

Grain refinement in shape casting of aluminium alloys – part I

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The present review, presented here in two parts, considers the grain refinement of aluminium alloy shaped castings and particularly Al-Si alloys. It examines the methods of grain refinement, benefits of grain refinement, procedures for assessing grain refinement, the efficiency of different refiners and factors affecting grain refinement. The review is intended to be of practical interest to foundrymen as well as providing an academic background to the subject.

Introduction

Though practised widely in the aluminium shaped casting industry, grain refining is still a matter of concern to many foundrymen because of the lack of a definitive source of data and opinion related to the topic. Whereas users of castings may specify the addition of other inoculants to melts, e.g. eutectic modifiers to Al-Si alloys, they rarely, if ever, specify grain refinement. The advantages of grain refinement of the primary aluminium phase, of specific alloys, for certain casting geometries and in particular casting processes, have therefore been recognised from the experiences of the foundryman.

However, since grain refining represents an add-on expense and many foundries are required to produce shaped castings at minimum cost, knowledge of what is a necessary amount of refiner to produce adequate refinement is very important. Refining practices vary considerably from foundry to foundry, possibly ranging from no grain refining at all to grain refining all castings to maintain conformity of in-house procedures.

Foundrymen rely heavily on the producers and suppliers of grain refiners to supply them with necessary technical information. In turn, however, many of the producers of grain refiners have developed their products for the direct chill (DC) casting of wrought alloys and may be unaware of the various problems and/or variables affecting grain size control in shape casting alloys. One of the significant differences between the two types of alloy is that the majority of shape casting alloys are based on Al-Si. Unlike most solute elements, which enhance the grain refinement induced by the addition of refiners, above ~3 wt-%Si grain size increases with increasing Si content. Commercial alloys contain well in excess of the critical Si level in order to obtain sufficient eutectic to ensure adequate castability, feeding to compensate for shrinkage and resistance to hot tearing. Grain refiner tests (developed by producers and users of refiners, e.g. Alcan and Alcoa), to assess the efficiency of batches of refiner, have invariably been designed to correlate with the solidification conditions during DC casting of aluminium alloys (steep temperature gradients ahead of the solidification front). Shaped casting is often associated with thin sections and significant melt undercooling at the time of pouring. The lifetime of potential nucleants in the melt (i.e. the time from grain refiner addition to the nucleants becoming active in nucleating equiaxed grains) is relatively short in DC casting, of the order of a few minutes. However, in shape casting, the 'holding time' (the time from grain refiner addition to the alloy bath to the pouring of a casting) may be hours. During this time, the bath chemistry could be continually changing and there may also be a tendency for the nucleants to settle. Finally, foundries obtain their base aluminium alloys from different sources. These alloys may be supplied with compositions of certain elements, e.g. Ti already specified by the foundry. Nowadays, a significant proportion

of foundry aluminium alloys are secondary alloys and usually contain residual levels of Ti even if Ti levels are not specified.

Because of the interest in the use of shaped aluminium castings for more critical load bearing components, particularly in the automotive industry, in the last decade there has been a renewed interest in all aspects of structure/property control of aluminium castings. Many of the refiners used for shaped castings are the same as those developed for the wrought industry (especially the master alloy type refiners). Identical questions have therefore arisen regarding the nature of the active nucleants. This topic will not be reconsidered here. The purpose of the present study is to provide the foundryman with an overview of the behaviour of different types of grain refiner and, at the same time, to give the academic an insight into the variables influencing grain refinement. Most of the data reported relate to the use of master alloy type refiners because they facilitate the addition of controlled levels of refiner in laboratory scale studies.

Methods of grain refiner addition and benefits of refinement

Resulting from the early studies of the grain refinement of Al,⁽¹⁾ currently available commercial grain refiners usually contain Ti. They are added to the melt either as master alloys or salts. The master alloys can either be Al-Ti or Al-Ti-B, the latter now being the more popular since B enhances the grain refining action, i.e. a much finer grain size can be achieved for a given level of Ti addition. Master alloys with various Ti/B ratios are available, mostly with greater than the stoichiometric weight ratio (2.2:1) for the formation of the TiB₂ phase, i.e. Ti is in excess. Traditionally, foundries have used the latter type of refiner with Al5Ti1B being the most common. The refiners can also be obtained in a variety of forms, e.g. rod (alloy continuously cast followed by rolling to final cross-section size), nuggets (alloy continuously cast to cross-section size and cut to nugget length), waffle plate (alloy cast into moulds). More recently, Al-Ti-B refiners containing less than the stoichiometric ratio have become available, i.e. B is in excess. This type of alloy is now being used in sectors of the foundry industry. However, in comparison with refiners with above stoichiometric Ti/B ratios, the efficiency appears to depend to a greater extent on the level of residual Ti in the base alloy; see the section '*Comparison of effectiveness of different refiners*' below and '*Residual Ti levels*' in part 2 of this review.

During recent years, alternative master alloy refiners have been examined. Al-Ti-C refiners have been produced, with different Ti/C ratios,

offering potential advantages for certain DC cast wrought alloys. Therefore, their application to the grain refinement of shape casting alloys has also been studied. Likewise, the use of binary Al-B alloy refiners has also been investigated. Studies of the use of B alone as a grain refiner addition were neglected for many years following early observations that, although Ti was a very effective refiner, B did not refine pure aluminium⁽²⁾.

As mentioned above, refiners can also be added in the alternative form of compacted powder tablets, usually containing mixtures of K_2TiF_6 and KBF_4 salts. These work by dissolution and reaction in the melt to produce active nucleants. Although this is the cheapest method of grain refining, there is greater variability in refining performance and byproducts of the reaction have to be removed as dross.

The benefits of grain refinement have been claimed to include improved fluidity, improved feeding, better distribution of porosity, better dispersion of secondary phases, improved surface finish, improved machinability, better mechanical properties, e.g. fatigue strength and better pressure tightness. It is probable that both of the latter two benefits relate to the changed porosity distribution. A number of investigators have reported that mechanical properties are related to volume fraction of porosity and particularly to the maximum pore size.⁽³⁻⁵⁾ However, there have only been a limited number of studies directly related to the influence of grain size on the nature of the porosity (amount, pore size, pore density, pore length) in aluminium alloys.^(6,7) This is probably because in most casting alloys, based on Al-Si, the form of the eutectic silicon phase also has a significant effect on mechanical properties. Second, it is experimentally difficult to isolate the influence of grain refinement from the other variables that influence porosity namely hydrogen content, alloy composition, cooling rate and modification. For example, variations in Si content and cooling rate, which both influence porosity, also affect primary aluminium grain size even when a grain refiner has been added (see section 'Influence of Si content' below and 'Cooling rate' in part 2 of this review).

Similarly, small differences in hydrogen content can markedly influence the amount of porosity and pore sizes. Studies of the effect of grain refinement on porosity must therefore involve accurate measurement of hydrogen levels.

Nevertheless, it is recognised by foundries that grain refinement is particularly beneficial for long freezing range (LFR) alloys, e.g. Al-10Mg or Al-7Si2Cu which can be difficult to feed. Without grain refinement, castings in LFR alloys may not pass x-ray examination, may fail pressure tightness tests or may not attain required minimum ductility values in test bars. Because of their LFR, some of these alloys (those with low eutectic contents) may also be susceptible to hot tearing and might therefore be sand cast

in order to reduce imposed strains on hot spot regions. Without grain refinement, the lower cooling rates occurring in sand casting will result in larger grain sizes. Depending on the specific alloy, improvement in mechanical properties/ quality may be as a result of either improved feeding and/or improved distribution of porosity.

Possible influences of grain refinement on solidification behaviour will now be discussed.

Fluidity

Fluidity is the measure of the ability of a liquid to flow along a channel of uniform cross-section while solidifying. It is therefore quoted in units of length and relates to the ease with which an alloy will enter and fill a mould cavity. It is influenced by a number of alloy and mould parameters and in particular alloy composition, superheat, mould thermophysical properties and mould temperature. Alloy composition determines the solidification characteristics (solid/liquid interface morphology and grain structure). Generally speaking, pure metals and eutectics have high fluidities and LFR alloys have poor fluidity. Increasing alloy freezing range adversely affects fluidity by promoting dendritic growth and the formation of equiaxed grains. Movement of these grains with the metal flow may lead to flow termination by accumulation of equiaxed grains at the flow front.

It might be anticipated that reducing grain size would increase fluidity by delaying the formation of a coherent equiaxed dendritic network at the flow front. However, from the limited research reported,⁽⁸⁻¹²⁾ there is no clear evidence to support this. Since other factors influencing fluidity can be readily controlled, e.g. superheat, die coating thickness, fluidity does not appear to be a significant factor governing a foundry's decision to grain refine. In one of the most recent studies of the influence of grain refinement on fluidity, using an Al5Ti1B master alloy, Dahle *et al*⁽¹²⁾ examined the effect of Ti content on the fluidity of two commercial alloys, Al7SiMg and Al11SiMg. Since both of these contained high Ti levels (0.12%), model alloys of similar nominal compositions were also employed in order to also examine lower Ti contents. Alloys were investigated in the range 0-0.32%Ti. For both types of alloy, it was found that fluidity was impaired with increased grain refinement below 0.12%Ti but that it increased with increase in content above 0.12%Ti.

Dendrite coherency and feeding

Many people have suggested that 'mass feeding' in the early stages of solidification may lead to an overall reduction in porosity. Mass feeding is the term applied to the consolidation of the mixture of equiaxed grains and liquid before the formation of a coherent dendritic network. It is therefore expected that this feeding process will continue to longer times and that the coherency fraction solid will increase as grain size decreases. Chai *et al*⁽¹³⁾ have studied dendrite coherency during the solidification of equiaxed dendritic Al-Si alloys using continuous torque measurement. They found for a commercial A380 alloy (Al-8.5Si3.4Cu2.7Zn0.04Ti) that the coherency fraction solid increased from 11% to 16% for a 0.1%Ti addition of an Al5Ti1B master alloy.

As pointed out by Campbell, a reduction in porosity because of mass feeding per se is unjustified. This is because the critical interdendritic feeding stages leading to the formation of microporosity occur at much higher solid fractions, some time after mass feeding has ceased.⁽¹⁴⁾ In addition to its influence on mass feeding, grain refinement will also result in a change in dendrite morphology. This may be responsible for enhancing interdendritic feeding in the latter stages of solidification by increasing the permeability of the mushy region. This might be particularly effective in LFR alloys containing high volume fractions of primary phase. At the present time, there is only limited understanding of the interrelationship of alloy system, alloy composition, solidification conditions and grain size on dendrite morphology and the permeability of equiaxed structures.

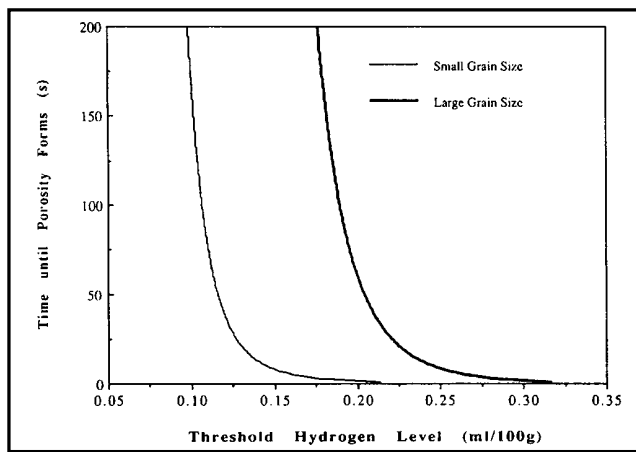


Fig. 1 Threshold hydrogen content for onset of porosity formation; smaller grain size (grain refined) sample shows much lower threshold level⁽⁶⁾

Porosity

It does not appear that grain refinement necessarily leads to a reduction in the amount of porosity in aluminium castings. However, it probably leads to an increase in pore density and a decrease in pore size. In two recent multi-parameter studies of the effect of grain refinement on Al-Si type alloys, it was concluded that, in addition to the nucleation of equiaxed grains, the grain refining particles also act as heterogeneous nucleation sites for gas bubbles.^(6,7) Tynelius *et al*⁽⁶⁾ carried out a quantitative characterisation of porosity in aluminium alloy A356 using a multiple regression analysis of alloy and process parameters affecting pore formation. One of their significant findings was that the threshold hydrogen level, for the onset of porosity at a given solidification time, decreased considerably with grain refinement (fig. 1).

From a metallographic investigation of an Al9Si3Cu alloy, Roy *et al*⁽⁷⁾ showed supposed evidence of the nucleation of pores on what were believed to be TiB₂ particles. They also showed micrographs to illustrate the marked reduction in pore lengths with grain refinement.

For the same level of porosity, it might be anticipated that smaller, more numerous pores would be of benefit to all aluminium alloys. The tendency to interconnected sheetlike porosity is likely to be reduced with consequent improvement in pressure tightness, ductility and fatigue behaviour.

Assessment of grain refinement

Assessment of grain refinement is achieved by either direct or indirect measurement techniques. The only method of direct measurement is the determination of grain size from metallographically prepared samples, e.g. using the mean linear intercept technique. This is the method invariably chosen by grain refiner producers and industrial/academic researchers. Alternatively, the grain sizes can be compared to standard samples having known grain sizes or ascribed particular grain size numbers. However, metallography is a time consuming and therefore expensive activity and would rarely be used in the foundry. Also, in the time required to prepare and examine a specimen, the bath chemistry may have changed.

The alternative indirect measurement techniques involve either chemical or thermal analysis of the melts. In both cases, some form of correlation must be predetermined relating analysis data to grain size. These are the generally used foundry techniques, with chemical analysis being the most widely practiced. These techniques are subject to limitations as will be discussed.

Assessment by grain refiner producers and researchers

Several grain refining tests have been developed for wrought aluminium alloys which are widely employed as standard techniques

by both industrial and academic research organisations. They are used in quality control procedures, in fundamental studies of the efficiency of different refiners and for examination of the factors that influence refiner behaviour. The tests involve the measurement of grain sizes from small castings produced under prescribed conditions. The most common of these tests are the Alcan Test, the Aluminum Association TP-1 test, the Alcoa test, the KBA calibrated ring test and the Reynolds golf tee test.

These tests differ considerably in the shape and manner of solidification of the samples, namely the temperature gradients that prevail during solidification and the cooling rates imposed. The same tests have often been used for cast aluminium alloys, although investigation of grain refinement of cast alloys has been significantly more limited. It must be appreciated that the measured grain sizes are markedly determined by the prevailing solidification conditions in a particular type of test. They will therefore differ from those determined from the other types of test for a given alloy and grain refiner addition. This makes evaluation and comparison of data in the literature complex and translation of reported findings to commercial practice even more fraught. The important observations using the above tests and others are presented in the sections 'Grain refinement of Al-Si alloys' below and 'Factors affecting grain refinement' in part 2 of this review.

Assessment by foundries

Chemical analysis

This continues to be the most widely employed method of assessment of bath composition and grain refining potential, although there does not appear to be any consistency in the way in which the analysis data is utilised. Most foundries are using grain refiners that contain both Ti and B and may also be buying in aluminium alloy that contains as much as 0.1%Ti. Based on the bath analysis, the correct amount of refiner will be deemed to be present or additional refiner will be added. As will be shown in the section 'Comparison of the effectiveness of different refiners', grain refinement is dependent on both the Ti/B ratio and the level of B present. High Ti levels *per se* with an inadequate amount of B may not provide the necessary refinement. In addition, it must also be borne in mind that local cooling rate in the casting will have a marked effect on grain size.

It is highly unlikely that the foundryman will know, *a priori*, what range of grain sizes will be achieved in the casting or what grain size is required in order to obtain the anticipated benefits. Present knowledge of the overall relationship between type of grain refiner, amount of refiner and cooling rate, for specific alloys, is extremely limited.

Thermal analysis

The thermodynamic barrier to nucleation

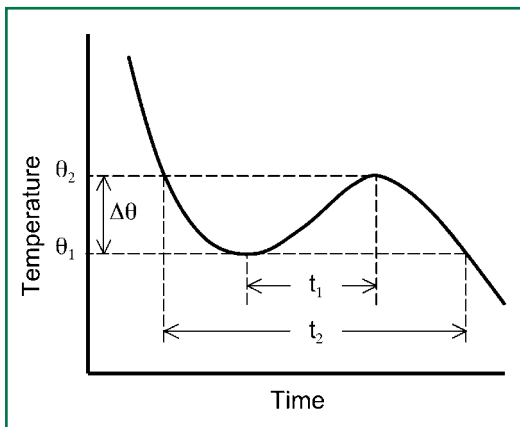


Fig. 2 Thermal analysis curve associated with nucleation of primary aluminium phase

means that a melt supercools before the formation of aluminium solid solution grains. Under conditions of slow cooling, nucleation of the grains will be followed by recalescence of the melt. In the presence of a perfect grain refiner, there would be no supercooling or recalescence. A number of researchers have therefore investigated how features of the shape of a thermal analysis curve accompanying supercooling and recalescence (fig. 2), relate to grain refining potential.⁽¹⁵⁻¹⁷⁾ As will be seen, there is no consensus on a single thermal or temporal parameter governing the potential. Different makes of commercial equipment are now available for analysing thermal analysis curves, and predicting nucleating potential in terms of one or other of the various suggested parameters, and are used in foundries worldwide.

Charbonnier⁽¹⁵⁾ reports that two parameters are necessary in order to estimate grain size. The first is the apparent supercooling, defined as the difference between the minimum temperature associated with inception of solidification (θ_1) and the maximum temperature reached by the alloy during solidification (θ_2), $\Delta\theta$ in fig. 2. The second parameter is the period of supercooling t_1 , i.e. the time separating the minimum from the maximum on the curve. The curves in fig. 3 indicate how the two factors vary with grain size. An instrument for the automatic interpretation of thermal analysis data and grain size prediction, based on these parameters, was developed by Pechiney and marketed as Thermatest. Apelian *et al*⁽¹⁶⁾ obtained thermal analysis curves for three alloys A356, Al-7Si and A319 using sand cup moulds containing thermocouples. From the curves for each alloy, they obtained the values of θ_1 and θ_2 as a function of amount of grain refiner added. At the time each sand cup was poured, a KBA ring test sample was also cast to obtain the grain size by a metallographic technique. The measured grain sizes were also compared with the grain size number predicted by a commercial AluDelta thermal analysis instrument. Grain size was found to increase as $\Delta\theta$ increased. They quoted typical grain sizes as being medium (600-900 μm), very fine ($\sim 500 \mu\text{m}$) and extremely fine ($\sim 200\text{-}300 \mu\text{m}$).

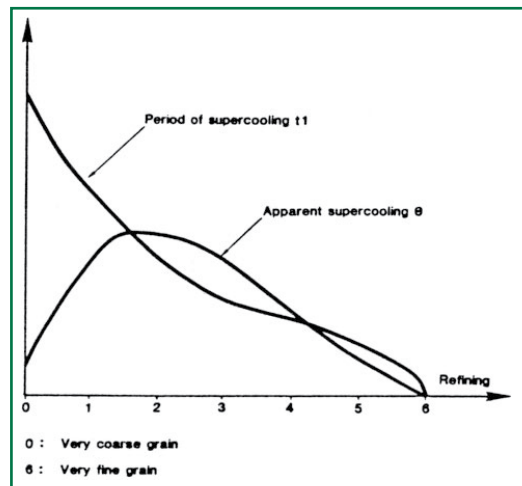


Fig. 3 Change in apparent supercooling and period of supercooling with change in grain size in hypoeutectic Al-Si alloy¹⁵

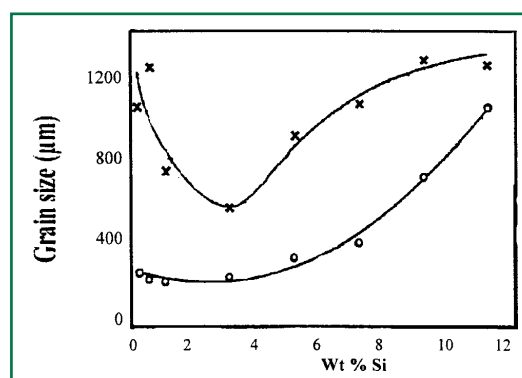


Fig. 4 Effect of increased Si content on grain size in Al-Si alloys; without refiner addition (upper curve) and with 0.01 wt-%Ti-Al; Ti1B refiner (lower curve)¹⁹

From observations on an Al7SiMg type alloy, Bekaert and Wettinck⁽¹⁷⁾ concluded that the parameter that correlated best with grain size was t_2 (determined from horizontal projections of the minimum and maximum temperatures onto the cooling curve) (fig. 2). As t_2 (s) increases, grain size increases, defined as fine ($t_2 < 12.5$ s), medium ($t_2 12.5\text{-}18.8$ s) and coarse ($t_2 > 18.8$ s). Grain sizes were obtained from castings produced using the Alcan Test and thermal analyses from Quick Tip sand cups made by Electronite.

It appears that a number of parameters associated with an undercooling and recalescence curve can be correlated with grain size and that the different types of commercial test equipment for assessing nucleation potential employ different parameters. In order to obtain a well defined curve, slow cooling is required in the test. A severe limitation of such equipment appears to be the inability to predict the actual grain sizes in the components being cast, since the cooling rates in the cast components will almost certainly differ from those in the thermal analysis tests. As will be discussed later, for a given level of grain refiner addition, cooling rate has a significant effect on grain size. What can be stated with some certainty is that if a test indicates a high nucleating potential (very little undercooling) then any section of a casting experiencing a higher cooling rate than the test is likely to have a fine grain size.

Grain refinement of Al-Si alloys

Since the majority of shape casting alloys are based on Al-Si, the remainder of the present study will deal with observations relating to this system. It is generally recognised that hypoeutectic Al-Si alloys are more difficult to grain refine than most wrought aluminium alloys. The level of Ti addition to wrought alloys, using the most common Al5Ti1B refiner, is normally in the range 0.005-0.01%. In the case of Al-Si alloys, the addition is an order of magnitude greater.

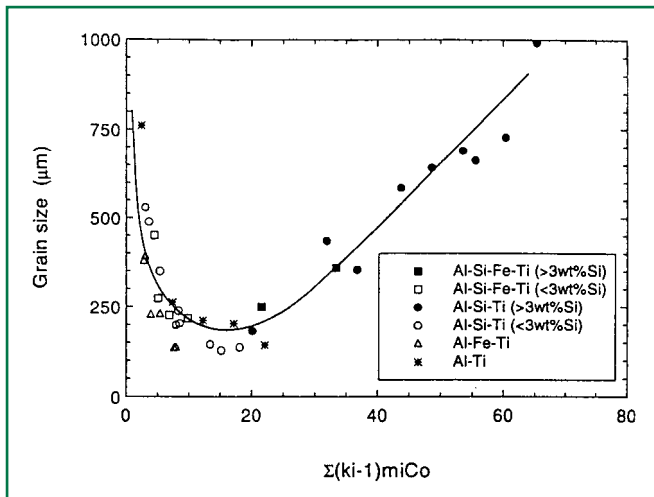


Fig. 5 Average grain size versus growth restriction factor (sum of constitutional contribution from different alloying elements) for several alloy compositions²⁰

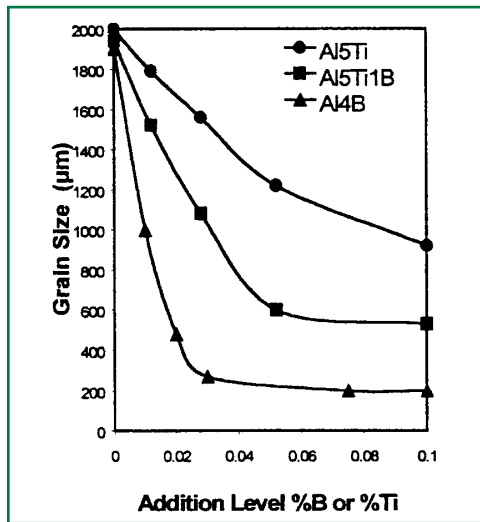


Fig. 6 Data of Wu et al.²⁵ for grain refinement of 356 aluminium alloy with three different refiners

Influence of Si content

A number of researchers have reported that as silicon content initially increases, the aluminium solid solution grain size decreases. However, beyond a critical value of ~3%Si the grain size increases. This trend is observed in both grain refined⁽¹⁸⁻²²⁾ and non-grain refined^(18,19,22-24) alloys (fig. 4), with the non-grain refined alloys exhibiting coarser grains. In the case of the grain refined alloys, conventional AlTiB refiners with Ti/B weight ratios in excess of 2.2:1 were used and the Ti addition was 0.01% in all studies. In one instance,⁽²⁰⁾ the grain size variation was also plotted against the growth restriction factor, $(k_i-1)m_iC_0$, as shown in fig. 5, 3%Si corresponding to a factor value of ~18. k_i is the equilibrium distribution coefficient, m_i is the liquidus slope and C_0 is the alloy composition.

It is generally believed that the initial decrease in grain size with Si content is due to growth restriction associated with Si redistribution on freezing. However, the reason for coarsening beyond the critical Si level is still unclear. A number of explanations have been proposed including the effect of the change in solidification interval,⁽¹⁸⁾ a change in crystal growth morphology from cellular to dendritic (and a corresponding increase in crystal growth rate and grain size)⁽²⁰⁾ and Si poisoning of potential nucleant substrates.⁽²¹⁾ In line with foundry practice, the Si poisoning effect can be counteracted by increasing the level of grain refiner addition, as will be shown later in the section 'Type of grain refiner, level of addition, holding time and fade' in part 2 of this review.

Comparison of effectiveness of different refiners

As outlined in the section 'Methods of grain refiner addition and benefits of grain refinement' above, in recent years, there have been several investigations of alternative grain refiners including those based on Al-B, Al-Ti-C and Al-Ti-B with Ti/B weight ratios, <2.2:1.^(21,23,25-32) In these studies, investigators have frequently attempted to compare the grain refining 'efficiencies' of these alternatives with traditional refiners. The methods of comparison have, however, often led to confusion and misleading statements. Furthermore, in several of these studies, significant levels of residual Ti have been present in the alloys being refined masking the true effect of the refiner. Wu *et al.*⁽²⁵⁾ reported a study of the grain refinement of a 356 aluminium alloy with an Al4B refiner. Their results are shown in fig. 6 in comparison with Al5Ti and Al5Ti1B refiners. The x axis is %B or %Ti, which infers %B for the Al4B alloy and %Ti for the other two refiners. Plotted in this form, it appears that the Al4B refiner is superior to the other two. However, if the grain size results for both the Al4B and Al5Ti1B are plotted against %B, the two sets of data are comparable (fig. 7).

Sigworth and Guzowski⁽²⁶⁾ confirmed that Al-B is an effective refiner but commented that B additions to alloys containing high residual Ti levels would result in substantial TiB₂ sludge deposits. A number of alternative refiners, with different Ti/B ratios between 0 and 2.2, were therefore studied and optimum results were reported for a ratio of unity. Their results for the refinement of a 356 alloy containing a residual 0.02%Ti are shown in fig. 8 for a holding time of 5 min. In this plot, grain size is plotted against weight of grain refiner added. Plotted in this form, it appears that a 1:1 ratio (Al3Ti3B) is superior to either Al5Ti1B or Al3B. Again, if plotted against %B, the results for Al5TiB and Al3Ti3B are almost identical (fig. 9). It is also important to note that, at any of the addition levels studied, the presence of 0.02% residual Ti when adding the Al3Ti3B refiner would result in the Ti/B ratio being raised to above 2.2:1.

Bondhus *et al.*⁽³¹⁾ compared the grain refinement of three alloys with two grain refiners, Al5Ti1B and a nominal 1:1 ratio refiner Al1.6Ti1.4B, over a holding time of 1 h. The three alloys were Al7Si3Cu, Al7Si3Zn and Al7Si3Cu3Zn and in all three cases, 0.06%Ti and 0.02%Sr were also separately added. The refiners were added at a level of 2 kg/1000 kg. They concluded that the 1:1 refiner gave better 'efficiency' at the same addition rate compared with the Al5Ti1B refiner and fig. 10 shows one of their sets of results. Again, this method of comparing the data is highly confusing.

Taking into account the added Ti (and the 0.002%Ti in the original base alloy), for the refiner addition rate chosen the overall Ti and B concentrations in the alloy would be 0.072%Ti, 0.002%B (for the Al5Ti1B refiner) and 0.0652Ti, 0.0028%B (for the Al1.6Ti1.4B refiner). It is

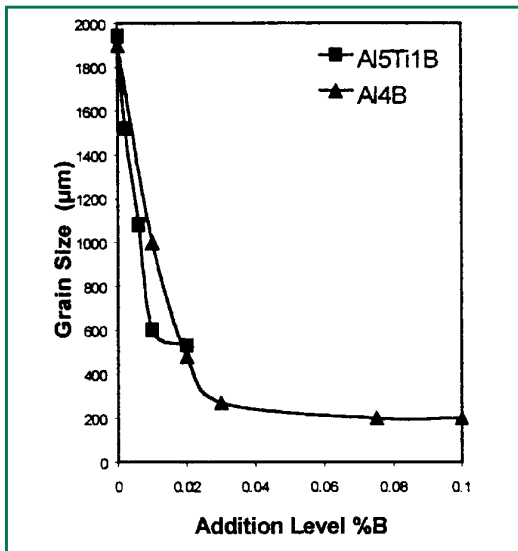


Fig. 7 Grain size data for two B containing refiners in Fig. 6 replotted as a function of B addition level

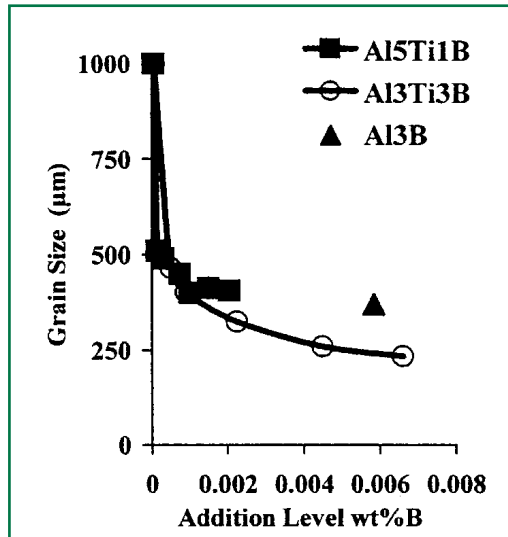


Fig. 9 Grain size data in Fig. 8 replotted as a function of B addition level

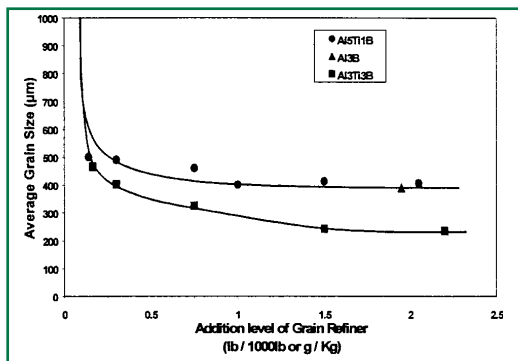


Fig. 8 Grain size data for refinement of 356 aluminium alloy for three different B containing refiners²⁶

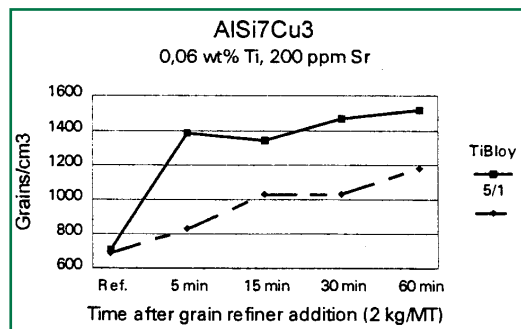


Fig. 10 Grain density data for Al₇Si₃Cu for two different refiners; upper curve for Al_{1.6}Ti_{1.4}B refiner and lower curve for Al₅Ti₁B¹

therefore apparent for the latter case that the amount of B added is 40% greater than in the former and the overall Ti/B ratio in the alloy is actually »2.2:1 not 1:1. It might therefore be anticipated that the Al_{1.6}Ti_{1.4}B addition would produce a finer grain size. However, this is no basis for saying it is more efficient.

Tonde⁽²³⁾ has similarly examined the grain refinement of Al_{9.6}Si using the grain refiners Al₆Ti, Al₅Ti₁B, Al₅Ti_{0.2}B and Si₁B. Plotting that author's data in the same manner as fig. 6, he concluded that Si₁B produced the finest grain structure at very low addition rates (~0.015%B).

Data by Kori *et al*⁽³²⁾ is even more confusing. They examined the refinement of an Al₇Si alloy with AlTiB refiners having different Ti/B ratios for different addition levels and for holding times of 5 and 120 min. The refiners examined were Al₁Ti₃B, Al₁Ti₅B, Al₃Ti₃B, Al₅Ti₁B and Al₃Ti₁B. They also plotted their data as in fig. 6. However, for no logical reason, they plotted the data for the 1:3, 1:5 and 3:3 alloys in terms of %B and the 5:1 and 3:1 alloys in terms of %Ti (yet all refiners contain both Ti and B). They then concluded that the Al₁Ti₃B was the most efficient refiner at all the different addition levels (fig. 11). Again, it is interesting to note that if all the data had

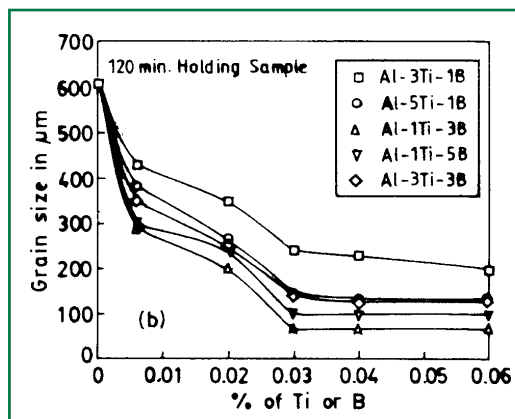


Fig. 11 Grain size data for refinement of Al₇Si with several AlTiB refiners having different Ti/B ratios, for a holding time of 120 min³²

been compared against %B, then for an addition of 0.01%B (which is reasonably typical for the addition of Al₅Ti₁B commercially), the refiners with above stoichiometric ratios would be superior to the other three ratios and the Al₅Ti₁B would be by far the best.

It is therefore evident that comparing the effectiveness of different refiners on the basis of weight of refiner addition, or by comparing the grain size for one grain refiner at a given %Ti with that for another refiner at the same %B, can result in misleading conclusions. Assuming that a number of refiners are capable of producing fine grain sizes if added at an appropriate level, and that they do not have any adverse effects, the only commercial means of comparison would

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be 'the cost to achieve an acceptable grain size'. However, values for this might be difficult to establish. Since the refiners have different compositions, it is far more important to establish what substrates are likely to give rise to nucleation and the grain refining response to refiner addition level and other factors.

It appears from the evidence above that for boron containing alloys, whether Al-B or Al-Ti-B in type, the degree of grain refinement is dependent on the level of boron addition and, in the latter case, by the Ti/B ratio. This has been clearly demonstrated by Spittle and coworkers^(21,28,30) and Cook and Spooner⁽²⁹⁾. They examined a range of Al-B and Al-Ti-B refiners and plotted their grain size results as a function of B level for a given holding time or, as a function of holding time for a fixed boron addition. These data are examined in more detail in the section 'Type of grain refiner, level of addition, holding time and fade' in part 2 of this review and indicate that TiB₂, AlB₂ or mixed (AlTi)B₂ particles are likely to be important substrates for heterogeneous nucleation.

Please find below the full set of references for parts 1 and 2 of this paper. Note this is the complete set and so some of these are only relevant to the second part.

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Part II will be published in the next issue of Foundry Trade Journal

Grain refinement in shape casting of aluminium alloys - Part I

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