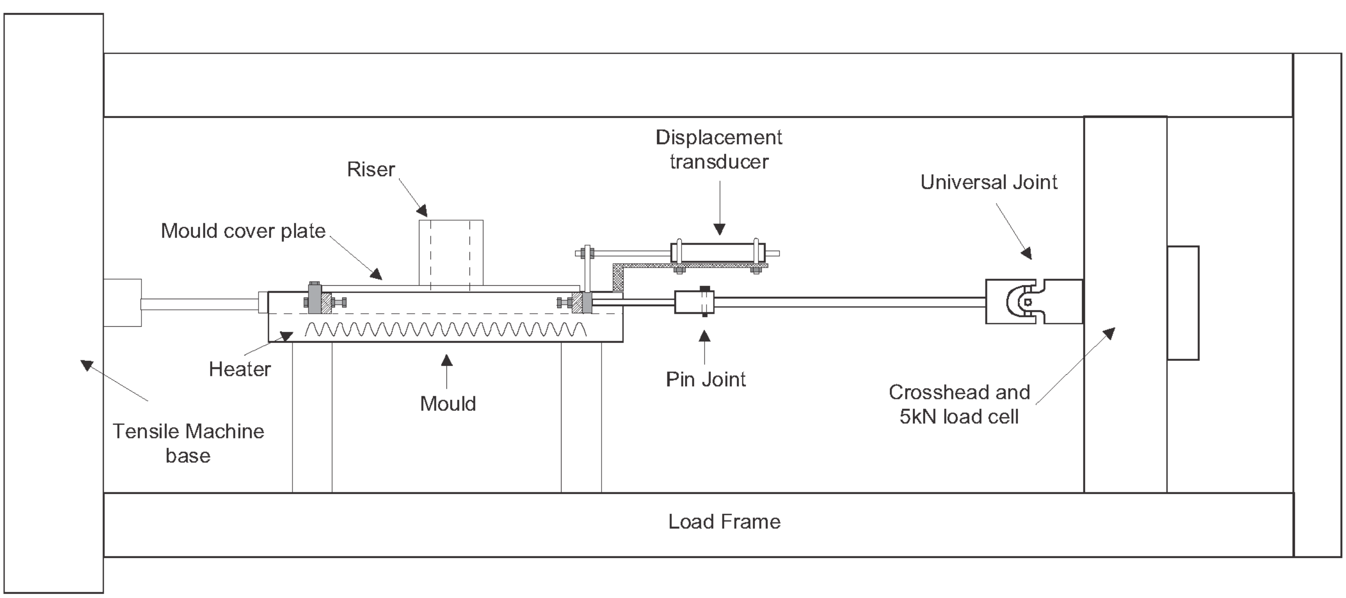


Figure 3. Schematic diagram of the hot tear rig showing the load train.

Table I. Chemical composition, load measured at solidus temperature, and grain size of the alloys tested.

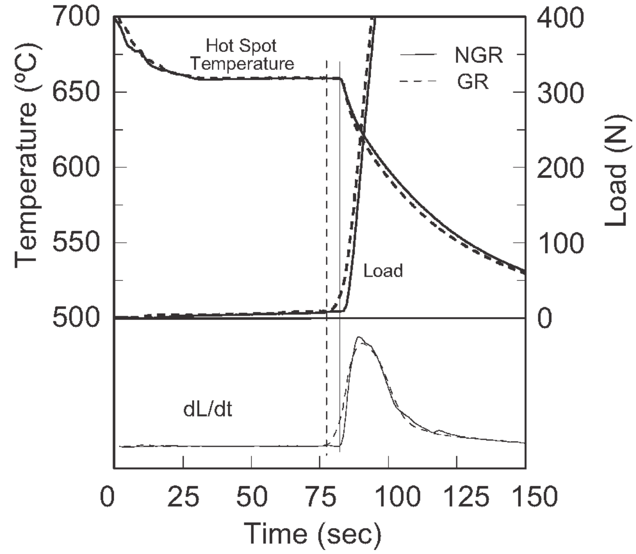
Target Cu wt%	Measured Cu wt%	Load at Solidus N	
Non Grain Refined castings (NGR)			DAS† μm
0	0.0	114	-
0.25	0.25	787	490
0.5	0.52	507*	450
1.0	0.97	445*	390
2.0	2.35	400	331
3.0	3.45	330	312
4.0	4.38	198	275
5.0	5.31	74	256
Grain Refined Castings (GR)			Grain Size μm
0.0	0.0	163	260
0.25	0.24	806	184
0.5	0.52	874	167
1.0	0.96	805	148
2.0	2.33	475	138
3.0	3.34	290	132
4.0	4.27	174	111
5.0	5.18	75	96

† Primary Dendrite Arm Spacing of columnar grains.
* Tearing observed in the cast bar attached to the load cell.

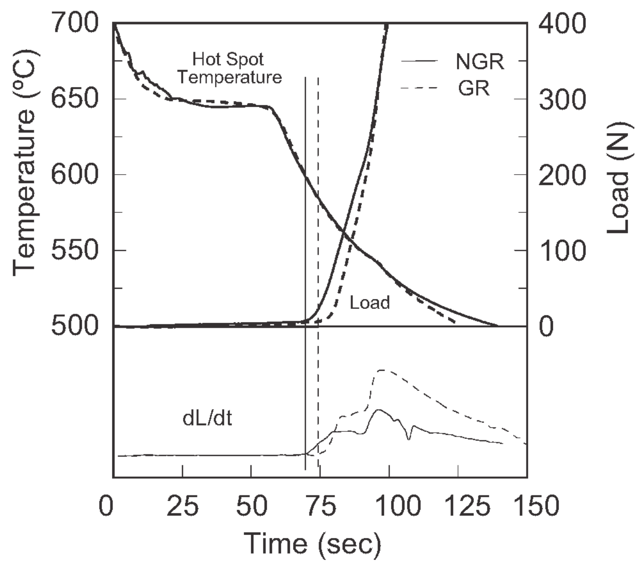
Figure 4 shows examples of the data generated from the test rig. Temperature recorded from the hot spot thermocouple and load recorded from the load cell are plotted as a function of time. The first derivative of the load is also plotted to help determine the point where load begins to develop. In Figure 4a, 0.25 wt% Cu, the grain refined casting develops load earlier than the non grain refined casting. The same observation was made with 0.5 wt% Cu (not shown). However, in castings containing greater than 0.5 wt% Cu the opposite trend was observed. This trend is reflected in Figure 4b (4 wt% Cu) where the grain refined casting developed load later than the non grain refined casting.

The solid fractions at which load developed were calculated using ThermoCalc® assuming Scheilian conditions and plotted in Figure 5. In the non grain refined castings, the solid fraction when load is first detected becomes lower as the Cu content increases. With the grain refined castings however, the solid fraction when load is first detected first increases until 1 wt% Cu where it plateaus and then gradually decreases. At present this trend is not fully understood and will require further investigation. However, at this stage it would appear that the solid fraction when load is first detected is dependent upon a variety of interrelated factors including alloy composition, grain size and dendrite morphology.

A similar trend was observed by Grasso et al. [6] who found that the solid fraction at the beginning of load build-up decreased as the Cu concentration increased from 1 wt% Cu to 4 wt% Cu. They also found that grain refinement delayed load build-up in Cu content range. Unfortunately, they do not report any results for Cu contents below 1 wt% Cu.



(a) 0.25 wt %Cu



(b) 4 wt% Cu

Figure 4. Temperature and load development as a function of time for Grain Refined (GR) and Non Grain Refined (NGR) castings containing (a) 0.25 wt% Cu and (b) 4 wt% Cu. The first derivative of the load is plotted below each graph and the vertical lines indicate the start of load development.

Hot tearing susceptibility was quantified in two ways. The first method involved measuring the load at the solidus temperature (548°C) and the second method was to radiograph the hot spot in the fully restrained cast bar and measure the image density. Both methods had advantages and disadvantages. The load method is a simple but indirect measurement. Due to the low compliance of the load cell, there was usually enough relaxation allowed to

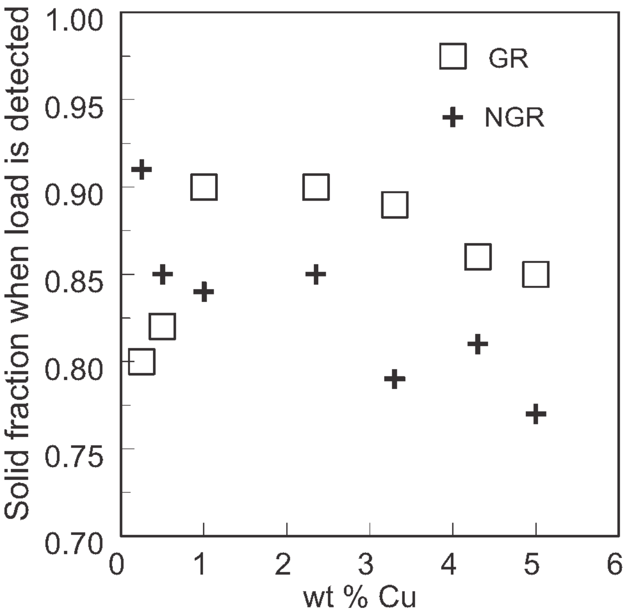


Figure 5. Solid fraction when load is first detected as a function of Cu concentration.

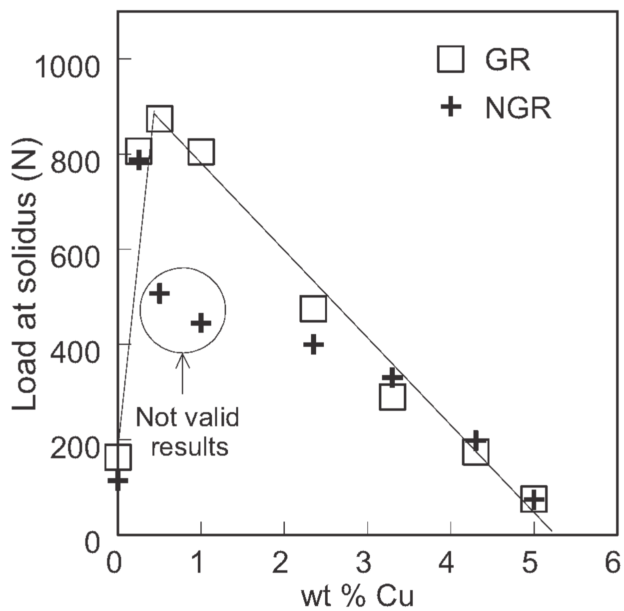


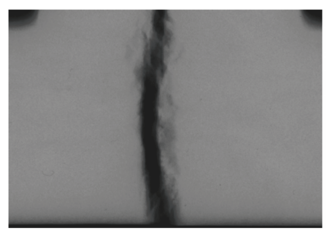
Figure 6. Load recorded at solidus temperature (548°C) as a function of solute content. For castings not containing Cu, the load recorded at the end of solidification was plotted.

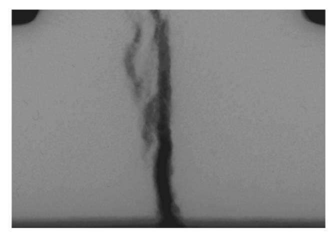
prevent tearing occurring in the cast bar attached to the load train. However, with extremely sensitive alloys (0.5 and 1.0 wt% Cu non grain refined), tearing did occur in the cast bar attached to the load cell and this resulted in a reduced load recorded at the solidus temperature. The radiographic method required the surfaces of the cast bars to be milled before being X-rayed to remove roughness and ensure parallel faces. This was done to improve detection efficiency. The radiograph film was then scanned using a high quality flat bed scanner. Standard image editing software was used to measure the mean brightness level (*BL*) of a rectangular area containing the hot tear ($BL_{Hot\ Tear}$) as well as an area adjacent to the hot spot that was free of tears ($BL_{No\ Tears}$). Hot tearing was quantified as:

$$Hot\ Tearing\ Index\ (HTI) = \frac{BL_{No\ Tear} - BL_{Hot\ Tear}}{BL_{No\ Tear}} \quad (1)$$

Some of the castings with higher Cu contents showed areas of brightness associated with segregation of the high-density Cu-rich solute. If a casting contained tearing as well as segregation, the darkness created by the tear would in some part be cancelled by the brightness caused by segregation and would lead to an inaccurate result.

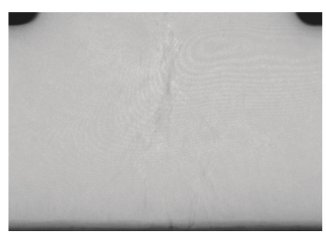
Load at solidus as a function of solute content is plotted in Figure 6. For the grain refined castings, load at solidus follows a lambda curve with a peak at 0.5 wt% Cu. The results for the non grain refined castings were mostly similar to grain refined castings except in the cases when tearing was observed on the cast bar attached to the load cell. This indicates that for the same solute content, a delay in the start of load development, either through grain refinement or dendrite morphology, has little affect on the load recorded at the solidus temperature. The delay in the start of load development is compensated by a more rapid increase in load. Therefore, by the time the solidus temperature is reached





(a) 0.25 wt% Cu, Non Grain Refined

(b) 0.25 wt% Cu, Grain Refined



(c) 4 wt% Cu, Non Grain Refined

(d) 4 wt% Cu, Grain Refined

Figure 7. Radiographs of the hot spot regions in fully restrained cast bars.

both grained refined and non grain refined castings are recording similar loads.

Figure 7 shows some examples of radiographs taken of the hot spot region in the fully restrained cast bars. In the 0.25 wt% Cu castings (Figures 7a and 7b), the non grain refined casting had one large tear through the center of the hot spot while the grain refined casting had a slightly more branched tear. In the 4 wt% Cu castings (Figures 7c and 7d), the radiograph of the non grain refined casting showed a fine tear while the grain refined casting appears clear.

The Hot Tearing Index (HTI) was determined for each casting and the results are presented in Figure 8. The results of hot tearing experiments carried out by Spittle and Cushway [7] using a 50°C superheat are also displayed in Figure 8 for comparison. In contrast to the load at solidus measurements displayed in Figure 7, the Hot Tearing index (HTI) shows that grain refinement slightly reduces hot tearing severity in the most susceptible solute content range (0.25 wt% Cu to 1 wt% Cu). The results from this study compare favorably with those of Spittle and Cushway [7]. In their experiments, Spittle and Cushway [7] conducted hot tearing experiments at 50°C superheat (reproduced in Figure 8) and 250°C superheat. They found that as the superheat increased, the peak of the lambda curve shifted to lower solute contents and that the curve became broader. They also reported that grain refinement had little effect at 50°C superheat but did reduce hot tearing susceptibility at 250°C superheat. The superheat used in this study was approximately 100°C which is in between the superheats used by Spittle and Cushway [7]. Results from this study indicate that at 100°C superheat, the peak of the lambda curve lies between 0.5 and 1 wt% Cu and that grain refinement does reduce hot tearing severity.

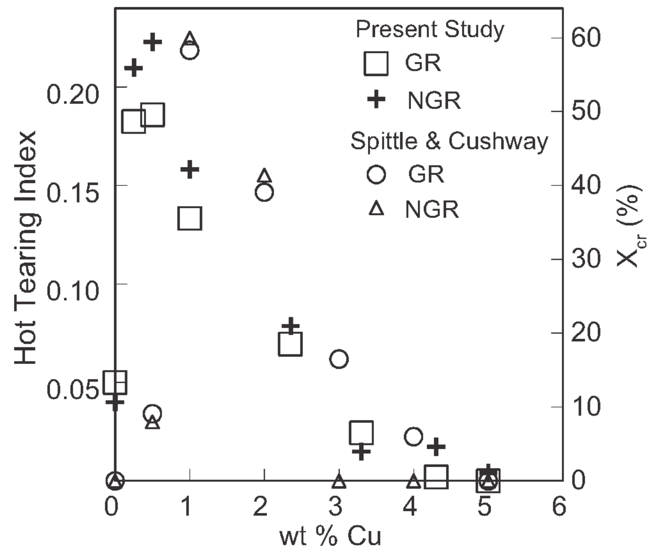


Figure 8. Hot Tearing Index determined from equation (1) verses solute content. Results from Hot tearing experiments carried out by Spittle and Cushway [7] at 50°C superheat are also reproduced.

Conclusions

The following conclusions have been reached regarding the influence of composition and grain refinement on the hot tearing susceptibilities of Al-Cu alloys in the range 0-5 wt% Cu cast with 100°C superheat.

1. The solid fraction when load is first detected is dependent upon a variety of interrelated factors including alloy composition, grain size and dendrite morphology.

2. At the same Cu composition, any delay in the start of load development as a result of grain refinement is compensated by a more rapid increase in load. The load recorded at the end of solidification was very similar for grain refined and non grain refined alloys.

3. Measuring the image density of radiographs taken of the hot spot region proved an effective tool for quantifying hot tearing.

4. Grain refinement reduced the severity of hot tearing in the most susceptible solute content range (0.25 wt% Cu to 1 wt% Cu).

5. Results from the test rig correlated well with other published data.

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