

Mechanical Properties of Stir-Mixed SiC_p-Reinforced Aluminium Composites

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Abstract

Aluminium composites have found their strength in engineering applications such as automotive, electrical and light-weight applications. To achieve uniform microstructure and good mechanical properties, the fabrication techniques are prime factors in controlling wettability and porosity problems. This research therefore aimed for studying microstructure-mechanical property relation of SiC_p-reinforced 356 aluminium composites fabricated by a cost-effective stir casting process, to which three elemental additions, Al-5Ti-B, Sr, and Mg, were investigated. Furthermore, effects of SiC_p additions (0-15 wt.%) and T6 heat treatment (530 °C/12h + 155 °C/4 h) on mechanical properties of the composites were also studied. The 356 aluminium ingot was melted at 700 °C then stir-mixed with pre-heated SiC_p of 10.5 µm average size at 500 rpm, 615 °C prior to casting into cylindrical permanent molds at 650 °C. Microstructure examination along with hardness and tensile tests were carried out. The results showed that, with Mg and Al-5Ti-B and Sr additions, the optimum SiC_p addition was observed to be at 10 wt.% to achieve microstructure homogeneity beneficial for hardness and tensile properties.

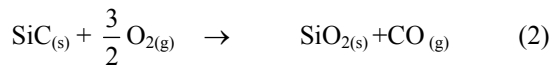
Introduction

Aluminium alloys are gaining more significance in engineering applications. This is viable in the automotive industry, where light - weight components are required to enable highest fuel efficiency consumption. Thus, many studies have been continuously attempted to improve mechanical properties of aluminium alloys, in search of composites suitable for specific engineering needs and to extend the boundaries on which aluminium alloys can be applied or substituted for other materials. In recent years aluminium composites have been considered as an alternative for property improvement such as higher strength, specific modulus and wear resistance. Mechanical properties of aluminium composites depend on important controlling parameters such as type, size, morphology, distribution and relative quantity of the reinforcing materials. Moreover, matrix structure such as grain

size, morphology of eutectic silicon and intermetallics also play important roles.⁽¹⁾

However, low wettability between reinforcing material and matrix makes it difficult for SiC_p to be distributed evenly throughout the aluminium matrix. Difference in the material's density also keeps them separated; Al = 2.7 g/cm³ and SiC_p = 3.22 g/cm³, leading to sedimentation problem.⁽²⁾ The distribution of SiC_p in the matrix using mixing blades depends on the characteristics of the blade as well as speed and time used for the mixing process.⁽³⁾

Furthermore, the formation of aluminium carbide (Al₄C₃) at Al-SiC_p interface, as shown in equation 1, is highly fragile and detrimental to mechanical properties. This can be prevented by creating SiO₂ buffer layer on the SiC_p surface, as expressed in equation 2.⁽⁴⁻⁵⁾



The SiO_2 layer also increases wettability by decreases contact angle between the aluminium melt and SiC_p .⁽⁶⁻⁷⁾ Magnesium, which is added to increase wettability, will also enhance the dispersion of SiC_p in the aluminium matrix and increase the stability of the SiO_2 layer at high temperatures.⁽⁴⁾ Additionally, aluminium melt treatments via grain refinement by adding Al-5Ti-1B or Al-3Ti-1B and modification through the addition of Sr at 0.058 wt.% aided mechanical property improvement.⁽⁸⁾ Post-heat treatment (T6) was reported to effectively increase hardness and strength.⁽⁹⁻¹⁰⁾ Since these aforementioned factors have been reported to be beneficial for composite properties, this research therefore investigated the summarized effects of the improvised techniques to improve mechanical properties of aluminium composites produced by stir-mixing process. Microstructure and mechanical property assessment was carried

out to identify factors influencing the properties of the composites.

Materials and Experimental Procedures

The commercial 356 aluminium alloy and SiC_p with an average size of 10.5 μm were used to produce the composite by using a cost-effective stir casting process, as shown in Figure 1. Silicon carbide was preheated at 1000 °C/4 h, cooled down to room temperature, and then reheated to 650 °C/1 h prior to mixing. Aluminium ingot was melted at 700 °C in a steel crucible, followed by mixing of 1 wt.% Al-5Ti-B, 0.06 wt.% Sr and 1 wt.% Mg according to experimental conditions, as listed in Table 1. The melt temperature was then decreased to 615 °C, followed by SiC_p addition and then stir-mixing was carried out at 500 rpm for 5 minutes. The mixture was re-heated up to 650 °C with constant stir - mixing for 10 minutes. The melt was poured into cylindrical permanent molds. T6 heat treatment was carried out for selected conditions by solution treatment at 530 °C/12 h and quenching in warm water at 70 °C before aging at 155 °C/4 h.

Table 1. Experimental conditions and properties.

No.	Experimental Condition					Property					
	Additions (wt.%)				T6-Heat Treatment	Theoretical Density (g/cm^3)	Measured Density (g/cm^3)	Hardness (BHN)		UTS (MPa)	
	Mg (1)	Al-5Ti-B (1)	Sr (0.06)	SiC_p				As cast	T6	As cast	T6
1	✗	✓	✓	0	✓	2.701	2.617	60.5	101.33	94.42	109.75
2	✗	✓	✗	10	✗	2.741	2.586	64.33	-	74.51	-
3	✗	✗	✓	10	✗	2.740	2.558	64.15	-	73.34	-
4	✗	✓	✓	10	✗	2.740	2.559	61.89	-	76.13	-
5	✓	✓	✓	10	✓	2.726	2.557	72.94	121.00	174.45	180.59
6	✓	✓	✓	15	✓	2.744	2.557	70.43	86.60	99.24	101.32



Figure 1. Equipment used for stir mixed casting.

Microstructure was analysed using a digital optical microscope coupled with an image analyser. Density was measured by Archimede's method. Brinell hardness test was carried out using samples being cut from top, middle and bottom parts of the castings. Tensile test was conducted using 12.5 mm. diameter and 62.5 mm. gauge length specimens operating at 0.5 mm./min crosshead displacement.

Results and Discussion

During the fabrication of the composite, it was evident that the SiC_p could not be incorporated well without Mg addition, as visible from SiC_p left-over, as shown in Figure 2a. Figure 2b signifies that there was less SiC_p segregation observed as 1 wt.% of Mg was added. The segregation of SiC_p from aluminium melt is a major threat in the production of SiC_p -reinforced aluminium composites, causing variation in the amount and distribution of SiC_p .

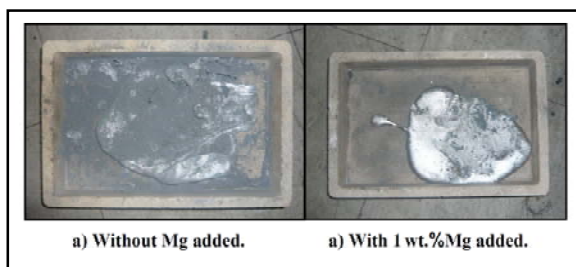


Figure 2. SiC_p left over.

Microstructure Analysis

Microstructure of SiC_p -reinforced aluminium composites consisted of hypoeutectic aluminium alloy and SiC_p , as shown in Figure 3. The distribution of SiC_p was present as SiC_p -clusters along with porosity areas. Microstructures of the composites without Mg addition, as shown in Figures 4a - 4c, appeared to have relatively larger SiC_p -clusters and porosity areas, giving non-uniform distribution of phases. Without Mg addition, individual additions of Al-5Ti-B or Sr or the combination of both only slightly altered the matrix structure in terms of refining and modifying effects respectively. However such additions did not provide positive effects on SiC_p incorporation. The composite microstructure with Mg addition, as shown in Figure 4d, revealed more uniform distribution of SiC_p in the aluminium matrix. There were also less SiC_p -clusters, which appeared in smaller sizes.

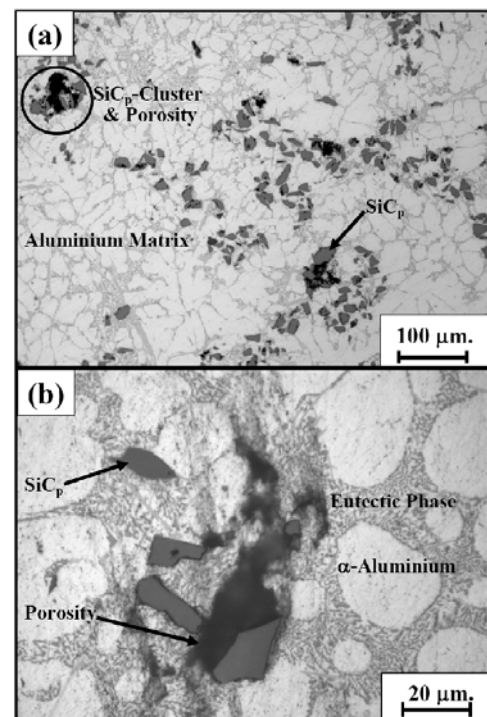


Figure 3. Microstructure of SiC_p -reinforced aluminium composite showing, a) at low magnification, and b) at higher magnification.

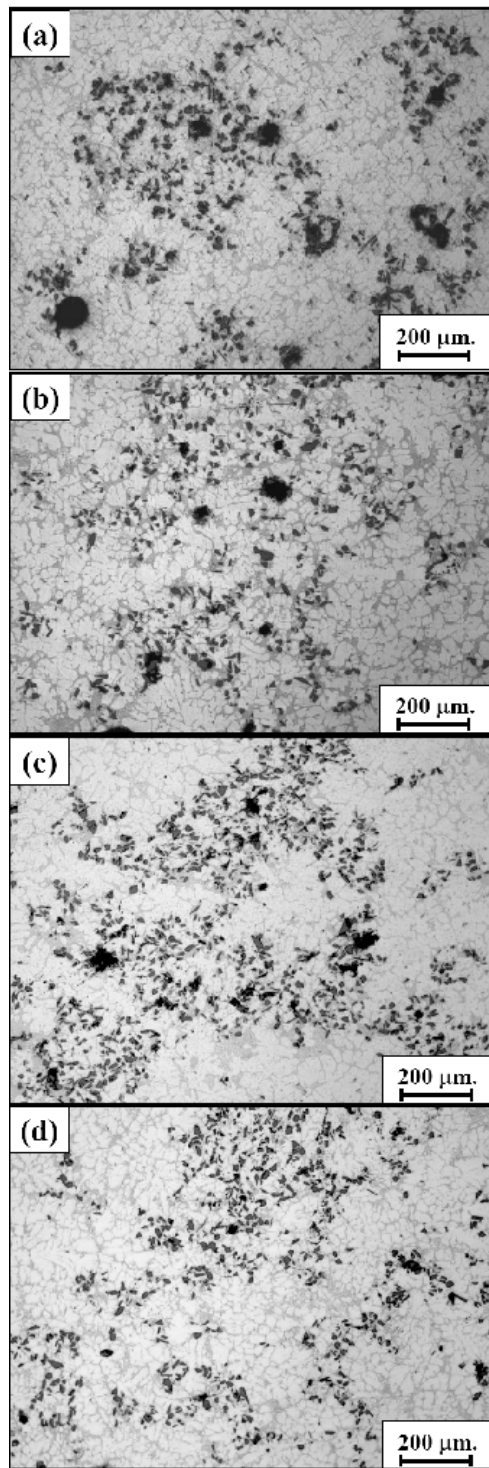


Figure 4. Microstructures of 10 wt.% SiC_p reinforced aluminium composites of, a) 1 wt.% Al-5 Ti - B, b) 0.06 wt.% Sr, c) 1 wt.% Al-5Ti - B, 0.06 wt.% Sr and d) 1 wt.% Al-5 Ti-B, 0.06wt.% Sr, 1wt.% Mg.

If the amounts of SiC_p addition are considered (0%, 10% and 15 % by weight, according to conditions 1, 5 and 6), as shown in Figures 5a - 5c, it can be seen that sizes and amounts of SiC_p- clusters are larger and more abundant in 15 wt.% SiC_p-Al composite. However higher porosity was observed with higher SiC_p addition. Phase analysis of the matrix, SiC_p and porosity using at least ten analyzed fields for each condition is illustrated in Figure 6. The analysis assumed the area fraction to be the volume fractions of the matrix, SiC_p and porosity. Without SiC_p addition, 0.89% porosity was observed. Higher amounts of porosity were obtained with higher SiC_p additions, especially in 15 wt.% SiC_p-Al composite, giving 3.16 % porosity.

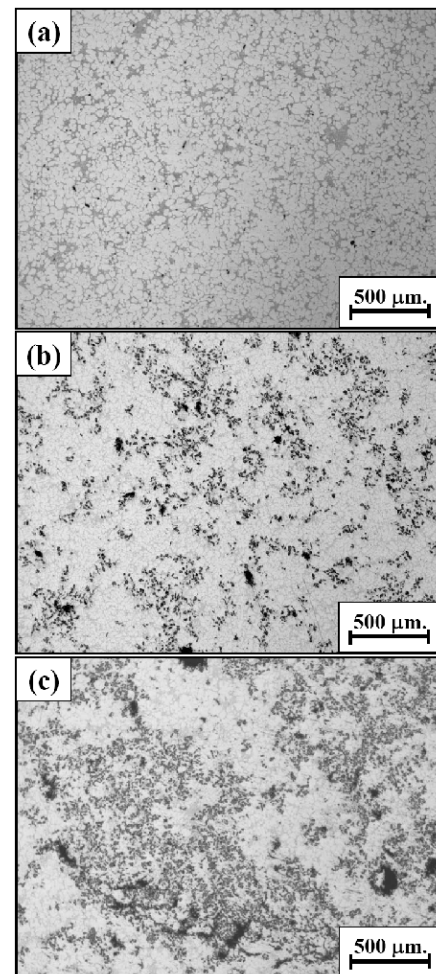


Figure 5. Microstructures of SiC_p - reinforced composites; a) 0wt.% SiC_p, b) 10 wt.% SiC_p, c) 15wt.% SiC_p.

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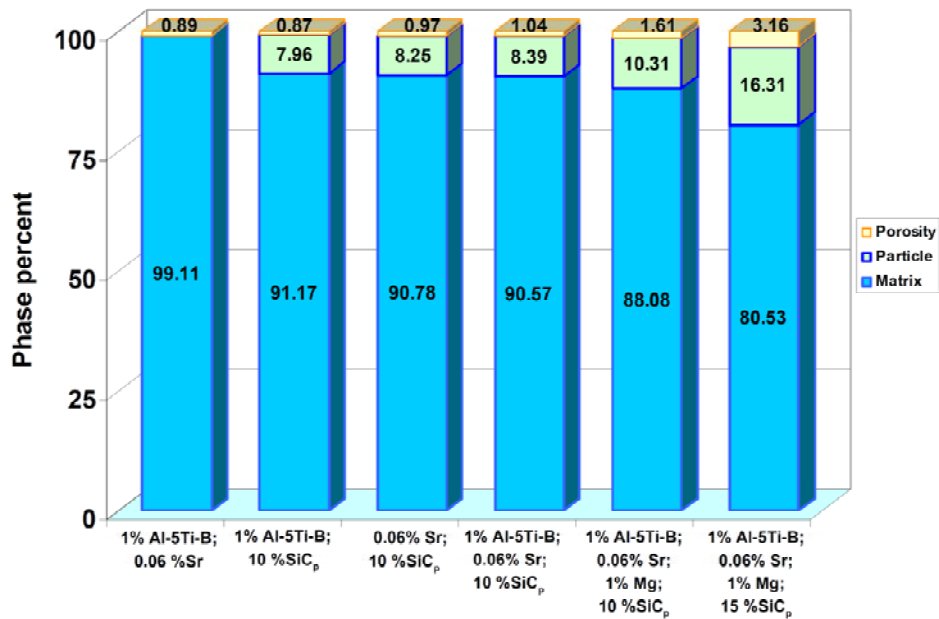


Figure 6. Phase analyses showing SiC_p, porosity and the matrix using image analyser.

If the rule of mixture is considered, the calculated porosity (%) can be obtained as shown in Figure 7. It can be seen that the calculated porosity is always higher than the analyzed porosity (obtained by phase analysis). The underestimated porosity obtained by 2D phase analysis is due to irregular shape of porosity, which is typical for the combination of gas and shrinkage porosity observed in the composites. Moreover the result also substantiated that Mg addition influenced the SiC_p incorporation, as demonstrated in test conditions 2-5 at 10 wt.% SiC_p

addition. It can be seen that individual additions of Al-5Ti-B or Sr or the combination of both (conditions 2-4) showed relatively lower amount of SiC_p, as compared with condition 5 (with Mg addition). The SiC_p left-over was evident, as previously shown in Figure 2a, even when enforcing with mechanical agitation. As the Mg was added along with Al-5Ti-B and Sr (conditions 5-6) the amount of SiC_p observed from composite microstructures became relative higher, enforcing better SiC_p incorporation.

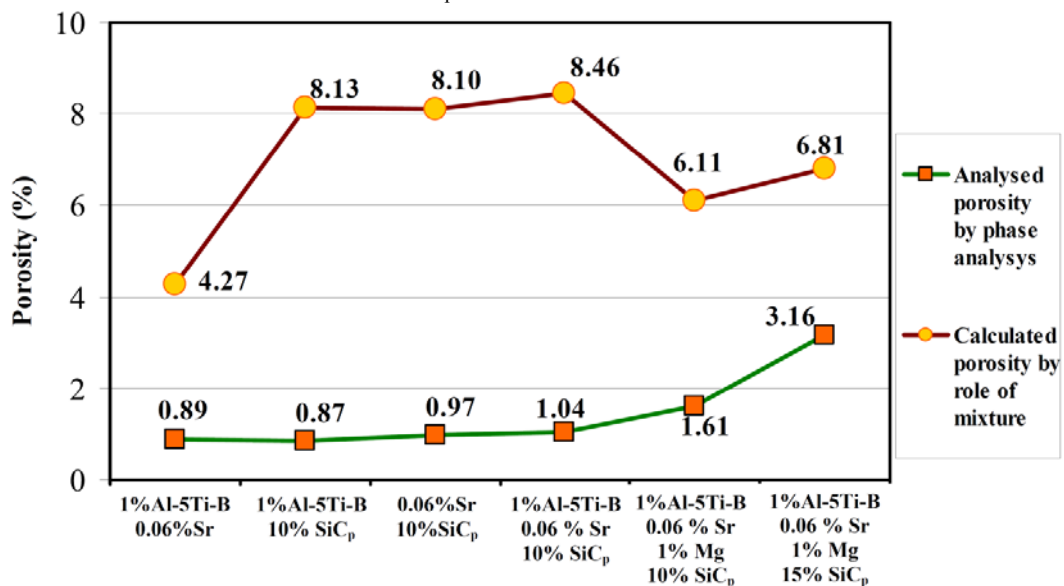


Figure 7. Analysed porosity and calculated porosity.

Density

According to the Archimedes's method, the result as illustrated in Figure 8 shows that the monolithic alloy (without SiC_p addition) has the highest density (2.586 g/cm³). Based on 10 wt.% SiC_p addition, the best density of 2.559 g/cm³ can be obtained by additions of Mg, Sr and Al-5Ti-B. Increment of SiC_p from 10 wt.% to 15 wt.% did not offer higher density as opposed to the intended purpose. This is expected to be due to the interference of porosity (3.16 %). It is noted that Mg addition provided the composites of higher density with smaller standard deviation; thereby, suggesting more uniform

distribution of SiC_p and porosity in this case. It can then be deduced that the addition of 1 wt.% Mg provided good SiC_p incorporation with the matrix by reducing the surface tension of the melt via increasing wettability between the particles and the molten aluminium. It has been reported by previous study⁽¹¹⁾ that the addition of lower surface tension Mg (0.599 Nm⁻¹) into aluminium melt of higher surface tension (0.817 Nm⁻¹) would reduce surface energy from 680 dyn.cm⁻¹ to 650 dyn.cm⁻¹. It was therefore confirmed according to this experiment that 1wt.% Mg addition provided more efficient control of the amount of reinforcing material being mixed in the molten matrix.

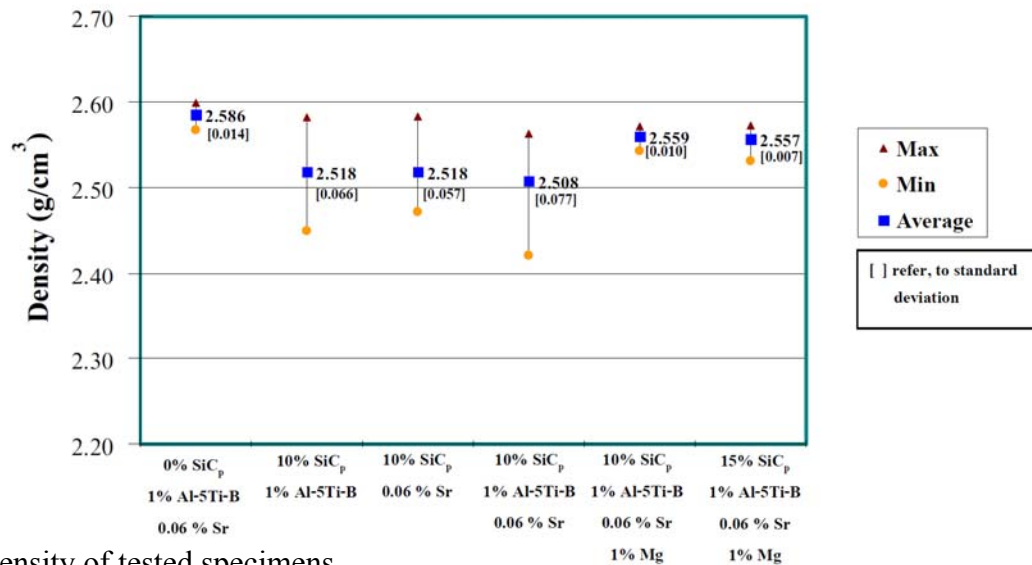


Figure 8. Density of tested specimens.

Hardness and Tensile Tests

Hardness and tensile strength results are illustrated in Figure 9. In case of 10 wt.% SiC_p addition, the composites with additions of Al-5Ti-B or Sr alone or both offered lower Brinell hardness than those with Mg, Al-5Ti-B and Sr additions. The similar effect of Mg addition was also obtained in tensile strength result, giving the highest value of 174.45 MPa in comparison to the tensile strength of 74.51-76.13 MPa obtained in other conditions without Mg addition. Better hardness (72.94 BHN) and ultimate tensile strength (174.45 MPa) of 10 wt.% SiC_p composite

with Al-5Ti-B, Sr and Mg additions are associated with uniform distribution of SiC_p and finer SiC_p clusters.

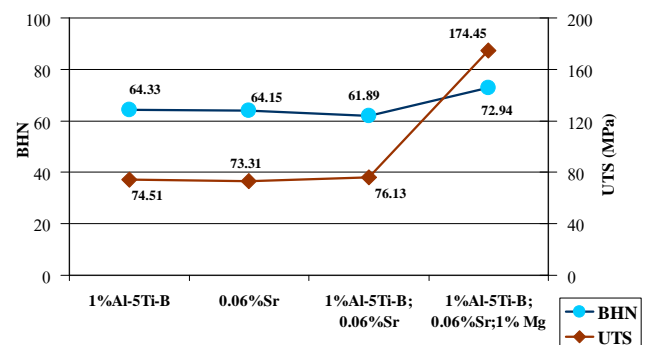


Figure 9. Brinell hardness and tensile results of 10 wt.% SiC_p-reinforced aluminium composite.

Brinell hardness and tensile strength results, according to Figures 10 and 11 demonstrated the effect of T6-heat treatment. The optimum SiC_p addition appeared to best at 10 wt.%. T6-heat treated SiC_p-Al composites provided significantly higher Brinell hardness values than those obtained in the as cast condition, due to precipitation hardening. Increment of 66% in hardness was obtained from T6 heat-treated 10 wt.% SiC_p-Al composite whereas significantly lower hardness increment (22.96 %) was obtained from T6 heat-treated 15 wt.% SiC_p-Al composite, as shown in Figure 12. This property degradation is due to the influence of higher porosity observed in the latter case. The effect of T6 heat treatment on tensile strength was however less pronounced. Only small increments in tensile strength were obtained. Therefore the effect of porosity seemed to be more harmful in the case of subjecting to tensile loading than in case of hardness (indentation).

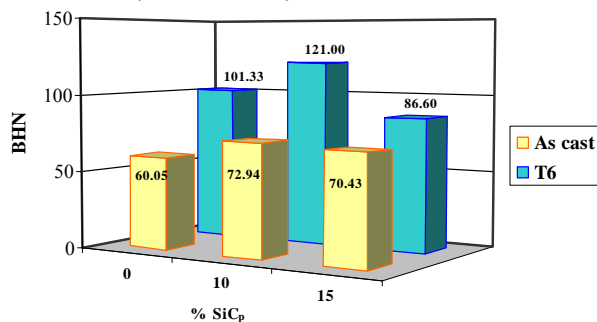


Figure 10. Brinell hardness of SiC_p-reinforced aluminium composite in as-cast and T6 heat-treatment conditions.

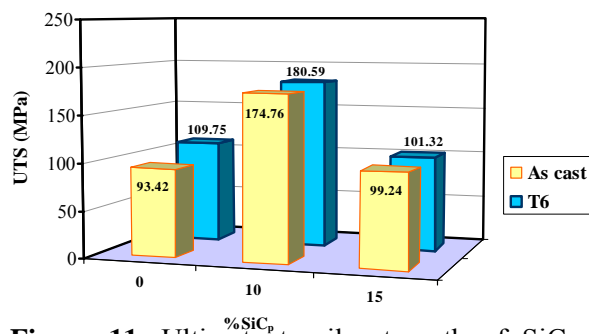


Figure 11. Ultimate tensile strength of SiC_p-reinforced aluminium composite in as-cast and T6 heat-treatment conditions.

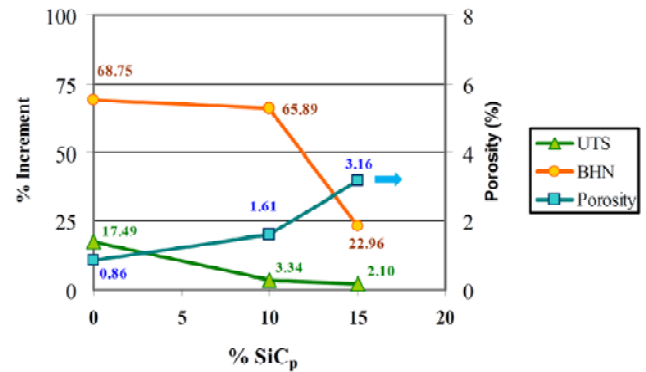


Figure 12. Increment of BHN and UTS versus Porosity after T6-heat treatment.

Effect of Mg, Al-5Ti-B and Sr Additions

According to experimental results, it can be seen that Mg addition has pronounced effects on microstructure and properties of SiC_p-Al composites, while additions of Al-5Ti-B and Sr alone did not provide significant improvement. Promotion of wettability via Mg addition allowed better SiC_p distribution, reduced size of SiC_p clusters, and more significantly aided better SiC_p incorporation with the least amount of SiC_p left-over, as previously shown in Figure 2. The additions of Sr and Al-5Ti-B without Mg however caused poorer distribution of SiC_p and larger SiC_p-clusters in numerous numbers observed in the composite microstructures.

Previous studies⁽¹²⁻¹³⁾ have indicated that more uniform SiC_p distribution and better SiC_p incorporation were obtained via Sr addition, as an active alloying element. The Al-Si matrix was modified by producing a transient layer between SiC_p and the liquid,⁽¹²⁾ allowing enhanced wettability. It was explained that Sr is an oxygen scavenger and trapped air layer was then consumed. Thereby, this prevented interfacial segregation and resulted in wettability improvement. In the case of grain refiner addition,⁽¹⁴⁾ it was indicated that the distribution of SiC_p was more uniformed with Al-5Ti-B addition. Since

SiC_p was rejected to the liquid at the moving solid/liquid interface as the solidification proceeded, finer primary α structure therefore relocated the SiC_p clusters in to smaller sizes. Though the previous studies⁽¹²⁻¹⁴⁾ confirmed promising results for Sr and Al-5Ti-B additions, this current investigation suggested parallel result only when Mg was added. Therefore Mg addition was considered as the first priority for SiC_p incorporation via wettability improvement and the additions of Sr and Al-5Ti-B later became significant.

Effect of SiC_p Addition on the Presence of Porosity

For the fabrication of SiC_p-Al composite via stir casting process, there are factors causing gas/shrinkage porosity in the castings such as i) adsorbed moisture and gas on SiC_p surface,⁽¹¹⁾ ii) dissolved hydrogen in aluminium melt,⁽¹⁵⁾ iii) air entrapment during mixing,⁽¹⁶⁻¹⁷⁾ iv) solid fraction of the mixture,^(16,18) and v) solidification shrinkage.⁽¹⁷⁾ In the case of gas porosity, the adsorbed moisture and gas on SiC_p surface, dissolved hydrogen in aluminium melt and air entrapment during mixing are considered. The adsorbed moisture on SiC_p surface was expected to be reduced due to surface treatment of SiC_p at 1000 °C/4h and reheating at 650 °C just before mixing. The dissolved hydrogen in the molten aluminium might be low when the ingot was utilized. Therefore, the trapped gas was believed to be the dominant factor in producing gas porosity in this case. Manual addition of SiC_p into the aluminium melt already made SiC_p agglomeration due to high surface area of the micron sized SiC_p and this then caused gas-trapped porosity in the solidified composites.

In the case of shrinkage porosity, solid fraction greatly influenced melt feeding during solidification. At the SiC_p mixing temperature of 615 °C, the aluminium melt would already

contain approximately 15.78 % of solid α aluminium phase, and the viscosity of the melt would be approximately 1.8×10^{-2} Pa.s.⁽¹⁸⁾ When the pre-heated SiC_p (650 °C) was introduced into the melt, the melt temperature remained more or less constant at 615 °C. However the viscosity of the mixture became higher due to increasing solid fraction of the mixture. This consequently made mixing more difficult when the SiC_p content increased. It has been proposed that during the solidification of long-freezing range alloys, SiC_p and gas bubbles were pushed away from solidifying front of the aluminium matrix.^(16, 21) As the melt temperature approached the eutectic temperature, remaining interdendritic liquid started to form eutectic structure and shrinkage porosity will result,⁽¹⁶⁾ if melt feeding was insufficient. Consequently, the presence of SiC_p caused higher melt viscosity due to higher solid fraction and angular shape of SiC_p.⁽¹⁹⁾ Melt feeding might be therefore obstructed because of SiC_p agglomeration in front of the solidified matrix and higher mixture viscosity. These in turn resulted in higher degree of solidification shrinkage in the presence of SiC_p. This can be evident from Figure 3, which shows agglomeration of SiC_p in front of primary aluminium, observed along with gas and shrinkage porosity surrounded by eutectic structure.

In many cases, shrinkage porosity was found to be associated with gas porosity. The reduced solubility of hydrogen with decreasing temperature allowed H₂ gas to form in the remaining liquid. Together with trapped air and H₂ gas, the SiC_p was also pushed away from the moving solidifying front, resulting in a combination of gas-shrinkage porosity and SiC_p clusters as the normal event observed in this investigation.

As the shrinkage/gas porosity and SiC_p were formed very late in the solidification process⁽¹⁶⁻¹⁷⁾ the refining and

modifying effects of the matrix structure helped to reduce the SiC_p of shrinkage/gas porosity and SiC_p clusters and aided melt feeding. This resulted in more uniform SiC_p distribution. It is further noted that the stirring speed and equipment used in this experiment might not be sufficiently effective to separate SiC_p clusters into individual SiC_p during mixing. Moreover, the stirring efficiency was reduced with distance further away from the mixing blade.⁽²⁰⁾ The melt viscosity also prohibited relocation of SiC_p and trapped gas porosity. This resulted in large groups of SiC_p-porosity clusters.

It can be seen so far that the presence of SiC_p not only supported shrinkage formation, but also triggered heterogeneous nucleation of pores.⁽²¹⁾ Greater amounts of SiC_p facilitated the formation of shrinkage/gas porosity to occur more readily, as shown in Figures 6 and 7. Thus, the addition of SiC_p at 10 wt.% was more beneficial for density and hardness property improvement than 15 wt.% SiC_p addition in this case.

Conclusions

Experimental results showed that the additions of Sr and Al-Ti-B without Mg caused poor distribution of SiC_p and large SiC_p-clusters in numerous numbers observed in the microstructures of the composites. The addition of Mg helped to improve wettability and offered better distribution of SiC_p in the aluminum matrix as well as reduced the size and amounts of SiC_p-clusters. The speed and duration of the stir mixing process could only distribute SiC_p-porosity cluster, but could not divide SiC_p clusters into individual particles. Finally, the T6-heat treatment provided improvement in the tensile strength and more significantly in hardness property of the composites. Porosity appeared to be a prime factor causing property degradation.

Acknowledgments

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