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A Comparison of Grain Refiner Master Alloys for the Foundry

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Abstract

Grain refiners are widely used in the foundry. They are considered to provide benefits in a number of ways including improved feeding during solidification, reduced and more evenly distributed porosity, and reduced hot tearing. There are a number of refiners for the foundry industry used industrially or mentioned in the literature. A program of laboratory tests has been carried out, which started with a pre-screening of a wide range of potential refiners, using standard laboratory grain-refining tests. The better-performing refiners were then tested in a permanent mould casting, designed to simulate conditions at the spoke-rim junction of a wheel casting. Results are presented in terms of the effect of refiner on grain size, hot tearing and porosity distribution. Recommendations are made in terms of the optimum refiners for the foundry.

Introduction

The principle grain refiners used in the foundry industry are the same as in the wrought industry, namely Al-5% Ti-1% B or Al-3% Ti-1% B. However, there has been an increased usage in recent years of Al-1.6% Ti-1.4% B (referred to hereafter as TiBAlloy™), particularly in wheel manufacture.

Many potential grain refiners for Al-Si casting alloys are suggested in the literature. Some of these are based on no Ti in the alloy[1,2], although these have found little use industrially. Spittle[3] studied several refiner systems and found that near-stoichiometric ratios of Ti:B did not refine as well as when excess titanium, or significant amounts of excess boron, is present. Near the stoichiometric ratio, the refinement was not reliable, and with fade occurring rapidly, this often results in a larger grain size. Industrial practice has suggested that 0.1% excess titanium is required to ensure good performance[4,5] from sub-stoichiometric refiners.

Other studies have suggested that the addition of excess titanium has no effect on grain size in Al-Si casting alloys. Easton and StJohn[6] tested the effect of increasing the titanium levels, while maintaining a constant level of TiB_2 addition, and found that there was a negligible change in grain size. This was attributed to the fact that Al-Si alloys already have a high growth-restriction factor and the effect of solute titanium on refinement should therefore be negligible. Sigworth and Guzowski[7,8] also suggested that only the particle (ie. boride) component of a master alloy is required to obtain effective grain refinement in Al-Si casting alloys.

Grain refinement has been associated with the formation of casting defects[9-18]. It is generally assumed that an increase in the level of grain refinement is beneficial for castability. However, there are some casting configurations where the addition of extra grain refiner causes an increase in porosity. This was clearly shown in a recent study by Easton and StJohn[19], where an increase in the amount of refiner resulted in an increase in localized porosity in the spoke-rim junction of permanent mould-cast wheels. However, complete removal of grain refiner caused hot cracking at the junction. It was found that the amount of hot cracking decreased as the refiner level increased, while the amount of localized porosity increased. Therefore, there is an optimum level of refiner required to obtain castings of optimum quality.

It is clear that grain refining tests, such as the Aluminum Association TP-1 test[20], are not sufficient to predict the effects and behaviour encountered in a shaped casting. In the work of Easton and StJohn[19], a steel permanent mould was designed to simulate a spoke-rim junction in a gravity die-cast wheel. This design causes the formation of a hot spot in the tapered region of the spoke where it joins the rim. This hot spot is fed down the spoke, which freezes off before the spoke-rim junction. Due to a lack of feed liquid, the shrinkage at the hot spot in the junction generates stress, which can result in slumping of the surface (surface shrinkage), hot cracking or the formation of porosity. When porosity occurred, the amount of slumping of the surface was reduced. Thus, the formation of slumping and internal porosity formation are related. This configuration was found to simulate the degree of defect formation observed by a foundry producing permanent mould- cast wheels.

The aim of the current study was to determine which of the grain refiner master alloys provides effective grain refinement of Al-Si casting alloy A356. The study also assesses the effect of excess titanium on grain size for selected grain refiner additions, as well as the effect of a combined Sr addition. The effect of the level of these refiner additions on the formation of casting defects in a permanent mould casting with a spoke-rim junction configuration has been determined.

Experimental Procedures

A series of laboratory grain-refining tests was conducted using an A356 base alloy, with the composition given in Table I. A deliberate addition of nominally 0.1wt% Ti was made to the alloy. The tests were based on the Aluminum Association TP-1 test[20]. A wide range of candidate grain refiner materials was selected as shown in Table II. Some were chosen because of known good industrial experience (as in the cases of Al-5% Ti-1% B and TiBAlloy™). Others were included because they are mentioned in literature, or simply to test how they perform. Addition rates were based on a nominally equal addition rate of boron, as shown in Table II.

Table I — Chemical analysis of A356 base alloy used in the pre-screening grain refining tests (wt%).

Al	Si	Mg	Fe	Zn	Ti	Others
Bal.	7.25	0.33	0.06	0.02	<0.01	<0.01

Table II — Chemical analysis of candidates used in laboratory grain refining tests and the addition rates tested.

Grain refiner	Composition (wt%)	Addition rate (kg/tonne)
TiBAlloy™	1.6% Ti-1.4% B	2.0
Hydloy™	1.2% Ti-0.5% B	5.6
Strobloy™	5% Sr-1.5% Ti-1.3% B	2.15
15Sr3Ti1B	15% Sr-3% Ti-1% B	2.8
Al-5% Ti-1% B	5% Ti-1.0% B	2.8
Al-3% Ti-1% B	3% Ti-1.0% B	2.8
Stoichiometric	2.3% Ti-1.0% B	2.8
Al-3% B	3% B	0.93
Al-8% B	8% B	0.35
Al-3% Ti-0.15% C	3% Ti-0.15% C	2.0
Al-Ti-C-B	2.9% Ti-0.10% C-0.04% B	2.0

Unfortunately, etching of the high silicon content alloys is notoriously difficult. Although photographic quality images could not be obtained, it was possible to screen the performance of the different refiners as shown in Table III.

Table III — Ranking of grain refiner performance in the pre-screening tests.

Poor refinement	Insufficient refinement	Good refinement (incubation period req'd)	Good refinement
Al-8% B	Al-3% B	Al-3% Ti-1% B	Remainder
Al-3% Ti-0.15% C	Al-Ti-C-B		(see Table II)

As a result of this "pre-screening" program, it was decided to further assess the performance of the good refiners by performing castability tests in a permanent mould casting. The refiners selected for castability testing included Al-5% Ti-1% B and TiBAlloy™. These were selected based on their good performance in the pre-screening program, and also because they are the most widely used refiners in the foundry industry. As they also performed well in the initial tests, two strontium-containing refiners were also selected for the next stage of testing.

Figure 1 — Photograph showing the three-part steel permanent mould used in the experimental work.

The steel permanent mould used in the castability evaluation is shown in Figure 1. The preparation of the die and die coat application is described elsewhere[19]. The base alloy used for the castability evaluation was alloy A356 with the chemical composition shown in Table IV.

Table IV — Chemical composition of the A356 base alloy used in the castability evaluation (wt%).

Al	Si	Fe	Mg	Ti	B	Sr	Cu, Mn, Ni	Cr, Zn, Zr
Bal	6.82	0.07	0.34	0.016	<0.001	<0.001	<0.01	<0.005

The melting operation was performed in an induction furnace. Once the melt reached 750°C, it was degassed for 10 minutes with argon gas at a flow rate of 1.5 litres per minute. The grain refiners were added at three additions levels: 1.4, 2.0 and 2.8 kg/tonne. An additional 0.1wt% Ti was added to the melt by an Al-Ti master alloy. Each refiner addition level had two separate melts made and two castings. This procedure provides an indication of the reproducibility of the results.

The desired amount of master alloy was added by submerging it into the melt until fully molten. The contact time for the grain refiner was a nominal 10 minutes, during which the induction furnace was kept switched on; both to maintain temperature and to mix the grain refiner. The melt temperature was monitored to ensure a pouring temperature of 725°C at 10 minutes ± 30 seconds. 30 seconds prior to pouring, the castability mould was removed from an electric preheat furnace set at 300°C. A sample for chemical analysis was taken directly after pouring of the casting was completed.

A qualitative method developed by Easton and StJohn[19] was used to examine the defects formed in the castings. Figure 2 shows the locations where visible external defects usually form on the castings. For each of the positions, a number between 0 and 3 was assigned to describe the severity of the casting defect. A rating of 0 was given when there was no externally observable casting defect and a rating of 3 was given to the most severe casting defect observed. Intermediate defects were given a rating between 0 and 3 depending on their severity.

Positions A, B, C and D are all indicators of external shrinkage or slumping. The sum of all of these positions provides an overall rating for the amount of external shrinkage of the casting. Position E, located at the junction between the vertical plate and the runner, is the location where hot cracks would form and this position was also rated on a scale from 0 to 3.

Grain size was measured by the linear intercept method on a cross-section of the spoke of each casting.

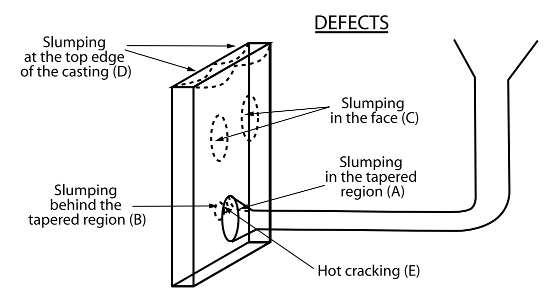

Figure 2 — Defects found upon external examination of the casting[19].

Results and Discussion

Figure 3 shows the grain size response of alloy A356 with 0.1wt% solute titanium to the addition of Al-5% Ti-1% B, TiBAlloy™ and Strobloy™ grain refiners. The grain refiners tested promote a rapid decrease in grain size with the lowest level of refiner addition and then stabilize at about 600 µm for the two higher levels. This result indicates that the grain size obtained is independent of which of the three grain refiners is used. An earlier investigation[21] of the same refiners with the same addition levels, but without the extra 0.1 wt% Ti, produced similar grain sizes indicating that the addition of excess titanium has no effect on grain size as found by Easton and StJohn[6]. However, the base A356 alloy already contains 0.016 wt% Ti, which may provide a sufficient excess of solute titanium to ensure good performance from sub-stoichiometric refiners[4,5].

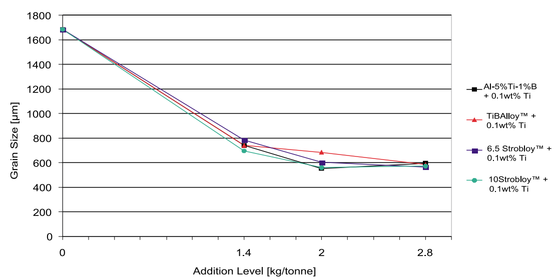

Figure 3 — Grain size as a function of addition level of the four refiners in A356 containing 0.1wt% excess titanium.

Figure 4 shows the degree of hot cracking observed at the spoke-rim junction of the castings for increasing addition levels of TiBAlloy™ and 10Strobloy™. Note that the amount of hot tearing decreases with an increasing amount of refiner addition, and that hot cracking is less severe for Strobloy™ additions compared with TiBAlloy™ additions. In fact, the highest level of Strobloy™ shows no hot cracking. Additional castings were carried out using TiBAlloy™ with a separate addition of strontium to determine whether the same casting quality is produced as was observed for the combined Strobloy™ master alloy. The grain size and casting quality obtained for TiBAlloy™ plus strontium was the same as for an equivalent addition of Strobloy™. The addition of strontium to Al-5% Ti-1% B refined castings had a similar effect.

A previous study[19] found a definite relationship between grain size and casting defects, and concluded that the defects experienced by a particular casting were related to the grain size and associated factors. The effect of different types of master alloy was not investigated in that study. By comparing the qualitative measures of hot cracking and shrinkage severities of the grain refiner master alloys used in this investigation, a difference between the refiners is observed. Figure 5 shows that the amount of external shrinkage differs for Al-5% Ti-1% B and TiBAlloy™. It also shows that the addition of strontium reduces the measured casting defects, producing high-quality castings. Figure 4 shows that this is also the case for hot cracking susceptibility. In the manufacture of wheels, strontium is normally added, thus minimizing the formation of these defects. However, although Figure 5 indicates that TiBAlloy™ without the addition of strontium appears to produce a slightly higher level of defects than Al-5% Ti-1% B without strontium, it is not of practical significance in the casting of wheels.

One explanation for the observed decrease in hot cracking susceptibility and external shrinkage when strontium is added, is that the amount of internal porosity increases. The formation of porosity reduces the amount of liquid required to feed the hot spot. Thus, the level of stress generated by shrinkage at the spoke-rim junction will decrease, therefore decreasing the likelihood of hot cracking and external shrinkage. By comparing the micrographs of Figure 6, it can be observed that there is relatively little porosity in the TiBAlloy™ samples and a significant amount of distributed porosity in the 10Strobloy™ samples.

Strontium is known to increase the amount of distributed porosity[22], so the effect of Strobloy™ on porosity is not

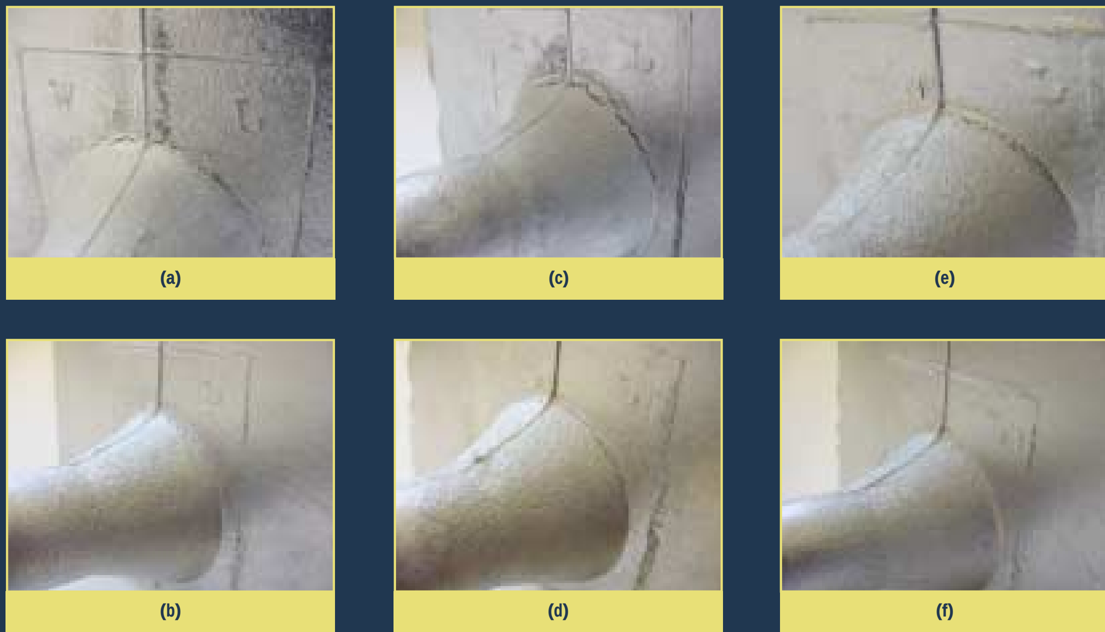

Figure 4 — Photos of the hot spots of casting for increasing addition levels of TiBAlloy™ (a-c) and 10Strobloy™ (d-f). The addition levels tested were: 1.4 (a&d), 2.0 (b&e) and 2.8 (c&f) kg/tonne.

surprising. The only apparent difference between TiBAlloy™ and Al-5% Ti-1% B, is that Al-5% Ti-1% B adds extra Ti in addition to the 0.1wt% Ti. It is difficult to imagine that the small additional amount of Ti could have an effect on the amount of porosity, and thus hot cracking. This aspect should be investigated further.

It appears from these laboratory tests that the addition of strontium is likely to provide benefits to the wheel producer in terms of freedom from defects. Grain refining is also beneficial, but it appears unimportant as to which type of refiner is used, although in practice, TiBAlloy™ may be preferred to Al-5% Ti-1% B as its finer particle size could result in less settling and tendency for sludging.

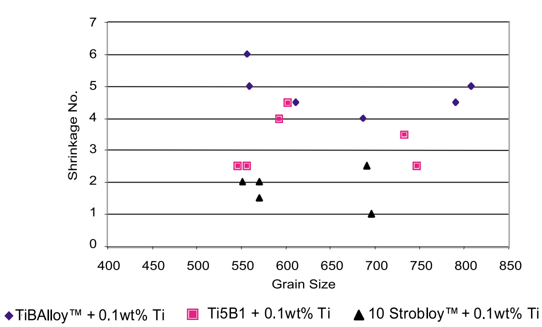

Figure 5 — Shrinkage number as a function of grain size of three types of grain refiner when 0.1wt% excess titanium was present in the alloy.

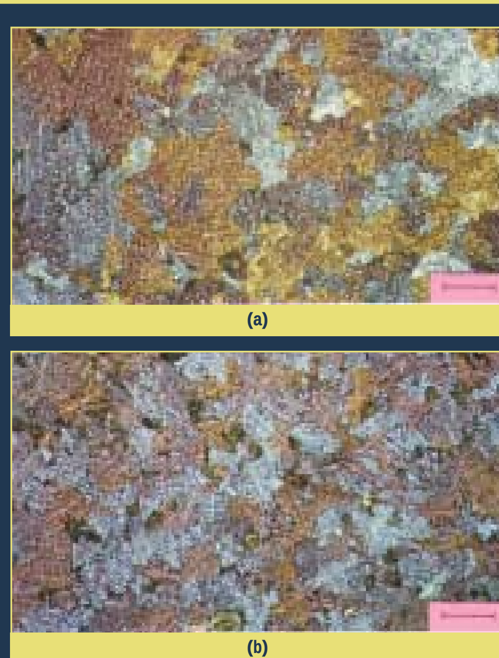

Figure 6 — Micrographs of (a) TiBAlloy™ and (b) 10Strobloy™ refined castings with an addition level of 2.0 Kg/tonne. Specimens were anodized and micrographs taken under polarized light. The scale bars are equivalent to 500μm. Porosity is observed as black phase in the micrographs.

Conclusions

- The addition of 0.1wt% titanium to grain-refined foundry alloy A356 had a negligible effect on grain size. However, the base A356 alloy contained 0.016 wt% Ti, which may have provided sufficient excess titanium to ensure good grain-refiner performance.
- The addition of extra titanium to all of the grain-refined alloy A356 castings produced in this study, had little or no effect on the quality of the final casting.
- 10Strobloy™ + 0.1wt% Ti produced castings with the best external appearance observed in this work. This was due to an increase in the amount of internal porosity, which would reduce the shrinkage stresses developed during solidification.
- TiBAlloy™ + 0.1wt% Ti, without the addition of strontium, produced castings with the least internal porosity.
- The separate addition of strontium to TiBAlloy™ and Al-5% Ti-1% B had a negligible effect on grain size. However, hot cracking was eliminated, consistent with the results of the 10Strobloy™ castings.
- In the absence of Sr, the Al-5% Ti-1% B refiner produced more internal porosity and less hot cracking and external shrinkage than the TiBAlloy™ refiner. The cause of this difference is not known.

Recommendations

The use of grain-refining tests alone is not a good predictor of performance in the Al-Si foundry. These tests do not take account of the particular thermal and feeding conditions related to a casting's design and the casting process utilized. It is the interaction between these factors and the alloy chemistry (in particular grain size) that determines the degree of porosity and hot cracking. The test casting used in this study has been shown to be useful for predicting spoke-rim defects in wheel manufacture. Further work could investigate the role of grain refiner in affecting the casting quality of other major industrial castings such as engine blocks, cylinder heads and structural parts such as cross members. Therefore, it is recommended that the alloy to be used in production is also cast into a test casting configuration that simulates the critical areas of the production casting design and the special characteristics of the casting process being used. This allows the suitability of the alloy and the level of grain refiner to be assessed before a production run commences. Also, if there are sudden changes in casting quality, the test casting can be used to determine whether the alloy chemistry is the cause.

Of the refiners investigated in this study, it appears that the addition of 10Strobloy™ refiner to alloy A356 is best for avoiding defects at the spoke rim junctions of wheels. However, it is expected that either of Al-5% Ti-1% B or TiBAlloy™ would perform equally well if strontium is added separately. The strontium creates a more uniform distribution of porosity that prevents localized porosity or hot cracking occurring at the spoke-rim junction. If for some reason strontium is not used, then Al-5% Ti-1% B appears to cause less hot tearing and external shrinkage than TiBAlloy™. It is important to note that these results apply to a particular casting configuration (spoke-rim junctions in wheels) and gravity filling of a permanent mould. It is expected that in some situations a higher level of refiner may be needed, or a type of refiner such as TiBAlloy™ that does not generate porosity, when no addition of strontium is made. However, the current work suggests that either of Al-5% Ti-1% B or TiBAlloy™ would perform equally well if strontium is added separately.

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