Journal of Manufacturing Engineering, 2009, Vol.4, Issue.1

STUDIES ON GRAIN REFINEMENT OF ALUMINUM ALLOYS

Dr. T. Chandrashekar

Department of Mechanical & Production Engineering,
Velammal Engineering College, Chennai – 600 066, India

ABSTRACT

Grain structure is an important and readily observable feature in aluminum alloy castings. Depending on the constitutional and heat-flow conditions in a solidified Al alloy, various morphologies are possible. Grain refining is one of the predominant techniques in controlling the quality of castings. It plays a vital role in improving metallurgical characteristics and mechanical properties of Al alloys. Fine equiaxed grains ensure remarkable benefits. There are a number of techniques to achieve fine equiaxed grain structure, but grain refinement by the addition of grain refiners referred to as grain refinement / inoculation is the most popular due to its simplicity. Grain refinement has been studied extensively by researchers for several decades, not only for developing efficient grain refiners but also for achieving an understanding of the mechanism of grain refinement. In spite of its commercial importance, benefits and numerous scientific studies in this area, the grain refinement of Al and its alloys is still a controversial subject. Solute elements like titanium segregate to the inoculants/melt interface affecting the dendrites and also affect the constitutional undercooling at the solid–liquid interface. This segregating power of an element is quantified by the growth restricting factor (GRF). In this paper, various aspects covering the wide spectrum of grain refinement has been presented for several Al alloy systems. A comparison of commercially available grain refiner's performance has been presented. Also fabrication of grain refiners and their morphological effects on grain refinement has been discussed. Further an attempt has been made to explain the mechanism of grain refinement.

Keywords: Grain refinement, Master alloys, Alcan test, Undercooling, $TiAl_3$ phase, Growth restricting factor (GRF).

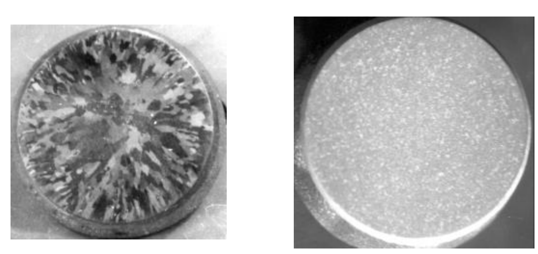
1. Introduction

The challenge of today's metal casting industries is to have high productivity while at the same time to produce good quality castings. A good quality casting can be achieved by controlling various parameters in the foundry. Grain refining is one of the predominant techniques in controlling the quality of castings. Grain structure is an important and readily observable feature in Al alloy castings. Depending on the constitutional and heat flow conditions a solidified Al alloy castings exhibits three different grain morphologies namely; equiaxed, columnar and twinned columnar grains [1]. Grain refinement may be defined as "the deliberate suppression of columnar, twinned columnar grains and to favour fine equiaxed grains by the addition of grain refiners to the molten metal before pouring" (Figure. 1). It plays a vital role in improving characteristics and properties of Al alloys.

1.1 Significance of Grain Refinement

It has been reported by the investigators [1,2] that the fine equiaxed grains ensure:

1. Uniform and improved mechanical properties throughout the material.



(a) (b)

Fig 1 Macrostructures of Al-Si alloy indicating (a) columnar and twinned columnar grains before grain refinement and (b) fine grains after grain refinement

Corresponding Author E mail: chandrashekarthi@yahoo.com

Courtesy: Proceedings of 2nd international conference on Recent Advances in Material Processing Technology-National Engineering College & Society for Manufacturing engineers, K. R. Nagar, Kovilpatti – 628 503, Tamilnadu, India

2. Distribution of secondary phases and micro-porosity on a fine scale which in turn improves machinability.
3. Better feeding to eliminate shrinkage porosity.
4. Improved ability to achieve uniformly anodized surface and super plasticity.
5. Better surface finishes on both the basic casting and the machined parts (cosmetic features).
6. Reduced ingot cracking and improved resistance to hot tearing.
7. Better strength, toughness, fatigue life and corrosion resistance.

1.2 Relation between Mechanical properties and Grain size

Grain boundaries are the obstacles to the motion of dislocations and since fine grains have large number of grain boundaries, the obstacles to the motion of dislocations are higher. Due to this, dislocation density rises rapidly increasing the stress necessary to cause plastic deformation. This results in higher values of yield stress. A general relationship [5] between yield stress (and other mechanical properties) and the grain size was proposed by Hall-Petch [3] is given by the equation:

$$\sigma_0 = \sigma_i + kD^{-1/2} \qquad \text{------ (Equation - 1)}$$

Where,

$\sigma_0 \rightarrow$ Yield stress

$\sigma_i \rightarrow$ 'Friction stress' representing the overall resistance of the crystal lattice to dislocation movement

$k \rightarrow$ 'Locking parameter' which measures the relative hardening contribution of the grain boundaries

$D \rightarrow$ Grain diameter

2. Literature Review

An exhaustive literature survey concerned to the topic starting from the very first paper in 1949 to the recent literature is collected and a critical review was made by the present investigator [4]. The literature review illustrates the fundamental aspects of grain refinement and the various theories proposed by the researchers to explain the mechanism of grain refinement. Many controversies that are prevailing for each of these theories to understand the mechanism of grain refinement were also reported.

3. Experimentation

The research work presented in this paper explains the fabrication of an Alcan experimental set up used to evaluate the grain refining performances. Then a comparative study of the available grain refiners with respect to the extent of grain refinement, their fading effect and mechanical properties evaluated are also discussed. The fabrication of binary Al-Ti and Al-B grain refiners in the form of master alloys with different morphologies and their complete characterization is deliberated. Subsequently the performances of the fabricated grain refiners and the effect of their addition rate to the melt are elucidated. Finally a set of experiments carried out to explain the mechanism of grain refinement is presented.

3.1: Fabrication of Alcan Experimental set up

The ideal test procedure for evaluating grain refiner's performance should predict, very closely, the refining performance to optimize the addition levels [1]. However, no easily constructed, robust, and reproducible test has yet been devised which will do this precisely. Aluminum Company of Canada has developed a grain refining test procedure, which is commonly known as the Alcan test [5]. This was followed by the development various experimental procedures. Among these, the Alcan test appears to be the pre-eminent one at present, and there is, unfortunately, no established method which quantitatively relate one test procedure with the other [1,5]. Therefore in the present investigation an Alcan experimental set up as shown in Figure 2 was fabricated to assess the grain refining performances.

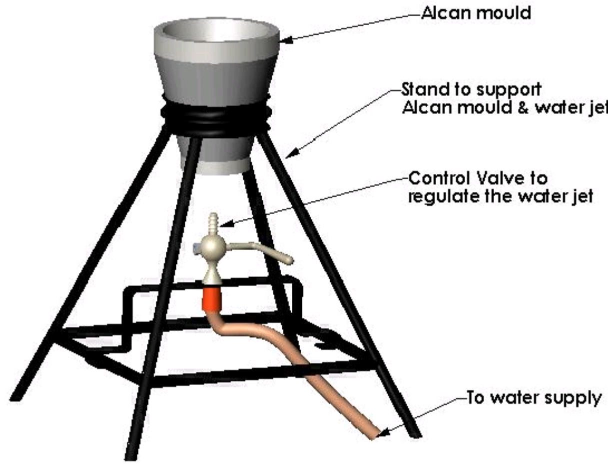


Fig 2 A model showing complete details of Alcan experimental set up

4. Results and Discussion

4.1: Comparative study of available grain refiners

A comparative study on grain refinement of Al-7Si alloy (LM25/A356) was carried out by adding the available grain refiners namely, Al-10%Ti, Al-5%Ti-1%B, Al-5%Zr master alloys and a proprietary compound called NUCLEANT-2 to the separate aluminum alloy melts. The grain refiners were characterized completely before they were added to the alloy systems. Later their grain refining performances and the mechanical properties such as tensile and hardness were evaluated.

The average grain sizes of Al-Si alloys refined with Al-10Ti, Al-5Ti-1B, Al-5Zr master alloys and a proprietary compound NUCLEANT-2 held for a holding period of upto sixty minutes are presented in Figure 3.

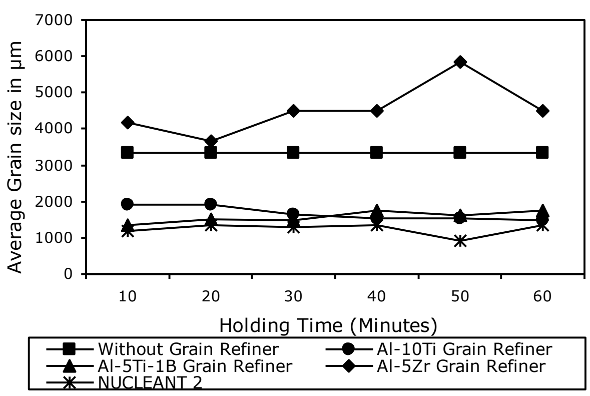


Fig 3 Graph showing the Average Grain size Vs Holding Time of Al-7Si alloys refined with the available grain refiners

It can be observed from the above graph that the average grain sizes of Al-7Si alloy decreased drastically by the addition of Al-10Ti, Al-5Ti-1B master alloys and NUCLEANT-2. This is attributed to high segregating power quantified by the growth-restricting factor (GRF) of titanium (GRF=245.6). This titanium segregate to the inoculant/melt interface and leads to a constitutionally undercooled zone in front of the growing interface within which nucleation can occur on the nucleants present [6]. Further, it is also evident that there is no considerable fading effect of the grain refiner's in the melt upto a holding period of sixty minutes.

On the other hand, the average grain size of Al-7Si alloy has increased with the addition of Al-5Zr master alloy indicating the poisoning effect of Zirconium. This is attributed to a very low GRF of Zirconium (GRF=6.5).

4.2: Mechanical properties Evaluation

Results of the mechanical properties evaluation indicated an improvement in tensile strength, proof stress, percentage elongation, and Brinell Hardness Number (BHN) with the decrease in grain sizes as shown in Figure 4. This is in conformance with the Hall-Petch equation which states that the mechanical properties improve as the grain sizes decreases.

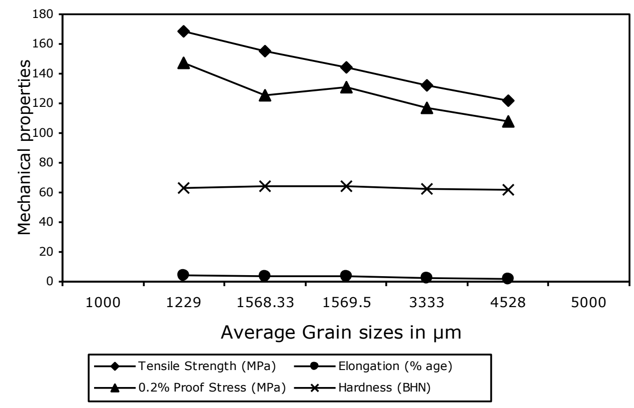


Fig 4 Graph showing the Average Grain sizes Vs Mechanical properties

4.3: Fabrication Al-Ti & Al-B Master alloys

In this part an Al-10%Ti master alloy was fabricated using titanium dioxide (TiO_2) and high purity Al. The master alloys were fabricated at different processing temperatures of 1000, 900 and 800^{0}C in order to achieve different $TiAl_3$ morphologies. The fabricated Al-10Ti master alloys are then added to Al-7Si (LM25/A356) alloy systems to study the effect of $TiAl_3$ morphologies on the grain refining performances. In addition, these fabricated Al-10Ti master alloys with different $TiAl_3$ morphologies were also added to high purity aluminum to study the influence of alloying elements during grain refinement.

4.3.1: Characterization of Fabricated Al-Ti Master alloys

The spectroscopic analysis of the fabricated Al-Ti master alloys at various processing temperatures indicated the amount of titanium very close to 10 percent. The Scanning Electron Microscopic (SEM) analysis indicated that an Al-10%Ti master alloy has developed completely blocky morphology of $TiAl_3$ (as shown in the Figure 5) when the processing temperature was 1000^{0}C. On the other hand, it has developed a completely flaky morphology of $TiAl_3$ (as shown in the Figure 6) when the processing temperature was 800^{0}C. But a combination of both flaky and blocky morphology of $TiAl_3$ as shown in the Figure 7 has been obtained at a processing temperature of 900^0C.

4.3.2: Effect of $TiAl_3$ Morphology on Grain Refining Performance

The fabricated Al-10%Ti master alloys possessing a completely blocky, completely flaky and a combination of both blocky and flaky morphologies of $TiAl_3$ are added to Al-7Si alloy systems to study the effect of $TiAl_3$ phase morphology on grain refinement.

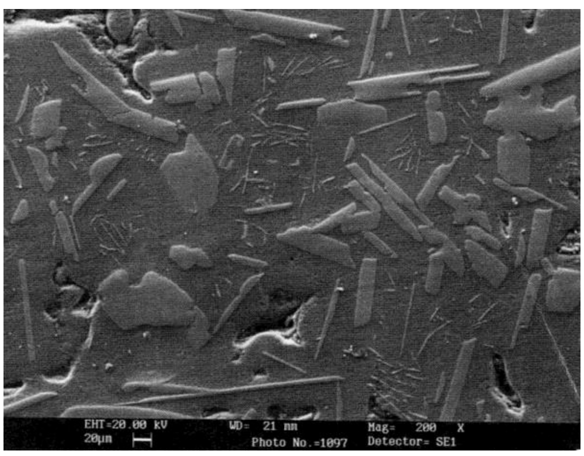


Fig 5 SEM photograph of Al-10%Ti master alloy processed at 1000^0C indicating a completely blocky morphology of $TiAl_3$

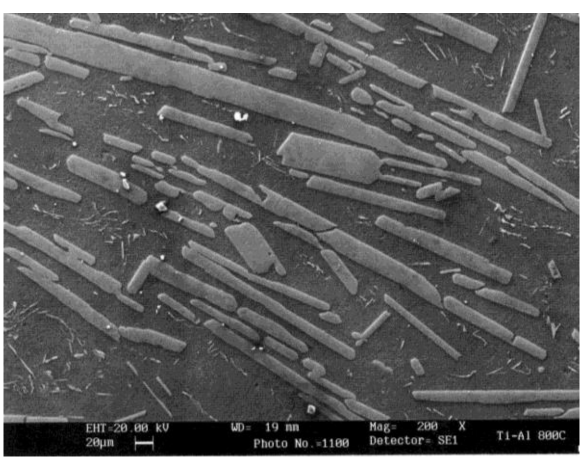


Fig 6 SEM photograph of Al-10%Ti master alloys processed at 800^0C indicating a completely flaky morphology of $TiAl_3$

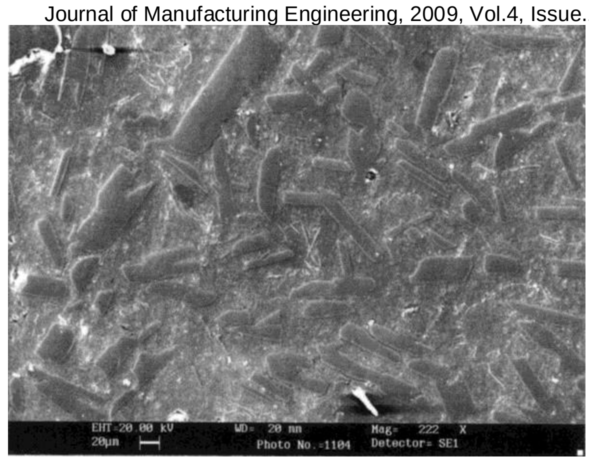


Fig 7 SEM photograph of Al-10%Ti master alloys processed at 900^0C indicating a combination of both blocky and flaky morphology of $TiAl_3$

Figure 8 shows the comparison of grain refining performances of these master alloys.

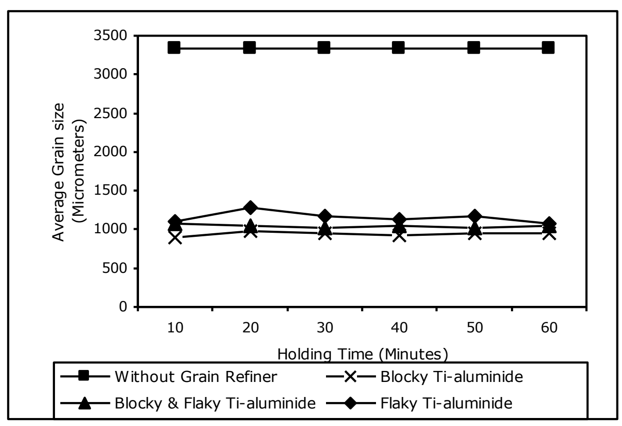


Fig 8 Average Grain size Vs Holding Time of Al-7Si alloys grain refined by Al-10%Ti master alloys possessing different $TiAl_3$ morphologies

It is quite evident that there is a considerable reduction in the average grain size of Al-7Si alloys after the addition of Al-10%Ti master alloys. A careful observation indicates that the grain sizes of Al-7Si alloys have reduced to a greater extent (around 900 µm) by the Al-10%Ti master alloys possessing blocky morphology of $TiAl_3$. While, a flaky morphology of $TiAl_3$ in Al-10%Ti master alloy showed a relatively lesser effect (around 1150 µm) in reducing the grain sizes of Al-7Si alloys. The grain refining performances of Al-10%Ti master alloys possessing a combination of both flaky and blocky morphology of $TiAl_3$ was intermediate to that of the master alloys possessing either a completely blocky or a completely flaky morphology of $TiAl_3$. In addition, it can be observed that there is no fading effect of Al-10%Ti master alloys in Al-7Si alloy melts up to a holding period of sixty minutes.

From the above results it is evident that there lies a specific crystallographic relationship between the blocky crystals of $TiAl_3$ and the aluminum matrix, which reduces the surface energy of the interface to facilitate nucleation of α-aluminum on the blocky crystals.

4.3.3: Effect of $TiAl_3$ morphology on grain refining performance in high purity Al.

Similarly, to study the influence of any other alloying elements and impurities present in the alloy on the solubility of Ti in liquid Al during grain refinement, the fabricated Al-10%Ti master alloys possessing the above three $TiAl_3$ morphologies are added separately to each of the high purity Al melts (99.85% purity).

The average grain sizes of high purity aluminum refined with Al-10%Ti master alloys possessing the three different morphologies of $TiAl_3$ are shown in Figure 9.

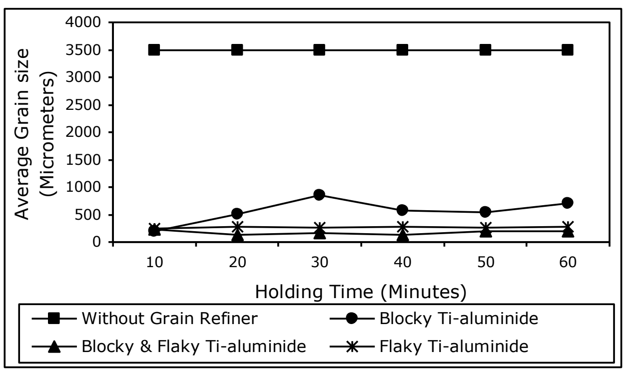


Fig 9 Average Grain size Vs Holding Time of high purity Al grain refined by Al-10%Ti master alloys with different $TiAl_3$ morphologies

It is very clear from the Figure 9 that there is a significant reduction in the average grain sizes in high purity Al (from 3500 to around 150 µm) refined by Al-10Ti master alloys possessing three different $TiAl_3$ morphologies. In addition, it can be observed that there is no considerable fading effect of Al-10%Ti master alloys in the melts up to a holding period of sixty minutes.

4.3.4: Comparison of grain refining performances in Al-Si alloys with High purity Al

The average grain sizes obtained in Al-7Si alloy system (Figure 8) and in high purity aluminum (Figure 9) by the addition of fabricated Al-10Ti master alloys possessing different $TiAl_3$ morphologies are compared and presented in Figure 10.

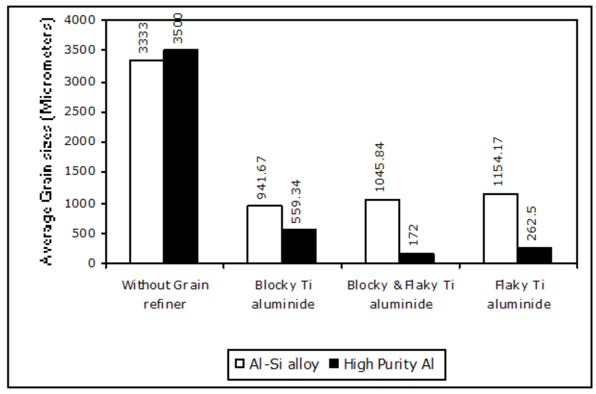


Fig 10 Bar chart indicating the Average Grain size obtained in Al-7Si alloy and High purity Al by the addition of Al-10%Ti master alloys with different $TiAl_3$ morphologies

The extent of grain refinement by the addition of fabricated Al-10%Ti master alloys to Al-7Si alloys is less when compared to that of high purity aluminum. This may be attributed to the poisoning effect of the alloying elements such as Cu, Si, Zn, Mg, Fe and Ni in the decreasing degree of their poisoning effect. This is because some of the Ti in $TiAl_3$ crystals, which are active nucleants for Al, is replaced by the above said poisoning elements producing less effective ternary compound nucleant particles. Thus, the poisoning effect is essentially due to the formation of complex aluminides which are found to be ineffective nucleants for Al. In addition, the poisoning behavior of the above elements may be attributed to their atomic size mismatch with the solvent aluminum.

These observations are also in support of the findings of Backerud et al [7], who have shown that the atomic attachment becomes favourable only when the segregated atoms are of similar size. Such similarity leads to a packing with minimum lattice distortion and an interface to provide higher nearest neighbour binding. The solvent/solute atomic size ratio will therefore dictate whether or not precipitation of a crystal layer is favourable. If atomic misfit is significant, even though segregation is thermodynamically favourable, stabilization of a crystal layer will not be feasible. When the solvent/solute size ratio is close to unity the probability of providing a well ordered crystal is greatly enhanced, and efficient grain refinement is achieved. On the other hand, significant mismatch leads to poisoning by hindering the precipitation of a stable crystal layer.

4.3.5: Fabrication of Al-B master alloy and their grain refining performance in Al-Si alloys

It is very clear from the literature [8] that Al-4%B master alloy is one of the most powerful grain refiners for hypoeutectic Al-7%Si (LM25/A356) alloys, compared to other grain refiners. Therefore an attempt was made to fabricate Al-4%B grain refiner in the form of master alloy using KBF_4 salts. Further, the fabricated master alloy was characterized completely by optical, SEM and XRD.

The wet chemical analysis and inductively coupled plasma combined with optical emission spectrometry of the fabricated Al-B master alloy by KBF_4 salt method indicated 2.65% boron.

Figures 11 shows the SEM photograph of the fabricated Al-2.65%B master alloy indicating the presence of some blocky particles. The EDAX spectrum of the same as shown in the Figure 12 indicated the presence of aluminum and boron peaks.

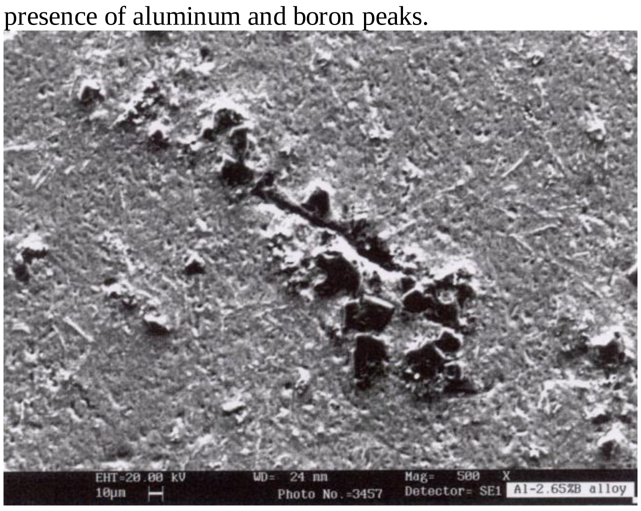


Fig 11 SEM microphotograph of Al-2.65%B master alloy showing blocky morphology

Then the grain refining performance of the fabricated Al-B master alloy was assessed in the Al-7Si (LM25/A356) alloy systems

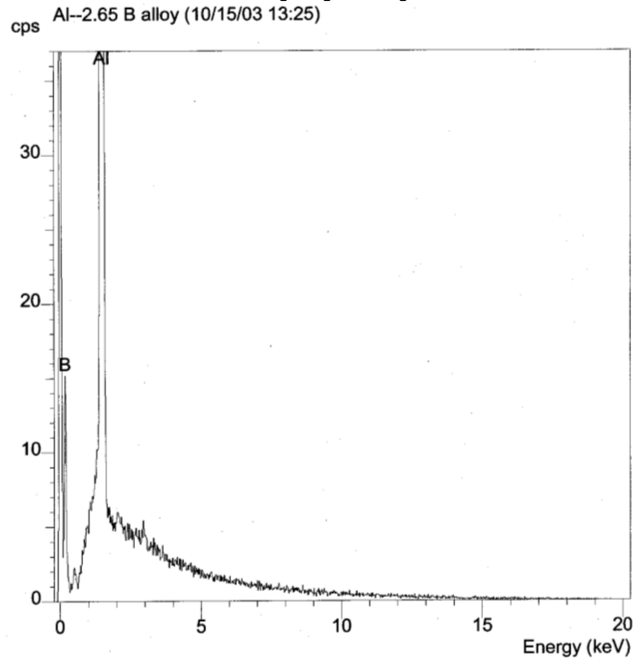


Fig 12 EDAX spectrum indicating Al and B peaks confirming blocky crystals in Al-2.65%B master alloy are possessing AlB_2 phase

.

In addition, it is evident from the literature [8, 9] that a minimum of 0.3% boron addition level is essential for effective grain refinement. Thus, in order to study the effect of addition level of the grain refiner, the fabricated Al-B master alloys were added to Al-7Si alloy melts at varied amounts to achieve different addition levels.

Initially, a fabricated Al-0.018%B master alloy was added to Al-7Si alloy melt to achieve an addition level of 0.0011% boron in the melt. Similarly, in another trial, a fabricated Al-2.65%B master alloy was added to Al-7Si alloy melt to obtain an addition level of 0.1256% boron in the melt.

The average grain sizes of the Al-7Si alloy before and after the addition of Al-0.018%B and Al-2.65%B master alloys, held for a holding period of upto twenty minutes are presented in the Figure 13.

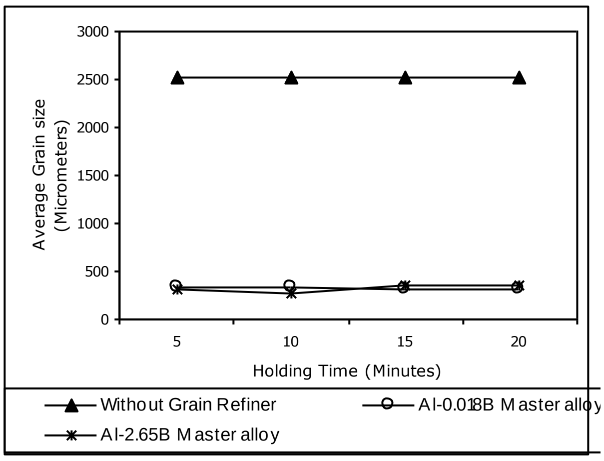


Fig 13 Graph showing Average Grain Sizes Vs Holding Time of Al-7Si alloy grain refined by Al-0.018B and Al-2.65B master alloys

It can be observed that there is drastic reduction in the average grain sizes (around 300 µm) of the Al-7Si alloy by the addition of Al-0.018%B and Al-2.65%B master alloys. Thus, it is apparent from the above results that Al-B master alloys are powerful grain refiners for Al-7Si alloys. It is also clear that there is no fading effect of these master alloys in Al-7Si alloy melts even upto a holding period of twenty minutes.

It is also evident that the extent of grain refinement achieved in the Al-7Si alloy systems is virtually same by the addition of Al-0.018%B and Al-2.65%B master alloys. Further, the extent of grain refinement is also same when boron addition levels are 0.0011% and 0.1256% respectively by the addition of Al-0.018%B and Al-2.65%B master alloys. This is in contrast with the literature [8], which states that only an Al-4%B master alloy is a powerful grain refiner and a minimum of 0.03% boron addition level is required for effective grain refinement [9]. The above results also indicate that 4% Boron in the master alloys is not a necessary criterion for effective grain refinement. However, as long as AlB_2 phase is present, even a master alloy with minute percentages of boron can act as good grain refiner.

Further, the grain refining performance of the Al-B master alloys are compared with that of Al-10%Ti and Al-5%Ti-1B master alloys (discussed earlier) and is presented in the Figure 14.

It can be observed that, Al-B master alloys are very powerful grain refiners for Al-7Si alloys compared to Al-10Ti and Al-5Ti-1B master alloys This is due to the presence of segregating elements in the alloy and hence, nucleating particles need to be added for effective grain refinement rather than more segregating elements

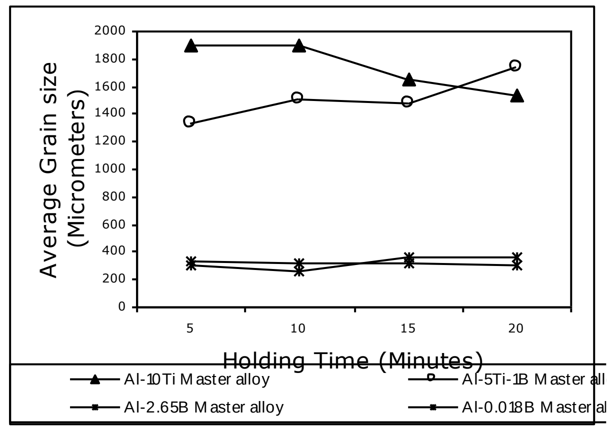


Fig 14 Graph showing Average Grain Sizes Vs Holding Time of Al-7Si alloy grain refined by Al-10Ti, Al-5Ti-1B, Al-0.018B and Al-2.65B master alloys

These results are in support of the findings of the researcher's Cibula [10] and Jones et al [5] who have suggested that borides are dispersed in the molten alloy and act as nucleating centers for Al.

4.4: Solute effects in grain refinement of Al alloys

Nucleation event is the most important event in the grain refinement, but the effect of the solute on the growth of dendrites and the constitutionally undercooled zone infront of the interface are also important. Thus, the addition of both nucleant particles and the amount of segregating elements quantified by the growth restriction factor (GRF) are important in grain refinement.

The segregating power of an element is described by the growth restricting factor during solidification. The GRF is a measure of the growth-restricting effect of solute on the growth of the solid-liquid interface of new grains as they grow into the melt.

It has been recognized [1,5] that, the segregating elements like titanium restrict the growth of the growing solid-liquid interface, leading to significant grain refinement. However, the fact that the solute concentration is fundamental part of the grain refinement mechanism has not been incorporated into the grain refinement theories proposed by the various researchers. It has been predicted[94] that, the nucleant potency, cooling rate, nucleant particle size, and the segregating potency of the solute elements have an effect on the final grain size, but the solute, as quantified by the Growth Restricting Factor (GRF), has the largest effect. The role of the solute is to restrict the growth rate of the growing interface, which, in turn, allows time for further nucleation events to occur. The powerful segregating ability of the titanium as a solute leads to a constitutionally undercooled zone infront of the growing interface, within which nucleation can occur on the nucleants that are present. The constitutionally undercooled zone activates the nucleants in front of the interface, hence, interrupting the growth of the previous grain.

Therefore, in this part of the investigation in order to determine the solute effects, the same grain refiner was added to two aluminum alloy systems possessing equivalent values of GRF. Then the resulting grain sizes in the two alloy systems are compared to explain the importance of solute effects during grain refinement.

The GRF's are calculated based on their typical compositions by using the following formula.

$$\sum mC_0(k-1) \qquad \text{----- (Equation 4.4)}$$

Where,
m → is the liquidus gradient
C_0 → is the concentration of the solute in the alloy
k → is the partition coefficient between the solid and liquid

Initially the GRF's of some of the Al alloys are calculated and among them LM9 and LM24 alloys were found to possess equivalent values of GRF's. The two selected alloys are further subjected to spectroscopic analysis in order to determine their actual percentages of alloying elements. The actual GRF's of these alloys are again calculated based on their actual percentages of alloying elements and are presented in the Table 1 and 2 respectively.

Then, each of the LM9 and LM24 alloys are melted separately as per the standard melting practice. These alloys are grain refined by adding Al-10Ti master alloy to each of the alloy melts to achieve an identical addition rate of 0.1% Ti. The resulting grain sizes in both LM9 and LM24 alloys are measured and compared. The grain sizes are also compared in each of the alloy systems before and after the addition of Al-10Ti grain refiner.

The grain refining performance of LM9 and LM24 alloys refined by adding Al-10Ti master alloy and the fading effect of the master alloy in the melts upto a holding period of sixty minutes are shown in the Figure 15.

Table 1: Spectroscopic chemical analysis of LM9 alloy and its calculated Growth Restricting Factor (GRF)

Alloy: LM9			
Alloying Elements	Composition in Wt. %	Segregating power m(k-1)	GRF $mC_0(k-1)$
Si	10.129	5.9	59.761
Fe	0.437	2.9	1.2673
Cu	0.054	2.8	0.1512
Mn	0.374	0.1	0.0374
Mg	0.390	3.0	1.1700
Ni	0.007	3.3	0.0231
Zn	0.061	---	---
Pb	0.003	---	---
Al	Remaining	---	---
Total of GRF or $\sum mC_0(k-1)$ =			**62.410**

Table 2: Spectroscopic chemical analysis of LM24 alloy and its calculated Growth Restricting Factor (GRF)

Alloy: LM24			
Alloying Elements	Composition in Wt. %	Segregating power m(k-1)	GRF $mC_0(k-1)$
Si	8.118	5.9	47.896
Fe	1.135	2.9	3.292
Cu	3.026	2.8	8.473
Mn	0.251	0.1	0.025
Mg	0.268	3.0	0.804
Ni	0.092	3.3	0.304
Zn	1.181	---	---
Pb	0.263	---	---
Al	Remaining	---	---
Total of GRF or $\sum mC_0(k-1)$ =			**60.794**

It can be observed that the grain sizes have decreased by the addition of Al-10Ti master alloy in both LM9 and LM24 alloy systems. In the case of LM9 alloy there is no fading effect and rather there is a continuous decrease in the grain sizes with the increase in holding time of upto sixty minutes. While there exists a very little fading effect of the Al-10Ti grain refiner in LM24 alloy beyond a holding time of 40 minutes.

The average grain sizes in both LM9 and LM24 alloy systems were of comparable values upon the addition of Al-10Ti master alloy. But, it is evident from the literature [11,12,13] that nucleating particles like TiB_2 or AlB_2 are responsible for nucleation. If it is so, then there should not have been any grain refinement by the addition of Al-10Ti master alloy which does not contain any boron in it. However, the reduction in grain sizes by the addition of Al-10Ti master alloy containing $TiAl_3$ suggests the powerful segregating ability of titanium (245.6) as solute is responsible for grain refinement. The presence of solute leads to a constitutionally undercooled zone infront of the growing interface within which the nucleation can occur on the nucleants that are present. This observation indicates that, though the nucleating particles are important the solute effects play a vital role in grain refinement.

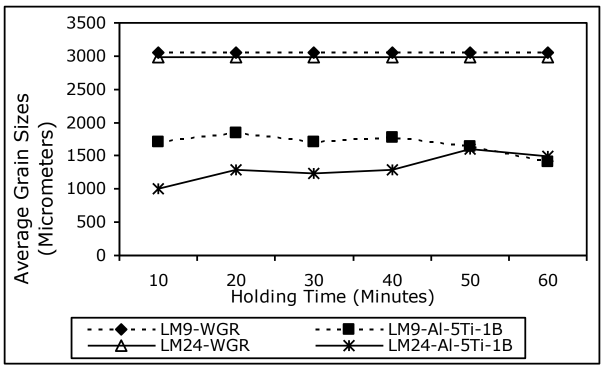


Fig 15 Graph showing Average Grain Sizes Vs Holding Time for LM9 and LM24 alloys grain refined by Al-5Ti-1B master alloy

In addition, a careful observation reveals that the extent of grain refinement in LM24 alloy was comparatively greater than that in LM9 alloy. This is due to a relatively lower value of GRF (60.7932) for LM9 alloy compared to that of LM24 alloy possessing a GRF of 62.4101.

Further, in order to have a better understanding of the mechanism of grain refinement another two aluminum alloy systems possessing different values of GRF are grain refined by adding same amount (0.06% boron) of Al-2.65B master alloys. The two alloys selected are LM6 and LM24 whose spectroscopic analysis and their calculated GRF's are as shown in the Table 3 and 4. It is clear from these tables that the LM24 alloy selected has larger amount titanium which results in higher value of GRF.

Both the LM6 and LM24 alloys are melted as per the standard melting practice and stabilized at 720^{0}C. These two alloys are grain refined by adding Al-2.65%B master alloy to achieve same addition level of 0.06% boron in both the alloy systems. The resulting grain sizes in both LM6 and LM24 alloys are measured and compared. The grain sizes are also compared in each of the alloy systems before the addition of grain refiner.

Table 3: Spectroscopic chemical analysis of LM6 alloy and its calculated Growth Restricting Factor (GRF)

Alloy: LM9			
Alloying Elements	Composition in Wt. %	Segregating power m(k-1)	GRF $mC_0(k-1)$
Si	12.994	5.9	76.6646
Fe	0.55	2.9	1.595
Cu	0.24	2.8	0.672
Mn	0.087	0.1	0.0087
Mg	0.251	3.0	0.753
Ni	0.02	3.3	0.066
Ti	0.029	245.6	7.1224
Al	Remaining	---	---
Total of GRF or $\sum mC_0(k-1)$ =			**86.8817**

Table 4: Spectroscopic chemical analysis of LM24 alloy and its calculated Growth Restricting Factor (GRF)

Alloy: LM24			
Alloying Elements	Composition in Wt. %	Segregating power m(k-1)	GRF $mC_0(k-1)$
Si	9.2	5.9	54.28
Fe	0.9	2.9	2.61
Cu	3.89	2.8	10.892
Mn	0.14	0.1	0.014
Mg	0.09	3.0	0.27
Ni	0.018	3.3	0.0594
Ti	0.158	245.6	38.8048
Al	Remaining	---	---
Total of GRF or $\sum mC_0(k-1)$ =			**106.9302**

The average grain sizes of LM6 and LM24 alloys before and after the addition of Al-2.65%B master alloy and held for a holding period of upto sixty minutes are presented in the Figure 16.

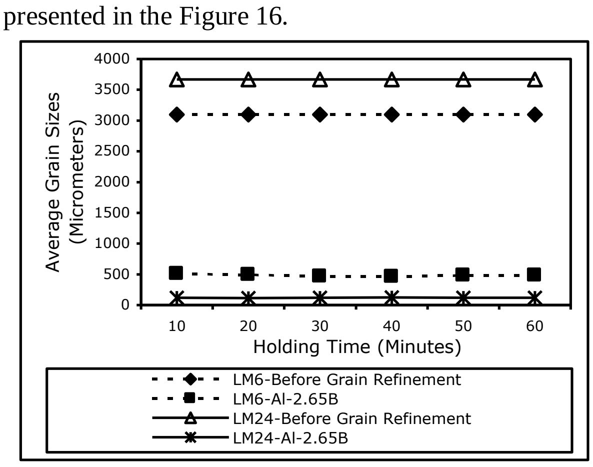


Fig 16 Graph showing Average Grain Sizes Vs Holding Time for LM6 and LM24 alloys grain refined by Al-2.65%B master alloy

It can be observed that the grain sizes of both alloys have decreased drastically by the addition of Al-2.65%B master alloy. It is also clear that, there is no fading effect of the master alloy in the melts held upto a holding period of sixty minutes. It is also apparent that the grain refining performance in LM24 alloy system is better than that in LM6 alloy system. This may be attributed to a relatively higher value of GRF for LM24 alloy (106.9302) when compared with LM6 alloy possessing a GRF value of 86.8817.

It is evident that, if only nucleating particles are responsible for grain refinement, then the extent of grain refinement that could be achieved by the addition of equal quantities of grain refiner to any two alloy systems must have been same.

But from the above results it is clear that even though the addition level of Al-2.65%B grain refiner is equal (0.6% boron) in both LM6 and LM24 alloy melts, the extent of grain refinement achieved in the two alloy systems are varying according to their GRF values. The average grain sizes in LM6 alloy possessing lower value of GRF (86.8817) is around 500 µm. On the other hand, the average grain sizes in LM24 alloy possessing comparatively higher value of GRF (106.9302) is around 120 µm. This observation indicates that though the additions of nucleating particles are very much essential for grain refinement the solute effects also play a vital role.

5. Conclusions

- Complete characterization of the fabricated Al-10%Ti master alloys gives an inference that, the $TiAl_3$ phase found in the master alloys can develop different crystal morphologies depending on their processing temperatures.

- From the grain refining performance tests, it was evident that the morphology of $TiAl_3$ particles present in Al-10%Ti master alloys has an influence on the efficiency of grain refinement. Further, it can be concluded that there lies a specific crystallographic relationship between blocky crystals of $TiAl_3$ and the aluminum matrix, which reduces the surface energy of the interface to facilitate nucleation of α-aluminum on blocky crystals of $TiAl_3$.

- The poisoning effect of the alloying elements such as Cu, Si, Zn, Mg, Fe and Ni in the decreasing degree of their poisoning effect is evident from the comparative grain refining studies of Al-Si alloys and high purity aluminum by the Al-10Ti master alloys. The poisoning behavior of the above mentioned alloying elements can be attributed to their atomic size mismatch with the solvent aluminum.

- In contrast to the literature [8], it is not a necessary criterion that only Al-4%B master alloy is required for effective grain refinement. And also a minimum of 0.03% boron addition level is essential for effective grain refinement.

- It can also be concluded from the comparative grain refining performances study that, an Al-B master alloy possessing AlB_2 phase is a powerful grain refiner for Al-7Si alloys compared to the other grain refiners namely; Al-10Ti or Al-5Ti-1B master alloys. In addition, it indicates the importance of the nucleating particles to be added for effective grain refinement rather than the addition of furthermore segregating elements.

- From the grain refining performance tests it is evident that the grain sizes in LM6, LM9 and LM24 alloy systems have reduced considerably by the addition of Al-10Ti master alloy.

- From the comparative analysis of grain sizes with respect to GRF it is evident that the extent of grain refinement in aluminum silicon alloy systems depends on the GRF value of the alloy system and the nucleating particles added.

- The Al-B master alloys are extremely powerful grain refiners for Al-Si alloys as evident from the comparative study on the grain refining performances of Al-10Ti and Al-2.65B master alloys.

- It is apparent that, though the nucleating effects are important in grain refinement, solute effects play a vital role.

6. References

1. *D.G. McCartney: "Grain Refining of Aluminium and its Alloys Using Inoculants", International Materials Reviews, 1989, Vol. 34, No.5, pp 247-260.*

2. *D. Apelian, G.K. Sigworth and K.R. Whaler: Transactions AFS, 1984, Vol. 92, pp 297-307.*

3. *George E. Dieter: Mechanical Metallurgy, Topic: 'Strengthening From Grain Boundaries' Metric edition, McGraw-Hill publications, 1988, pp 189-190.*

4. *K.T. Kashyap and T. Chandrashekar: "Effects and Mechanisms of Grain Refinement in Aluminium Alloys", Bulletin of Material Science, Vol. 24, No.4, August 2001, pp 345-353.*

5. *A Cibula: Journal Institute of Metals, 1949, Vol. 76, pp 321-360.*
6. *Mark Easton and David StJohn: "Grain Refinement of Aluminium Alloys: Part I. The Nucleant and Solute Paradigms – A Review of the Literature", Metallurgical and Materials Transactions. A., 1999, Vol. 30A, pp 1613-1623.*
7. *A. Cibula: Journal of Institute of Metals, 1951-1952, Vol. 80, pp 1-16.*
8. *J.A. Marcantonio and L.F. Mondolfo: "Grain Refinement in Aluminium Alloyed with Titanium and Boron", Metallurgical Transactions, 1971, Vol. 2, pp 465-471.*
9. *G.P. Jones and J. Pearson: "Factors Affecting the Grain-Refinement of Aluminium Using Titanium and Boron Additives", Metallurgical Transactions B, June 1976, Vol. 7B, pp 223-234.*
10. *G.K. Sigworth and M.M. Guzowski: Transactions American Foundrymen Society, 1985, Vol. 93, pp 907-912.*
11. *Mats Johnsson, Lennart Backerud and Geoffrey K. Sigworth: "Study of the Mechanism of Grain Refinement of Aluminium After Additions of Ti – and B – Containing Master Alloys", Metallurgical Transactions A, February 1993, Vol. 24A, pp 481-491.*
12. *L. Backerud and S.Y. Dong: Aluminium, 1991, Vol. 67, pp 910-915.*
13. *H.T. Wu, L.C. Wang and S.K. Kung: Journal Chinese Foundrymen's Association, 1981, Vol. 29, pp 10-18.*