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THE PRODUCTION OF CAST METAL MATRIX COMPOSITE BY A MODIFIED STIR CASTING METHOD

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Abstract. In a normal practice of stir casting technique, cast metal matrix composites (MMC) is produced by melting the matrix material in a vessel, then the molten metal is stirred thoroughly to form a vortex and the reinforcement particles are introduced through the side of the vortex formed. From some point of view this approach has disadvantages, mainly arising from the particle addition and the stirring methods. During particle addition there is undoubtedly local solidification of the melt induced by the particles, and this increase the viscosity of the slurry. A top addition method also will introduced air into the slurry which appears as air pockets between the particles. The rate of particle addition also needs to be slowed down especially when the volume fraction of the particles to be used increases. This is time consuming for a bigger product. This study propose a new approach of producing cast MMC. When all substances are placed in a graphite crucible and heated in an inert atmosphere until the matrix alloy is melted and then followed by a two-step stirring action before pouring into a mould has advantages in terms of promoting wettability between the silicon carbide particle and the A359 matrix alloy. The success of the incorporation of silicon carbide particles into the matrix alloy showed that the wettability between silicon carbide particles and mechanical properties such as hardness and tensile strength are comparable with previous data produced by other researchers.

Keywords: Metal matrix composite, stir casting, wettability, hardness, tensile strength, particle distribution.

Abstrak. Dalam praktik biasa teknik tuangan kacau, komposit matriks logam dihasilkan dengan cara meleburkan bahan matriks dalam suatu bekas kemudiannya leburan logam ini dikacau dengan kuat untuk membentuk vorteks dan bahan tetulang partikel dimasukkan melalui bahagian tepi vorteks yang telah terbentuk. Daripada satu sudut pandangan pendekatan ini mempunyai kekurangan, yang timbul daripada kaedah memasukkan partikel dan kaedah pengacuan. Semasa penambahan partikel ini dilakukan akan berlaku pemejalan setempat dalam leburan tersebut yang teraruh oleh partikel, dan ini akan meningkatkan kelikatan buburan tersebut. Kaedah penambahan partikel melalui bahagian atas ini juga akan memasukkan udara ke dalam buburan yang muncul sebagai poket udara di antara partikel tersebut. Kadar penambahan partikel ini juga perlu diperlahankan terutamanya apabila terdapat peningkatan pecahan isipadu partikel yang digunakan. Proses ini akan memakan masa yang lama terutamanya untuk produk yang lebih besar. Kajian ini mencadangkan satu pendekatan baru untuk menghasilkan tuangan MMC. Apabila semua bahan dimasukkan ke dalam mangkok grafit dan dipanaskan dalam atmosfera lengai sehingga aloi matriks menjadi lebur dan kemudiannya diikuti dengan tindakan kacauan dua-langkap sebelum penuangan ke dalam acuan, mempunyai kelebihan daripada segi menggalakkan kebolehbasahan di antara partikel silikon karbida dengan aloi A359 aloi matriks. Kejayaan penambahan partikel

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silikon karbida ke dalam aloi matriks telah menunjukkan bahawa kebolehbasahan di antara partikel silikon karbida, dan sifat mekanikal seperti kekerasan dan kekuatan tegangan adalah setanding dengan data sebelumnya yang dihasilkan oleh penyelidik lain.

Kata kunci: Komposit matriks logam, tuangan kacau, kebolehbasahan, kekerasan, kekuatan, penyebaran partikel

1.0 INTRODUCTION

Considerable research from all over the world has been devoted to metal matrix composite (MMC) research over the past few decades involving a broad area of MMC fabrication. In any type of the fabrication method used, wettability and distribution of the reinforcement material in the alloy matrix are among the main problems. Many methods have been proposed to overcome this situation. However ideas normally suitable for the preparation of materials and their use may not be suitable for different approaches.

In general stir casting of MMC involves producing a melt of selected matrix material followed by the introduction of reinforcement material into the melt and the dispersion of the reinforcing material through stirring. Stirring is carried out vigorously to form a vortex where the reinforcing particles are introduced through the side of the vortex. The formation of the vortex will drag not only the reinforcement particles into the melt, but also all impurities which are formed on the surface of the melt. The vortex will also entrap air into the mould which is extremely difficult to remove as the viscosity of the slurry increase.

In this approach of fabricating cast MMC, magnesium was used as a wetting agent and two stirring steps in which the MMC slurry in the semi-solid condition was applied in order to enhance wettability between the silicon carbide particles and matrix alloy. The emphasis was on the wettability and chemical reaction between the substances. The MMC produced by using this approach was evaluated in term of microstructure observation and mechanical testing such as hardness and tensile testing.

2.0 EXPERIMENTAL PROCEDURE

2.1 Material

The aluminium alloy A359 was used as a matrix material and silicon carbide was added as reinforcement particles. The A359 aluminium alloy, silicon carbide particles and magnesium powder were supplied by the Aluminium Powder Company

Table 1 Chemical Analysis A356 Alloy Matrix – wt% (from Supplier)

Si	Mg	Cu	Al
8.5 – 9.5	0.55 – 1.2	<0.03	Balance

Table 2 Properties of SiC Particles and Mg Powder Used (from suplier)

Material	**Hardness [Vickers]**	**D_{50}APS* [Microns]**	**Chemical analysis [wt %]**					
SiC	2800 – 3300	29.2	SiC	SiO_2	Si	Fe	Al	C
			98.73	0.48	0.3	0.09	0.1	0.3
Mg	–	256	Mg	O_2				
			99.79	0.1				

*D_{50}APS = Average Particle Size which is based on the cumulative frequency size distribution.

Limited, UK. The properties of these materials are shown in Tables 1 and 2, whereas the thermal properties are shown in Table 3. Magnesium is a well-known wetting agent used to promote the wetting of the ceramic by the liquid alloy.

Table 3 Thermal Properties of A359 Alloy and SiC

Properties	**A359**	**SiC**
Thermal conductivity [W/m°K]	152.0	83.6
Specifiec gravity [g/cc]	2.68	3.21
Liquidus temperature [°C]	600	–
Solidus temperature [°C]	565	–
Coefficient of Thermal Expansion [$\times 10^{-6}$/K]	20.9	4

2.2 Fabrication Method

The A359 alloy was placed into a specially designed rig with bottom pouring mechanism as shown in Figure 1. 1 wt% of magnesium particles was used as a wetting agent and the amount of silicon carbide particles used in each MMC was varied from 5 to 25 vol%. A J-type thermocouple was inserted to give a feedback of the temperature inside the rig, and the nitrogen gas was set to flow continuously at a rate of 3 cc/min. The temperature inside the rig was controlled below 7500°C in order to minimise the chemical reaction between substances. Two stirring steps were used to disperse the silicon carbide particles in the matrix alloy. For the first step the stirring took place when the slurry was in a semi-solid condition, and the second step when the slurry was re-melted to a temperature 50–70°C above liquidus to make sure the slurry was fully liquid. The stirring was continued before the composite is poured in a mould made of graphite with a mould cavity of 20 mm diameter and 150 mm long. In order to minimise gas entrapment in the molten matrix during stirring, the stirring speed and the stirrer location was placed at a specific location based on

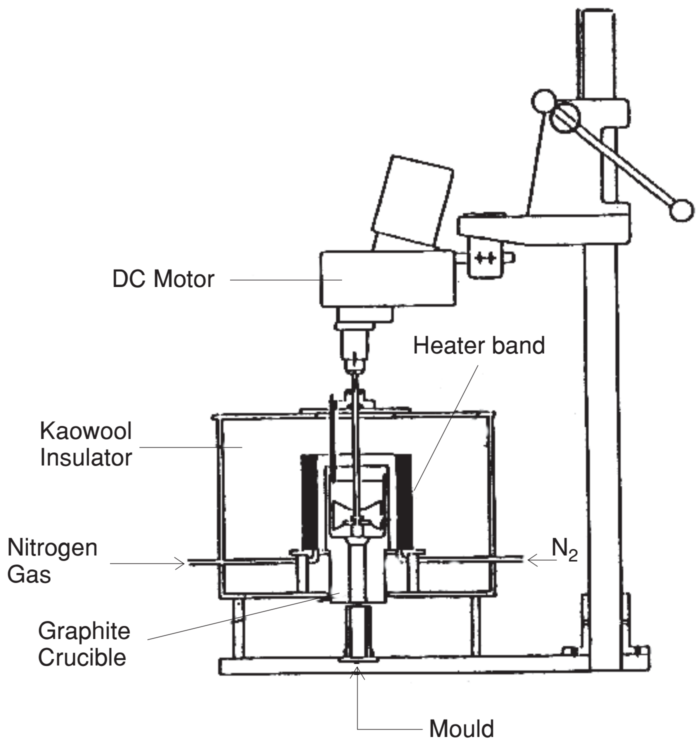

Figure 1 Rig Used to Produce Cast MMC

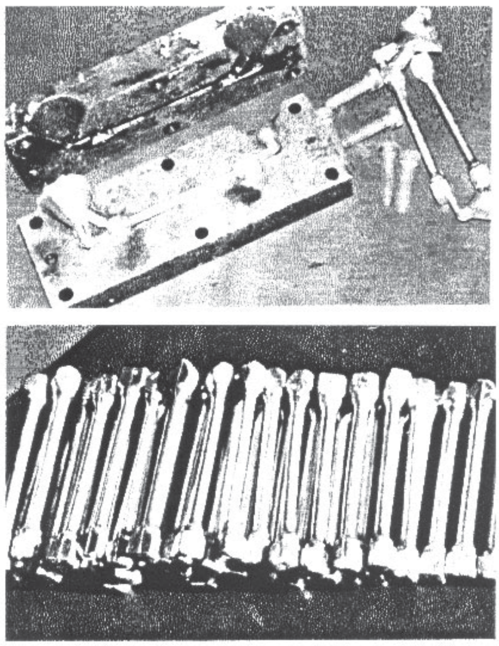

Figure 2 Mould Used and Tensile Specimens Produced

result of computer simulation which has been done previously. The details of the simulation have been published elsewhere [1]. The stirring speed used was 100 rpm and the stirrer was placed a distance of 20% from the bottom of the rig.

2.3 Specimen Preparation

Metallographic preparation of particle-reinforced MMC was quite a challenge, as the reinforcement particles are very hard and fragile compare to the matrix materials. This combination of hard and soft materials makes it difficult to avoid damages like cracks and broken reinforcement particles, and relief the particle and soft matrix during preparation. Silicon carbide paper is often used for grinding of metals, and this must be avoided when the MMC is reinforced with silicon carbide particles. This is because the soft matrix will quickly be removed whereas the silicon carbide particles will in general remain intact. Plane grinding was performed on a TEXMET grinding disc 30 μm diamond. This grinding was done manually and only a very light pressure was applied. The plane grinding took about 5–10 minutes. This was followed by fine grinding using TEXMET grinding disc with 9 μm, 6 μm, 3 μm and 1 μm diamond suspended in water as lubricant. Scratches as a result of silicon carbide particles during polishing sometimes are unavoidable. Micro hardness testing was carried out on polished specimens and hardness was measured as a function of the ingot length.

Normally tensile specimens may be produced by machining or turning on a lathe from an ingot to the desirable shape or dimension, by following a certain standard. However, for MMC materials machining is a great challenge. Therefore it is advantages if this tensile specimen of MMC is fabricated directly from casting so the machining process can be minimised. In this study the tensile specimen were produced directly from casting. The mould used and specimens produced are as shown in Figure 2. The dimensions of the sample used in the present work followed MPIF Standard no.10 which is comparable to ASTM B783, ASTM E8 and ISO 2740.

3.0 RESULTS AND DISCUSSION

The foundry technique is seen to be the cheapest method of producing MMC compared to other methods such as powder metalurgy, and the size of the product limited to 500 kg [2]. However the main MMC fabrication problems such as wettability between substances, the chemical reaction between them, the distribution of the reinforcement particles in the matrix and also the porosity content in the matrix still remain and research continues aiming to solve them. In normal stir casting technique, cast MMC is produced by melting the matrix materials then the molten metal is stirred thoroughly to form a vortex and the reinforcement particles are introduced through the side of the vortex formed. Research related to this type of cast MMC producing method is broad and still going on. However the main approach used remains the same as mentioned above. From other point of view, this approach of producing MMC by stir casting has disadvantages, mainly rising from the particle addition and the stirring method. Particles will induced local solidification to the molten matrix and this increase the viscosity of the slurry. A top addition method and the vortex formation will introduce air into the slurry. The rates of particle also need to be slowed down, especially when the volume fraction of the particle to be used increase. This is time consuming for a bigger product.

Placing all substances in a graphite crucible and heating in an inert atmosphere until the matrix alloy is melted, has advantages in terms of promoting wettability between silicon carbide particles and the matrix alloy. In general the wettability between a ceramic an a metallic melt is poor. In this research the wettability enhancement was done by using magnesium as a wetting agent, and the silicon carbide particles were also heat treated during the fabrication process. These two combined methods of enhancing the wettability seem to give a very good wettability between silicon carbide particles and the matrix alloy. In completely liquid state the mechanical stirring mixes the particle into the melt but when the stirring is stopped the particle return to the surface. However, stiring the MMC slurry in a semi-solid state at a temperature within the solidification range of the alloy matrix helps to incorporate the ceramic particles into the alloy matrix. In the semi-solid state, primary alpha-aluminium phase exist, and the stirring action assists this solid phase to trap the silicon carbide particle between the dendrite arms, thus stopping them from settling. In other words, the growing solid phase helps to drag the ceramic particles into the alloy matrix. However, in the semi-solid state the slurry cannot be poured into the mould because at this stage its viscosity is very high and the fluidity is very low. Therefore before pouring the slurry into the mould, it is necessary to re-melt it to a fully molten condition, and re-stir before pouring. The re-stirring process will help to disperse the silicon carbide particles to a more uniform distribution.

3.1 Microstructural Analysis

The microstructure of A359 alloy is composed of an aluminium matrix containing eutectic silicon. In general the eutectic silicon is not uniformly distributed, but tends to be connected at inter-dendiritic boundaries. Figure 3 shows the microstructure of A359 alloy in the as-cast condition. It can be seen that the eutectic silicon is not uniformly distributed and most of silicon accumulated at the grain boundaries. The silicon carbide particles were observed to be accommodated on the grain boundries as shown in Figure 4. In can also be seen that the aluminium grain structure is equaixed in shape. This is attributed to the effect of stirring action in the semi-solid condition. This stirring action breaks the dendrite shaped structure and leaves the structure in equaixed form.

Another important aim of microstructural observation in the case of non-reinforcement and reinforced samples investigated in the present study, was to quantify

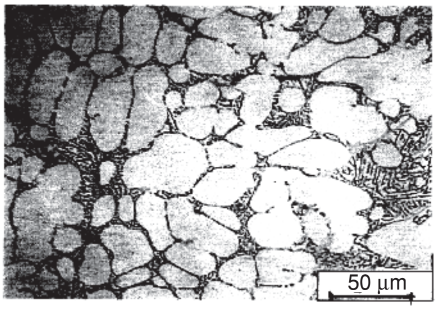

Figure 3 Microstructure of A359 Matrix Alloy as-cast Conditon Showing Eutectic Si between Grain of α-Al

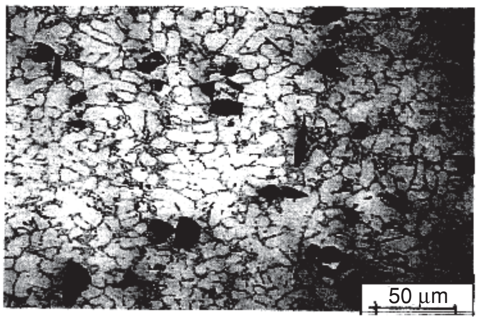

Figure 4 Microstructure of A359/SiC/5p cast MMC

particle distribution in-homogeneities. The simplest approach was to consider the number of particles in a fixed test area [3–5]. Some researchers have attempted to do this by visual inspection [6]. In this study visual inspection method was used. It can be seen that the composite materials made by the investigated processing technique had a cast microstructure of the matrix with particle distributed homogeneously. Relatively uniform distribution was observed in almost all the composites produced. However, there are some particle-free zones due to particle pushing effects during solidification and some particle agglomeration.

It has been reported that the presence of foreign particles, fibres or other constraint significantly affects the solid-liquid interface morphology and microstructure [7–9]. For example the cellular-dendritic solid-liquid interface of an Al-2%Mg alloy was highly disturbed by the presence of silicon carbide [8], and the orderly directional microstructures of aluminium-silicon alloy were also disrupted by the entrapment of silicon carbide [2].

3.2 Micro Hardness

Theoretically the hardness of the cast ingot should be uniform from the top to the bottom of the ingot. This is, if the distribution of the particles throughout the ingot is uniform. However, other factors such as cooling rate, gravity effect and non-uniform distribution of the particles in the ingot will give different values of hardness. The experimental data shows that the hardness of the ingot is lower at the top and at the bottom of the ingot, and it is higher in the middle. 13 ingots have been tested, and all of them gave an identical trend. The results of Vickers micro hardness testing are shown in Figure 5 as a function of distance from the top to the bottom of the ingot (referring to the original position of the ingot during pouring).

In this experiment it was found that the value of hardness of A359 matrix alloy in as-cast condition is 68.22Hv. Comparing to the hardness between three different composite ingot as shown in Figure 5, it was found that the maximum value is at the middle part of composite. For example the hardness of A359/SiC/5p, A359/SiC/15p and A359/SiC/25p at the top, middle and bottom of the ingot is shown in Table 4 and presented in a graphical form as in Figure 5.

Table 4 Micro Hardness Value as-cast Condition for Three MMC Ingots

Ingot's Position	Hardness [Hv]		
	A359/SiC/5p	A359/SiC/15p	A359/SiC/25p
Top	88.9	75.4	79.5
Middle	116.5	104.3	90.2
Bottom	84.4	87.5	82.1

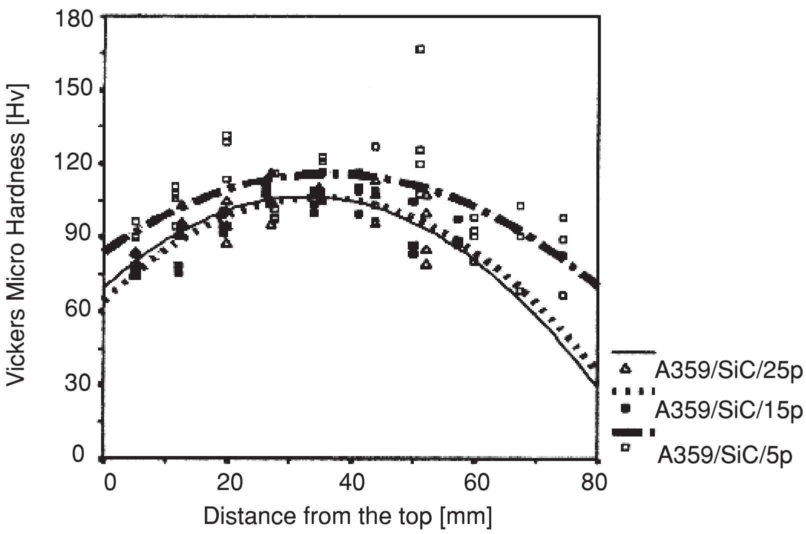

Figure 5 Micro Hardness as a Function of Ingot's Distance from the Top

The variation of the hardness values in the ingot is possibly attributed to the non-distribution of the silicon carbide particle in the ingot. Because of the pouring method used in this experimental rig, the first drop of slurry occupied the bottom part of the mould, and therefore contains less particle. Because the size of the mould was not too big, this part of ingot will also solidify first and prevent the silicon carbide particles from settling to the bottom. The settlement of the silicon carbide particles occurs in the middle part of the ingot. The top part contain less silicon carbide particle than in the center part. The high concentration of silicon carbide particles in the center part of the ingot may be the reason why the hardness at this part is maximum compared to the very top or bottom parts of the ingot. This is shown in

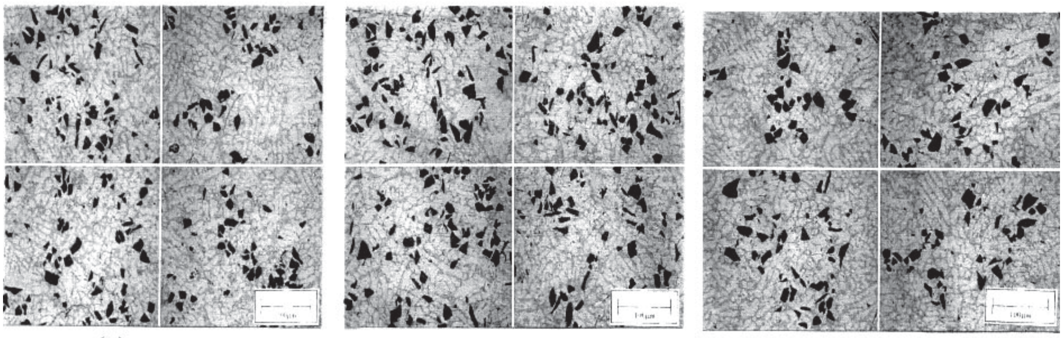

Figure 6 The Variation of Distribution of Silicon Carbide Particles in 150 mm Long A359/Sic/15 Composite Ingot (a) 5 mm from the Top, (b) at the Middle (c) 5 mm from the Bottom

Figures 6(a)(b)(c) for A359/SiC/15p composite. The concentration of the silicon carbide particles at the top, middle and the bottom of the ingot is 60, 95 and 50 percent of micrograph size respectively. The measuring method to determine particle concentration has been publish elsewhere [10].

The settlement of particles in the melts already starts to occur when the melts is still in the crucible. This is because the specific gravity of the reinforcements is higher than that of the molten alumunium, which leads to settling or sedimentation of the particle reinforcements. Sedimentation of silicon carbide particle from the top part of the crucible normally occurs when the stirring is stopped, leaving the upper regions of the melt become devoid of the reinforcement. This phenomenon can result in less particles being contained in the first drop of slurry which occupied the bottom part of the mould.

3.3 Tensile Strength

In this study the experimental result shows that in general the tensile strength of the MMC's produced are somewhat higher than that obtained for the non-reinforced A359 alloy. It can be noted that the addition of silicon carbide particles improved the tensile strength of the composites. It is apparent that an increase in the volume fraction of silicon carbide particle results in an increase in the tensile strength. Figure 7 shows the effect of the volume fraction on the tensile strength. The tensile strength of A359 alloy in non-reinforced condition in 103.73 Nmm^2, and this value increases to a maximum of 150 N/mm^2 for A359/SiC/10p which is about 65% improvement on that of the non-reinforced matrix material. The tensile strength obtained in this study is comparable to results from other researchers. This is summarised in Table 5.

Surface topography viewed from scanning electron microscope of the tensile fracture surface shows that the main reason for the fracture occurring at that specific location was agglomeration of silicon carbide particles and porosity. This is as shown

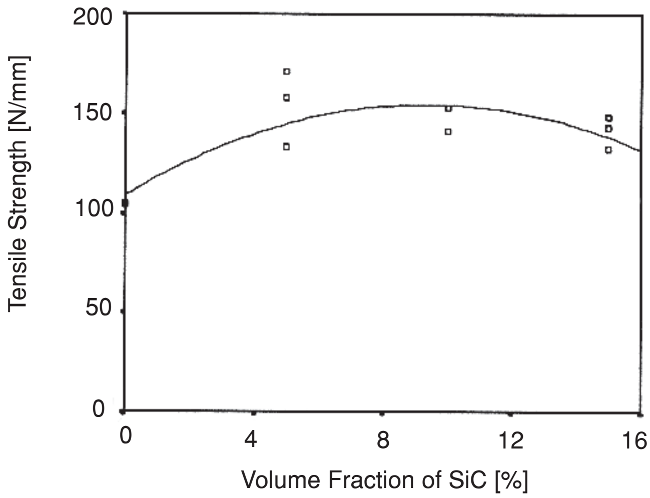

Figure 7 Tensile Strength as a Function of Volume Fraction of Silicon Carbide Particle

Table 5 Tensile Strength for Some Aluminium-Silicon Alloy Based MMC Produced by Casting Technique

Researches	Cast MMC system	Tensile Strength (MPa)
Present study	A359/SiC/10p	150
Samuel et al. [10]	A359/SiC/10p	115
Paray et al. [11]	A359/SiC/10p	105
Shivkumar et al. [12]	A359/SiC/5p	95.7

in Figure 8. Agglomeration of particles reduced the strong bond between matrix alloy and silicon carbide particles. In the study of McDaniels [11] it was found that in the silicon carbide particle reinforced aluminium alloy containing beyond approximately 30-40 volume fraction of silicon carbide, the rate of increase in strength with volume fraction decreases. Moreover, when the reinforcements cluster, the matrix material between individual reinforcement does not bond well. During subsequent deformation these interfaces are likely to separate.

The embedded hard particles in the matrix act as barrier that resists the plastic flow of composites when it is subjected to strain. This can explain the improvements of the tensile properties in silicon carbide composites and other mechanical properties such as compression strength and hardness. The presence of hard particle in a soft matrix increases the dislocation density. It was reported that Al-SiC composites have higher dislocation density that those of Al/Al_2O_3 composites [11]. The introduction of silicon carbide particles into aluminium alloy results in a significant reduction in their ductility. Flom and Arsenault [12] relate such a reduction in

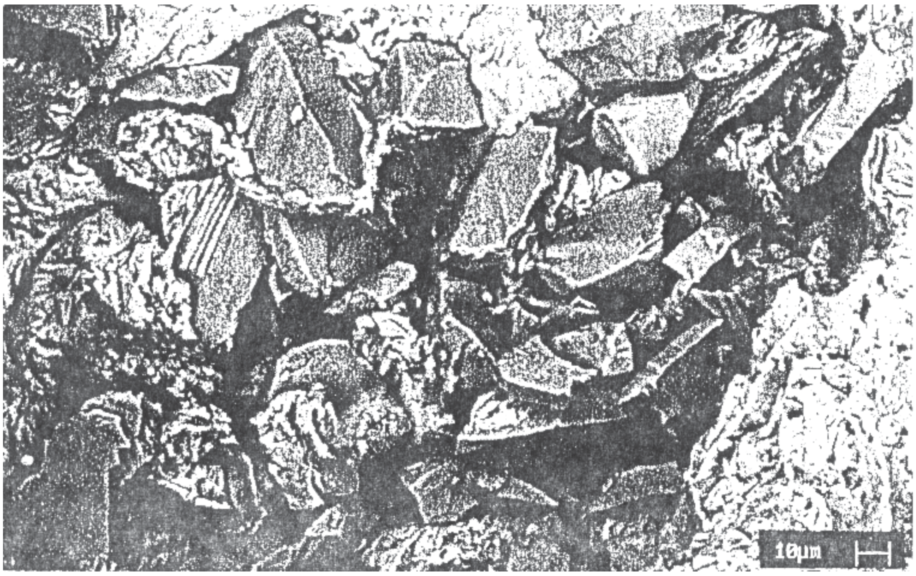

Figure 8 Surface Topography of Tensile Fracture Surface

ductility to an inhomogeneous distribution of silicon carbide particle and void initiation at the reinforcement matrix surface.

4.0 CONCLUSION

A new approach of fabricating cast aluminium matrix composite by using the stir casting method has proved to be successful. Placing all substance together for melting is experimentally a very convenient process. During the initial stage of heating, any moisture in the ceramic particles and the matrix materials is burn off and thus reduces the level of porosity. This advantage cannot be achieved by other methods in which the ceramic particles are introduced into the molten matrix material from the top. Microstructural observation suggests that the stirring action of the slurry produces cast MMC with smaller grain size compared to unstirred one. Stirring in a semi-solid condition breaks the dendrite structure into a small equiaxed or chill-type structure. The conditions of ceramic particle coupled with the smaller grain size are the factors that strengthen the alloy matrix.

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