Light Metals 2012 *Edited by: Carlos E. Suarez*
TMS (The Minerals, Metals & Materials Society), 2012

CHEMICAL ADDITIONS TO REDUCE HOT TEARING IN THE CAST HOUSE

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Keywords: hot tearing, grain refinement, launder, 6xxx, Al-Mg-Si alloys

Abstract

Hot tear susceptibility in VDC casting is strongly affected by the chemical additions of alloys, hardeners and grain refiners. This paper assesses a few different approaches to reducing hot tearing in the cast house. Grain refinement is one commonly used approach, including dosing at cast start. Another technique is to control the alloy content, through the additions of Si, Mg, Mn or Fe which can influence the type and amount of intermetallics present during the final stages of solidification when hot tearing occurs. This paper summarizes experimental findings which assess the influence of additions on a hot tear rating, particularly in 6xxx series alloys. Strategies which could be used in the cast house are discussed. While changes to the bulk metal can have consequences for alloy specification and quality control, additions at cast start could be used to reduce scrap from hot tearing without changing the composition of the saleable product.

Introduction

Direct Chill (DC) casting of billet is divided into two phases – start and steady-state. The cast start is the less stable phase, during which the temperature field, the solidification front and the meniscus shape change with time [1]. Often the occurrence of hot tearing during DC casting of billet is initiated in this phase. Once the hot tear begins, it can propagate outside the billet off-cut length, leading to rejection of the log. If however, the cast start can be controlled to eliminate cracking in the butt, then it is less common for a hot tear to be initiated during the run phase. There are various methods used to control the cast start with the aim of reducing hot tearing. These mainly fall into two categories – changes to physical casting conditions and control of chemical composition.

Changes to the physical conditions are not explored in this paper, but can include approaches such as using a slower speed at cast start [2], changing the casting speed or severity of the quench to suit a particular alloy [3,4] or the use of a domed starting head [5]. The second approach to reducing hot tear susceptibility is through control of chemical composition. This approach includes the reduction of impurities such as sodium which has been shown to have a negative effect on cracking both during casting [6] as well as hot rolling of Al-Mg alloys [7,8]. It also includes consideration of making deliberate additions of alloying elements, hardeners and grain refiners. The focus of this paper is how chemical additions can be managed to reduce hot tear susceptibility during DC casting. In Part 1, previous experimental work by the authors is reviewed: this includes, (i) the effects of grain refiner on hot tearing, (ii) the effects of Mg and Si content in ternary Al-Mg-Si alloys, and (iii) the effects of iron (Fe) and manganese (Mn) additions to AA6060 alloy. In Part 2, new work is presented showing the effect of increased Mg content on hot tear susceptibility in a range of aluminum alloys. The alloys described in both parts were tested using the CAST hot tearing (CHT) rig which is detailed in the experimental procedure.

Part 1: Summary of previous work

Grain refinement and hot tearing

Grain refiner additions are often made to reduce the hot tear susceptibility of an alloy through changes to the grain size and morphology [9-12]. In DC casting this is typically via continuous master alloy rod feeders. As a supplement, higher feeding speeds and/or cut pieces of rod are sometimes added to the launder at cast start to boost the initial grain refiner levels in order to reduce the risk of cracks starting during this critical phase [13].

Figure 1 shows the effect of increasing grain refiner level on AA6061 using Al-5Ti-1B master alloy additions on the grain size and severity of cracking in the hot spot area of cast bars produced in the CHT rig [10]. The alloy without grain refiner addition has a columnar grain structure with a very large grain size. With grain refiner at a level of 0.005%Ti, the material still has a columnar structure but also has some equiaxed features. Further increases in grain refinement lead to finer equiaxed microstructures. Figure 1 shows that the severity of the cracking decreases as the grain refiner additions are increased, and that in the range of grain sizes observed here, the hot tearing decreases with grain size.

The mechanism by which grain refinement works to reduce hot tearing is through controlling the grain size and morphology, in particular, delaying the dendrite coherency, and increasing the capillary pressures between grains as they become smaller, as long as the permeability of the mush is not adversely affected by the reduction in grain size [10]. However, adding too much grain refiner can have negative effects. Apart from cost considerations, grain refiner additions can lead to reduced billet quality through the agglomeration of borides.

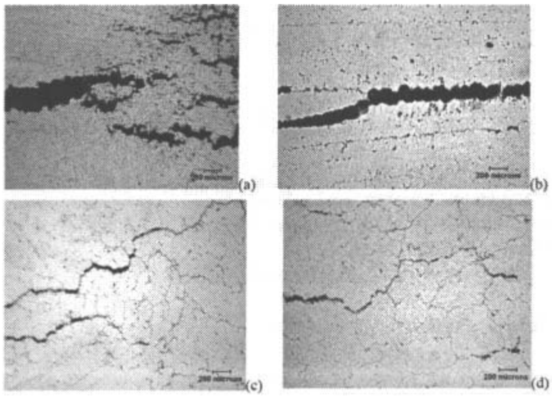

Figure 1. Optical micrographs showing microstructural features in the hot spot area of cast bars produced using the CHT rig for alloy AA6061 with Al-5Ti-1B rod grain refiner additions to achieve (a) 0.001%Ti, (b) 0.005%Ti, (c) 0.01%Ti and (d) 0.05%Ti levels [10].

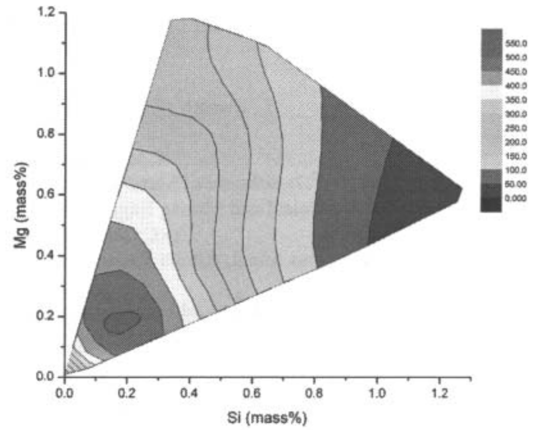

Figure 2. A contour map of the load at solidus (N) as a function of the solute content generated from a range of experimental Al-Si-Mg alloys with Fe content <0.02wt% [16].

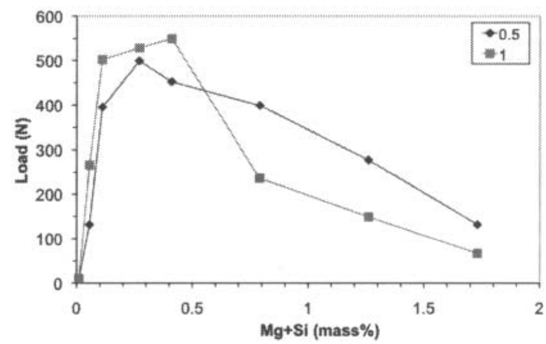

Figure 3. A comparison of the hot tear susceptibility (as measured by load at solidus) as a function of the solute content (Mg + Si) for a range of ternary alloys with Si:Mg ratios of 0.5 and 1 (Fe content <0.02wt%) [16].

Alloy composition and hot tearing

Alloy composition, including variations in minor elements, is known to cause changes in hot tear susceptibility. This has been well-described in binary alloys, as well as in some more complex alloys [14,15]. Changes in composition can influence the morphology, prevalence and precipitation sequence of intermetallics present during the final stages of solidification when hot tearing occurs.

Major elements, Mg and Si in ternary 6xxx alloys

Figures 2 and 3 show the peaks in hot tear susceptibility with alloy content as a function of Mg and Si separately (Figure 2) as well as the combined effect of Mg + Si content (Figure 3) in the ternary Al-Si-Mg (6xxx) system . These alloys were produced from high purity Al (99.94%) and therefore individual impurity elements including Fe were below 0.02% [16]. The peaks suggest that moderately lean alloys are worse than solute-rich alloys in terms of hot tearing.

This fits intuitively well with the low solute compositions for maximum cracking in experimentally-derived lambda curves for binary alloys [14]. However, the picture formed through this work does not match easily with industrial DC casting experience. In practice, lean alloys are less prone to cracking than high solute alloys. This is probably because high solute alloys also contain other possible minor element additions such as Fe, Mn, chromium (Cr) and copper (Cu). It is assumed that these may have an additional influence on tearing.

Minor elements, Fe and Mn in AA6060 alloy

Figure 4 shows the effect of Mn content on hot tear susceptibility in a multi-component Al-Mg-Si-Fe-Mn AA6060 alloy [17]. In this data, hot tear (crack) rating is a visual measure of tear size and intensity on cast bars from the CHT rig (minimum 0, no tear; maximum 6, full wide tear across whole cross section, see Table I). On the basis of the cracking data the effect of Mn on hot tear susceptibility is strong for Mn contents greater than 0.035%. As Mn content increased from 0 to 0.035%, no change was observed but further increases in Mn to 0.055% and then 0.090% both caused significant increases in hot tearing. Minor levels of Cu up to 0.2% were not found to have an effect on hot tear susceptibility in this study [17].

Table I: Definitions of the hot tear ratings (0 to 6) used to assess the CHT test bars.

Rating	Description
0	No cracks visible, not even in stereomicroscope.
1	Crack, but only visible under stereomicroscope.
2	Crack visible to naked eye.
3	Slightly opened crack (finite width to naked eye) and/or multiple cracks (more than a crack that has just branched once).
4	Intermediate cracks.
5	Crack (only around 0.5mm wide, or not clearly opened, or not across whole section).
6	Large crack (min 0.5mm wide, typically 1mm) across entire section.

Note: These integer ratings are applied to faces and the final value for each alloy condition is based on the mean hot tear rating for the number of faces examined.

The data for the mean hot tear rating as a function of Fe content in AA6060 alloy has been plotted in Figure 5 [18]. At very low Fe contents, i.e. 0.02%, hot tearing is common, although the severity varies. From about 0.04-0.17% Fe, all alloys showed a high amount of hot tearing. Between 0.17-0.22% Fe, there was another region where the hot tear susceptibility was highly variable, and above 0.22% Fe virtually no hot tearing was observed. Thus, the addition of Fe was found to have a strong effect on the hot tear susceptibility of these alloys with increasing additions decreasing the amount of hot tearing.

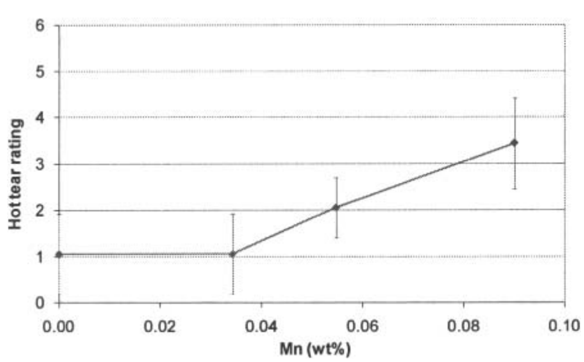

Figure 4. Plot of mean hot tear rating and standard error bars for the Al-Mg-Si (AA6060) alloy containing 0.18% Fe as a function of Mn [17].

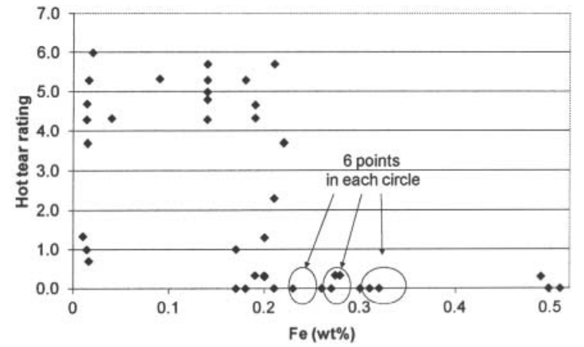

Figure 5. Plot of mean hot tear rating for Mn-free Al-Mg-Si (AA6060) alloy at different Fe contents [18]. In some instances the Fe content exceeds the Chemical Composition Limits for the Aluminum Association International Alloy Designations.

Part 2: Magnesium additions in multi-component alloys

Experimental Procedure

The CHT Rig, developed by Instone *et al* [19], is designed to simulate DC casting where the critical region is well fed with liquid metal during solidification and the cooling rate is approximately 2°C/s. The steel mould has a combined centre-pouring sprue and riser that feeds two cast bar cavities from their centres. In this work both bars were fixed at both ends to act as an I-beam for hot tearing observation.

For each hot tearing test, a melt of ~1.5 kg aluminum alloy was prepared in a clay-bonded graphite crucible using a 20kW induction furnace. Additions of lump silicon metal were made to the crucible along with 99.94% pure Al ingot prior to the heating-up phase. Once the Al was molten and the silicon had dissolved, the required additions of Cu, Fe, Cr and/or Mn were made to the melt at 750°C using commercially-pure Cu rod, AlTab Fe75, AlTab Cr80 and AlTab Mn80 compacts, respectively. After 10 minutes of dissolution time, the required additions of pure Mg, pure Zn and Al-5Ti-1B master alloy were added to the melt. To minimize the effect of grain size variation on hot tearing [20], alloys were grain refined using Al-5%Ti-1%B master alloy at a nominal 0.05% Ti level (an order of magnitude higher than that typically used in industry [21]). This ensured the grain morphology was globular [22], so that morphological changes would not influence the hot tear susceptibility [23]. In some instances, the test was repeated using reduced additions of grain refiner, targeting 0.01%, 0.005%, 0.001% and 0% Ti. Where deliberate sodium (Na) additions were required, a special preparation technique using NaF flux was followed. Chemical analyses were performed on disc samples using optical emission spectroscopy. The average target alloy compositions are shown in Table II. In some instances the additions exceed the Chemical Composition Limits for the Aluminum Association International Alloy Designations.

Table II: Average target compositions (wt%) of the experimental alloys. Note: "*var*" indicates variable target levels, which are listed in graph legends and plotted as actual on following graphs. In some instances these exceed the Chemical Composition Limits for the Aluminum Association International Alloy Designations.

	Si	Mg	Fe	Cu	Cr	Mn	Zn
AA6060	0.53	0.35	*var*	---	---	*var*	---
AA6005A	0.73	*var*	0.17	0.12	0.06	0.10	---
AA6061	0.45	*var*	0.17	0.20	0.06	0.10	---
3xxx	0.6	*var*	0.2	0.5	---	1.2	---
7xxx (1)	0.1	*var*	0.2	0.2	---	---	6.7
7xxx (2)	0.1	*var*	0.2	0.2	---	---	8.9

Magnesium additions and hot tearing

The cast bars were examined for the degree of tearing/cracking present against the standards shown in Table I, and the results are plotted in Figures 6-8. In Figure 6, the mean hot tearing rating versus Mg content for the various 6xxx series alloy compositions is shown. The curves clearly show that as Mg content increases hot tear severity decreases. A Mg level of 1% in AA6060 and 1.2% in AA6005A and AA60601 are sufficient to completely eliminate the occurrence of hot cracking on the rig test bars. This beneficial effect of Mg on hot tearing reduction appears to be consistent regardless of the Fe/Mn contents in AA6060 alloy.

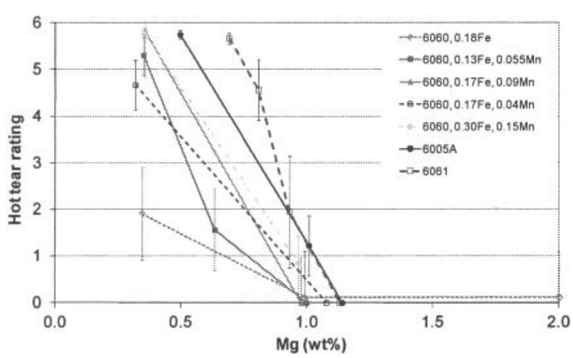

Figure 6. Plots of mean hot tear ratings with standard error bars versus measured Mg content in base alloys of (i) AA6060 with variable target Fe/Mn content, (ii) AA6005A and (iii) AA6061.

Sodium is known to have a detrimental effect on hot tearing. It was therefore decided to test whether or not the hot tearing tendency of a AA6060 alloy with 200 ppm Na could be reduced through the addition of 1% Mg. This Na level is much higher than occurs in practice, even from untreated pot line metal arriving in the cast house. The results plotted in Figure 7 indicate that the Mg addition is effective in the presence of substantial Na levels.

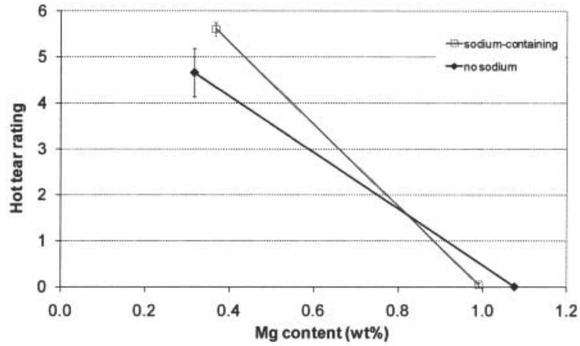

Figure 7. Plots of mean hot tear ratings versus measured Mg content for AA6060 alloy (nominal composition 0.17% Fe, 0.04% Mn) with and without Na.

While it may be useful to prevent Na-induced hot tearing during casting without removing Na, in some cases Na would still need to be removed from the melt to reduce the incidence of other processing issues. For example, an addition of Mg would not reduce Na liquid metal embrittlement which causes edge cracking during hot rolling in 5xxx alloys, even at very low levels of Na (e.g. 5ppm).

To further test the range of alloys that may benefit from an addition of Mg a generic 3xxx series alloy and two 7xxx series alloys with differing Zn levels (nominal 6.7% and 8.9%) were tested. In each case, it is seen that higher Mg contents result in reduced hot tear severity ratings (Figure 8).

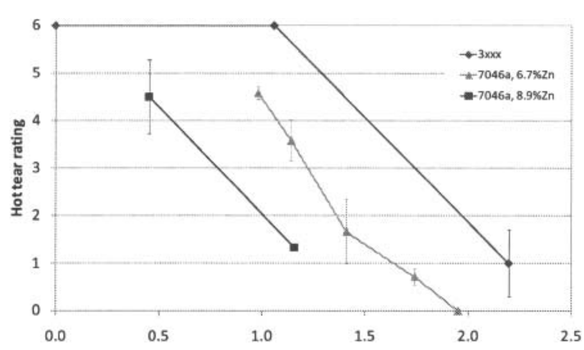

Figure 8. Plots of mean hot tear ratings versus measured Mg content for a generic 3xxx and two 7xxx series alloys.

It was also decided to test whether or not this beneficial effect of Mg on hot tearing persists through reductions in the level of Al-5Ti-B grain refiner in 6xxx series alloys. Starting at the nominal testing Ti level of 0.05% at which both alloys (high Mg-containing versions of AA6060 and AA6005A) were free of hot tears, the grain refiner additions were reduced. From Figure 9, it can be seen that the test bars remained crack free at 0.01%Ti, were marginally crack-prone at 0.005%, and that this increased steadily with further reductions thereafter. Thus, the curves clearly show that as Ti content decreases hot tear severity increases. Figure 9 includes a comparison of this data with the previously-determined hot tearing propensity of AA6060 and

AA6005A alloy compositions at base Mg levels containing 0.05% Ti, as well as a curve showing the effect of reducing grain refiner levels in the AA6060 base alloy. These results indicate that the elevated Mg alloys with reduced Ti may be less crack-prone than the standard alloys with high grain refiner levels.

The experimental findings presented suggest that elevating the levels of Mg in both "easy-to-cast" 6xxx series alloys (such as AA6060) and "harder-to-cast" alloys (such as AA6005A) may have a beneficial effect in reducing the instance of hot tearing. In addition this beneficial effect has been shown to extend to other alloy families such as 3xxx and 7xxx series.

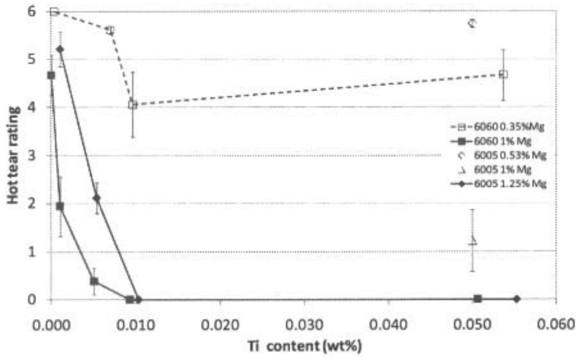

Figure 9. Graph showing the effect of Ti content (added as Al-5Ti-1B grain refiner) on the mean hot tear ratings (with standard error bars) of AA6060 and AA6005A alloys with elevated Mg contents. Data points for these alloys with nominal Mg contents and full amount of Ti grain refiner are shown for comparison.

Additions at cast start

Many 6xxx series commercial alloys are produced with Fe contents in the range 0.15-0.2 wt% Fe, even if the maximum Fe content according to the chemical composition limits for those alloys is significantly higher. Therefore, theoretically is would be possible to make Fe additions above 0.22 wt% to most 6xxx series alloys without pushing the alloy composition outside the chemical composition limits. Only the higher purity alloys such as AA6160 and AA6463 have low maximum Fe contents of 0.15 wt%, and 0.10 wt% in the case of AA6306.

This does not mean however, that adding Fe to change the bulk composition of the alloy would be the preferred option. Changing alloy specifications will not always suit the customer requirements for their product. Potential ramifications of changing Fe level include:

- Negative effects on extrudability through surface defects such as pick-up [24,25];
- Changing the anodizing response leading to color matching issues associated with changed intermetallic phases (size, type or density); and
- Changing the mechanical properties by changing the intermetallic phases and the Si content available for precipitation during ageing treatments.

In the case of the Mg additions, the levels explored here (~1%Mg) are too high for the given alloy specifications and therefore cannot be routinely targeted within the alloy window. Nevertheless because these alloys are VDC cast as billet which routinely allows for a start-up off-cut length, it is conceivable that an elevated Mg content could be employed at start-up provided the billet log composition could be brought back into specification within the off-cut length. The prevention of cracking at the start of cast would have positive impact in reducing overall cracking scrap because long billet cracks almost always originate in the transient-state butt zone and rarely start in the steady-state run phase.

To enable increased levels of Fe or Mg to be added to an alloy without changing the composition of the saleable product, it is necessary to contain the alloy change to within the butt of the billet and then revert to the standard alloy composition for the remainder of the billet length The concept of using a different alloy composition for the start-up phase compared to the run phase has been patented in Japanese patent JP2005000966 A [26], using JIS A7050 alloy. In this patent, molten metal of an aluminum alloy that is not susceptible to cracking in the starting period of casting, is poured into the casting mould; then after a designated length, the molten metal to be poured is switched to the molten metal of the second alloy (JIS A7050) which is susceptible to cracking.

In Australian provisional patent M81620491 [27], one proposed method is to make an alloy addition at cast start through dissolution of extra Fe or Mg in the launder, rather than using two completely separate alloys. This is similar to the concept currently used in industry whereby cut lengths of grain refiner rod are added to the launder at cast start to reduce the tendency to hot tearing. As the dissolution of magnesium in aluminum alloys is much faster than that of iron, it is believed that the addition of magnesium at cast-start would be a more practical approach to use in the commercial environment than the addition of iron. Methods to exploit this possible solution to hot tearing need to be explored from a practical and operational stand point.

Conclusion

One method of reducing hot tear susceptibility is through the control of chemical composition. This can be through the reduction of impurities such as Na or by consideration of the consequences of chemical additions of alloying elements, hardeners and grain refiners. Decreasing equiaxed grain size, an increase in Fe content or a decrease in Mn content have all been shown to reduce hot tear rating in a AA6060 alloy. Magnesium additions have been shown to reduce hot tear rating across a range of 6xxx, 3xxx and 7xxx series alloys.

While the concept of dosing via the launder has been used extensively in the industry to boost grain refiner additions at cast-start, the concept of dosing with Fe or with Mg is novel. Such additions could be used to reduce scrap from hot tearing without changing the composition of the saleable product. The findings suggest that an increase of Mg levels at cast-start may also allow a decrease in the levels of grain refinement used in the same period, while still providing significant reduction in hot tearing.

Acknowledgement

The CAST Cooperative Research Centre was established under and is supported in part by the Australian Government's Cooperative Research Centre's Program. The authors wish to thank Daniel Graham for performing the casting on the hot tearing rig.

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