

Production of A356–SiC_p composite by an innovative casting process

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Received: 23 June 2007 / Accepted: 26 August 2008 / Published online: 23 September 2008
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Abstract In the present study, a novel procedure was introduced for casting of metal matrix composites by adding a mortar consisting expandable polystyrene beads, carboxy methyl cellulose paste, SiC particles and water as a mould pattern. This process was applied for A356 Aluminium alloy/SiC_p composite. Technology of this method is based on a balance between the solidification rate and the buoyancy of the reinforcement particles. The experimental results show that effective parameters in fabrication of a sound part are density and size of pre-puff polystyrene beads, percentage of the reinforcement particles, mould material, thickness of mould cavity, casting temperature and cooling rate. However, the innovative method will only be successful for the thin-wall parts, which their solidification times become shorter than the floatation time of the reinforcement particles.

Introduction

The A356/SiC composite has shown a significant improvement in mechanical properties. The improvement is due to the transfer of shear tension at the matrix–reinforcement interface. Totally, an important consideration in the production of metal matrix composites (MMC) is interfacial characteristics between matrix and

reinforcement. For ceramic-reinforced MMC, it is generally desirable to obtain a strong interface, which leads to high load transfer capabilities and hence high modulus and strength of the composite. On the contrary, poor interfacial bonding has shown to result in a reduced elastic modulus and work hardening rate, which is an indicative of reduced load transfer capabilities. However, within the A356/SiC_p composite many variables such as volume fraction, size, distribution and surface morphology of reinforcement particles can affect mechanical properties [1–4]. According to many theoretical and experimental studies carried out on the Al/SiC_p composite, SiC_p reacts with Al to form Al₄C₃ and Si [4]. The Al₄C₃ phase tends to form discrete hexagonal-shaped precipitates at the interface between the Al SiC particles. Therefore the brittle Al₄C₃ and insoluble in the Al liquid has undesirable effects on the mechanical properties of the composite. On the other hand, this interfacial reaction is the function of the temperature and holding time ($\Delta G_0 = -88.5$ kJ/mol) [5–10]. Therefore, the use of adequate combinations of processing parameters, such as temperature, holding time, etc., can be the alternative solution to suppress the interfacial reaction. Although there are various methods employed in fabricating MMC using different processing parameters, melt process, squeeze casting, powder metallurgy (PM), hot pressing, thixo-forming and spray forming, are gaining commercial importance in recent year [6–8]. Melt processing methods, such as compo-casting and rheo-casting, have been the simplest and cost-effective methods for fabricating SiC_p/Al alloy composites. However, the process can only be applied to certain matrix alloys where prolonged contact time at elevated temperatures will not degrade SiC_p. For example, Al alloy have to contain high Si contents, such as 8 wt.% when fabricating at 700 °C, to

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avoid the interfacial reaction in Al/SiC_p alloy composites, especially for $A356/SiC_p$ and $A356/SiC_p$ composites. Therefore, compo-casting may not be suitable for making wrought Al alloys reinforced with SiC_p , such as the $2024Al/SiC_p$ composite due to the low Si contents within matrix alloy. PM hot pressing is known to be an effective processing method for making components, where solute segregation may cause a degradation of the product quality. This process, however, is costly not only due to the numerous intermediate steps involved in process, but also it cannot avoid the oxidation of matrix alloy when making Al/SiC_p composites. Thixo-forming is a kind of semi-solid processing technique, in which materials are processed in their final configuration at temperature between the liquidus and the solidus. In its potential for achieving near-net shape, thixo-forming offers advantages over other casting processes due to lower processing temperatures, i.e. approximately 100 °C lower than the conventional castings [9–11]. On the other hand, at the semi-solid region solidification shrinkage reduces. Since a considerable amount of the solidification latent heat is already removed before injecting the semi-solid alloy into the mould cavity, the fabrication of the products with a fine and equiaxed structure is possible. Spray forming is a process which can produce various axisymmetric products, such as billets, tubes and plates. The basic idea of this process is the use of both rapid solidification techniques and semi-solid processing such that molten metal is atomized in the form of a liquid droplet jet stream using pressurized inert gas and spray towards the rotating substrate plate to complete solidification. Since the cooling rate of liquid droplets during the flight is fast [12], macro-segregation of the solute atoms can be minimized. Low fabrication temperatures, such as near 560 °C during Al alloy billet fabrication and no-existence oxidation of the matrix alloy, are another advantages of this process [9, 13]. Therefore process that can reduce the time and the temperature of the production, due to avoid of harmful surface reactions between the reinforcement phase and the matrix, will be better.

In the present work an innovative method has been introduced, with the minimum of prolonged contact between the reinforcement and the metal matrix, during the production of the $A356/SiC_p$ composites. In this method SiC_p will be added to liquid metal into the mould cavity by a granulate-foam pattern. Before casting, a mortar that consists of the pre-Puff PolyStyrene (PPS), carboxy methyl cellulose (CMC), SiC_p , and water (H_2O) injected into the mould cavity and then the mortar dried. Finally effective parameters for producing a sound part were introduced. In fact this method is slightly similar to the conventional evaporative pattern casting.

Experimental procedure

First idea

Origin of the present method returns to disadvantages and advantages of the casting process when making the MMC composites. It is clear that the casting process is generally accepted as a particularly promising and commercially rout. Its advantages lie in its simplicity, flexibility and applicability to large quantity production [9, 10]. In general, the solidification synthesis of MMCs involves producing a melt of the selected matrix material followed by the introduction of a reinforcement ceramic into the melt, obtaining a suitable dispersion. The next step is the solidification of the melt containing suspended dispersions under selected condition to obtain the desired distribution of the dispersed phase in the cast matrix. In fabrication of MMC_S by casting method with optimum properties, there are several factors that need considerable attention. In order to achieve the optimum properties of the MMC_S , the distribution of the reinforcement material in the matrix alloy must be homogenous, and the wettability or bonding between these substances should be optimized. The porosity levels need to be minimized, and chemical reactions between the reinforcement materials and the matrix alloy must be avoided by reducing time on contact between the particles and the matrix during melting, casting and solidification stages [14, 15]. Then procedures that can reduce the time and the temperature of production, due to avoid of harmful surface reactions between the reinforcement phase and the matrix, will be better. Therefore, in present work, we introduce a new procedure which is capable of minimizing the time and the temperature of the process, and experimental producers were designed in three stages: (i) making a mortar that consists of the composite reinforcement particles, pre-PPS beads, cellulose glue, (ii) making granulated-foam pattern from the mortar into mould cavity and (iii) casting of metal matrix alloy of the composite into the mould cavity fulfilled in foam pattern

Mortar making

In the first step, as shown in Fig. 1a, b, by using a pre-expander steam machine, the polystyrene beads were expanded to the pre-PPS granule with 14 kg/m³ density. Experimental results showed that the PPS granules with approximate diameter of 1.8–2.5 mm are satisfactory. The silicon carbide powders with mesh <625, density 3.22 g/cm³ and purity 98.6% were used as the starting materials. In order to fabricate the PPS/SiC_p the silicon carbide particles must be coated on the PPS. However, the SiC_p need to an especial heat treatment in order to increase the wettability, and alter the SiC_p surface composition by forming



Fig. 1 Pre-puff beads of polystyrene for mortar making

an oxide layer on the surface, $\text{SiC} + 3/2\text{O}_2 = \text{SiO}_2 + \text{CO}$ [10, 16]. Therefore the silicon carbide particles are transformed to oxide at 1100 °C after 4 h. As shown in Fig. 2, after oxidation the SiC particles average size were 20 μm . In the next stage, a solution of the water and the CMC was utilized as glue. Obtained results from a number of testes showed that suitable volume percentage of the CMC soluble in water is about 2–3 wt.% CMC, and in the less amounts, there was no suitable adherence between the SiC_p and the PPS granules, and in above of the 3 wt.% CMC, because of high-concentration solution, the coat of the SiC_p on the PPS was not uniform, and clustering phenomenon was observed between the PPS granules, as shown in

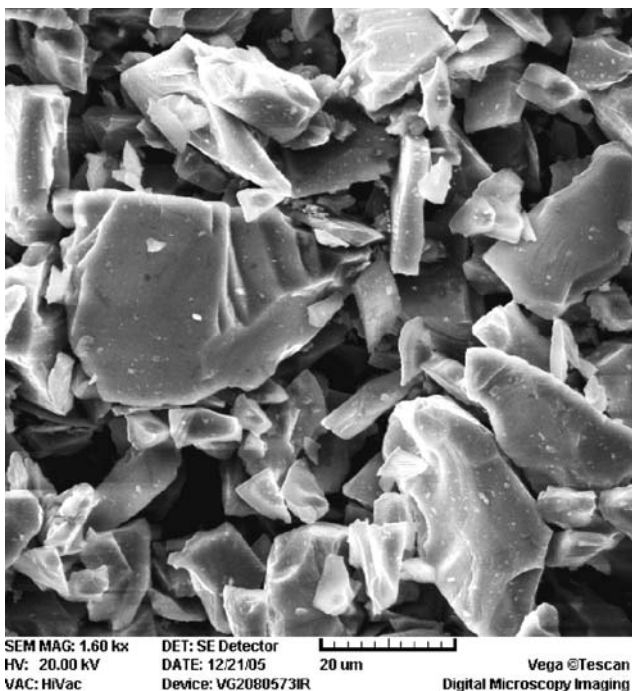


Fig. 2 The SiC particles after heat treatment at 1400 °C at 4 h



Fig. 3 Pre-puff poly styrene mixed with CMC glue and SiC_p

Fig. 3. Thus for preparing above mixture (or mortar), first the PPS granules were poured into a container and then blend of the CMC glue and the SiC particles after the heat treatment were added gradually and stirred continuously for about 5 min, using an impeller at a speed of 400 rpm. This mixture consist of the PPS, the CMC, the SiC_p and the water is named as PPS/CMC/ SiC_p /H₂O mortar.

Pattern making

In the second step, the CMC/PPS/ SiC_p /H₂O mortar was poured into a steel mould cavity. It is noticeable that design of the steel mould dimensions is very important for making a sound MMC cast part. Then the mould filled with mortar was dried in oven. Figure 4 shows the mould and the mortar after draying. As shown in Fig. 5 the dried mortar, PPS/CMC/ SiC_p , is a porous media that is named granular foam pattern (GFP). In fact the dried mortar or the GFP will be a porous foam pattern during casting process.

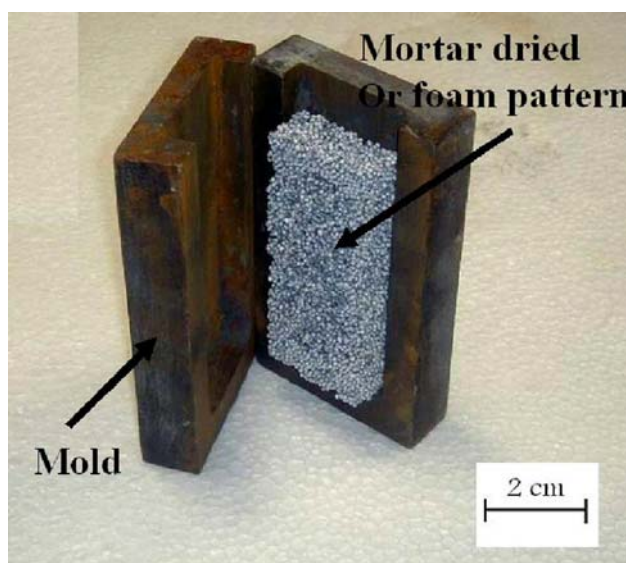


Fig. 4 View of the filled mould with the PPS/CMC/ SiC_p mortar



Fig. 5 View of the GFP after drying

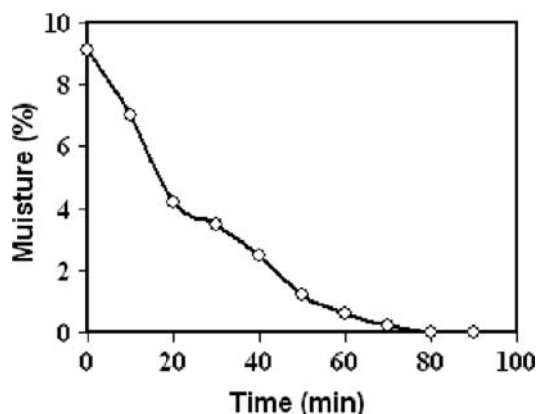


Fig. 6 Drying graph of PPS/CMC/SiC_p foam pattern

Experimental results showed that drying cycle shown in Fig. 6, i.e. 60 °C for approximately 80 min, is the most suitable cycle for drying the mortar or preparing the GFP.

Moulding and casting

In final step, A356 alloy with chemical composition of, Al: 98.14, Mg: 0.6, Si: 0.6 and Cu: 0.3 was melted in a 30-kW electric furnace. The molten alloy was suitably degassed with hexa-chloro-ethane (C₂Cl₆) and fluxed with 45 wt.%KCl–45 wt.%NaCl–10 wt.%NaF. In this work, pouring temperature of A356 alloy liquid was selected 775 ± 5 °C and pure magnesium was added to molten metal approximately 1.2 wt.% in order to enhance wettability. Therefore during casting, just at once the liquid contact to the GFP, it will burn and the SiC particles are added to the liquid alloy. Since the thickness of the mould is narrow, solidification process occurs rapidly, and there is not enough time to come up the SiC_p, and hence the SiC particles will be distributed as homogenous into the casting samples. Such condition happens when solidification rate is

more than floatation rate or the solidification time is less than the floatation time.

Results and discussion

Figure 7 shows the first mould cavity with dimension 210 × 70 × 40 mm³ as shown this part is full of defects including, miss run, crack, porosity, particles agglomeration and some fused GFP on the surfaces as well as interior of the sample. The reason is that the solidification velocity and the casting temperature were not sufficient and the solidification time was longer than the floatation time. Therefore in the next step we changed the mould dimensions by reducing ratio of volume-to-area of mould cavity to 210 × 90 × 28. As shown in Fig. 8, new dimensions of the solidification time was decreased without any floatation phenomena and accompanied by a sound part. In fact by increasing the internal surfaces of mould cavity and decreasing solidification time, SiC_p particle had no time to move up and float. Surface increase was calculated and designed by equilibrium between the solidification rate and the floatation rate.

Therefore the velocity of floatation, R_{float}^o, could be obtained from Archimedes principle as follow:

$$R_{float}^o = \frac{2 \rho_L - \rho_P}{9 \lambda} r^2 g, \tag{1}$$

where R_{float}^o is the floatation velocity of reinforcement particles into the liquid metal, r average radius of the reinforcement particle, λ liquid viscosity, ρ_L liquid density, ρ_p particle density. However, the solidification rate could be calculated from Eq. 2 [17]

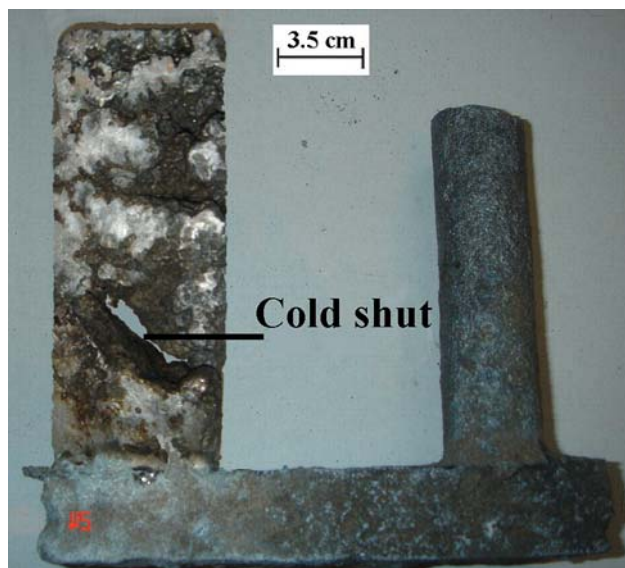


Fig. 7 Effect of mould cavity dimension on the casting part soundness. Dimensions: 210 × 70 × 40 mm³

$$R_{\text{solid}}^{\circ} = \frac{2}{\sqrt{\pi t}} \left(\frac{T_{\text{cast}} - T_0}{\rho_L \Delta H_{\text{me}}} \right) \sqrt{k_{\text{mo}} \rho_{\text{mo}} C_{\text{P}}^{\text{mo}}}, \quad (2)$$

where R_{solid}° is the solidification velocity, ΔH_{me} the latent heat, ρ_{mo} the mould density, C_{P}^{mo} the heat capacity of mould,

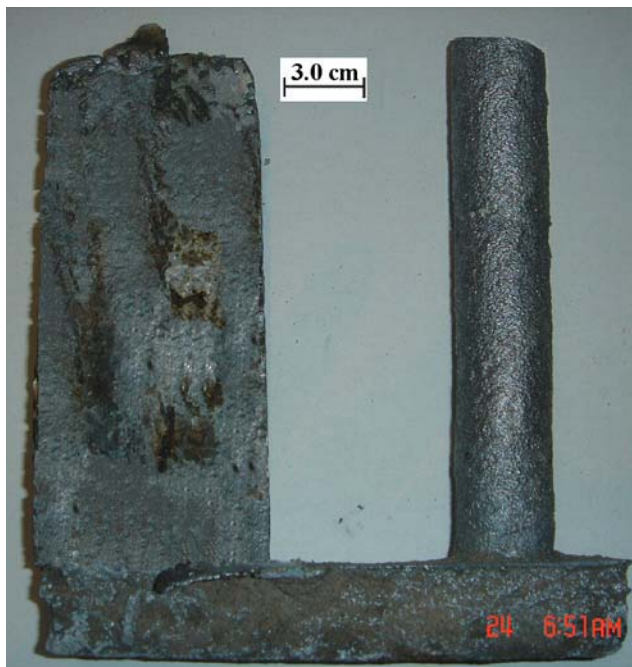


Fig. 8 Effect of mould cavity dimension on the casting part soundness. Dimensions: $210 \times 90 \times 28 \text{ mm}^3$



Fig. 9 View of the coming up SiC_p and clustering phenomenon for the part with dimensions $210 \times 70 \times 40 \text{ mm}^3$

k_{mo} the thermal conductivity of mould, t the solidification time, T_{cast} , T_0 are the temperatures of the pouring and the ambient, respectively. It is clear where the solidification

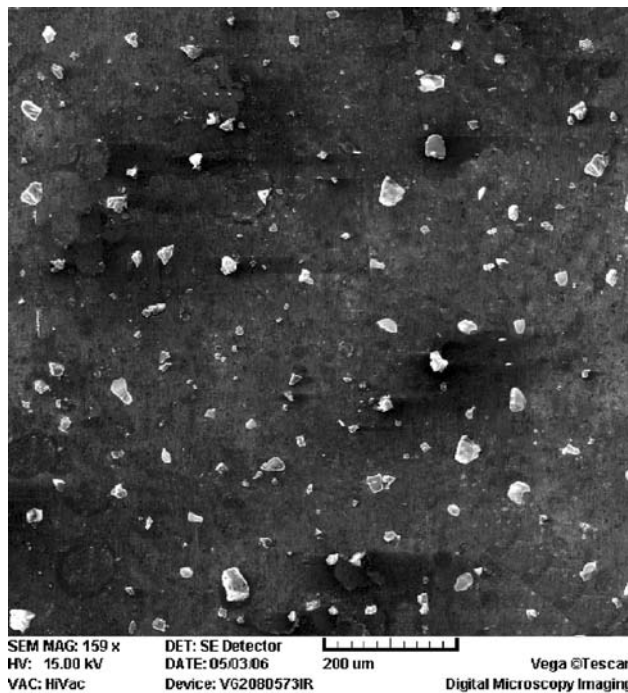


Fig. 10 View of the homogenous distribution of the SiC_p without and the clustering phenomenon for the part with dimensions $210 \times 90 \times 28 \text{ mm}^3$

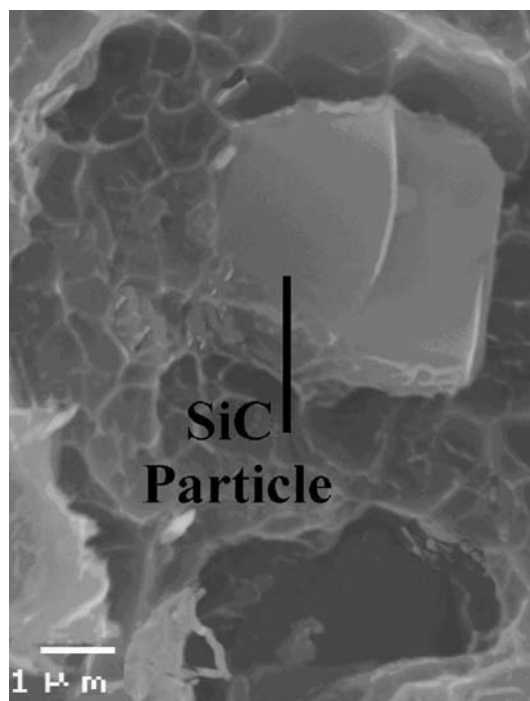


Fig. 11 View of the fracture cross-section of $\text{A356}/10\text{SiC}_p, \text{vol.}\%10$ composite, without any interfacial reaction

velocity, R_{solid}^o , becomes larger than the floatation velocity, R_{float}^o , there is no cluster and agglomeration into the casting MMC part. Then with substituting Eq. 2 into Eq. 1, solidification time that leads to a sound part without any cluster can be obtained from Eq. 3:

$$t < \left[\frac{9\lambda}{\sqrt{\pi}} \left(\frac{T_{cast} - T_0}{\rho_L \Delta H_{me}} \right) \left(\frac{r^2 g}{\rho_L - \rho_P} \right) \sqrt{k_{mo} \rho_{mo} C_P^{mo}} \right]^2 \quad (3)$$

In fact key to problem solution is Eq. 3. In other word, if solidification time was not satisfied by Eq. 3, we cannot

achieve a sound MMC part. Solidification time can be reduced by the volume-to-area ratio (of mould cavity). Therefore increasing the cooling area could reduce the solidification time for a fixed volume. Therefore we designed dimensions of the mould cavity based on above model and obtained dimensions of $210 \times 90 \times 28 \text{ mm}^3$ for the mould cavity. On the other word, mould thickness could be calculated from the $R_{solid}^o \times t$ based on the present model (Eqs. 2 and 3).

Figures 9 and 10 show micrographs of the A356/SiC_p 10 vol.% sample with dimension of $210 \times 70 \times 40$ and $210 \times 90 \times 28 \text{ mm}^3$, respectively. As shown in Fig. 9, there are a lot of clusters in the sample. However in Fig. 10 the clustering phenomena were not observed. Figure 11 shows an SEM micrograph of the fracture surface of a tensile test specimen. Also the SiC_p particle is completely covered by a thin layer of aluminium which has failed in a ductile manner. This demonstrates that the new casting method is getting excellent bonding, and there is not any brittle phase around the SiC_p such as Al₄C₃, which agrees well with results of Doel and Bowen [1].

Since in current technique connection time between the particles and matrix reduces dramatically, the Al₄C₃ brittle phase cannot form at the interface. XEDS technique was used to characterize various phases. Microstructure of the SiC_p-reinforced composites is shown in Fig. 12. Figure 13 shows line scan results of the SiC_p-reinforced specimens that selected from the Fig. 12 matrix. As shown, there is no excess composition or deleterious phase at interface between the SiC_p and the matrix alloy. In fact, above tests show that in the innovative casting, we could create a minimum time for contacting the reinforcement particles

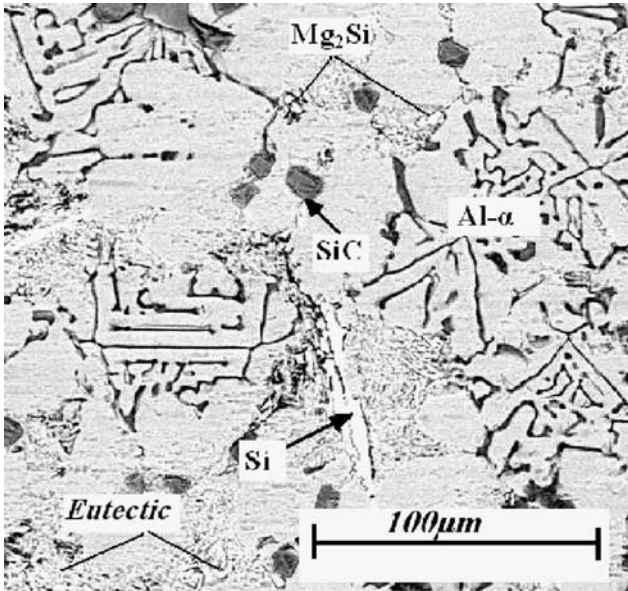


Fig. 12 Microstructure of the A356–10SiC_p vol.% composites, which prepared from at the centre of casting part

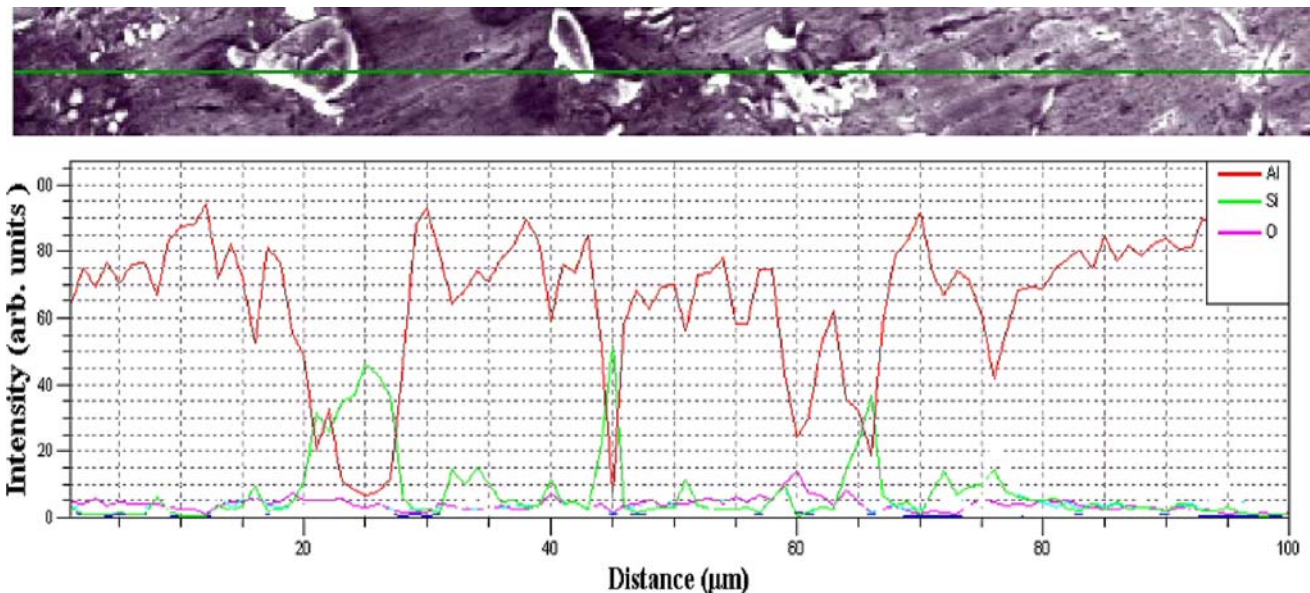


Fig. 13 Line scan results of the A356–10SiC_p vol.% composite

and the metal matrix, during the casting process without any interfacial reaction, coming up, agglomeration and sufficient wettability.

Figures 14a, b and 15a, b show the worn surfaces of the un-reinforced A356 alloy, the A356–5 vol.%SiC_p and the A356–10 vol.%SiC_p composites at 1 MPa applied load. It can be observed from the Fig. 14 that the un-reinforced A356 alloy shows largest wear traces via the MMCs as shown in Fig. 15. The reason is hard SiC particles improve wear resistance of the composite when compare to matrix alloy [18, 19]. Figure 15 also shows that SiC_p have uniform distribution in the worn surface of the composites. Table 1 shows wear rate and weight loss between the A356/SiC_p-vol.% composites and the A356 Al alloy. As shown in

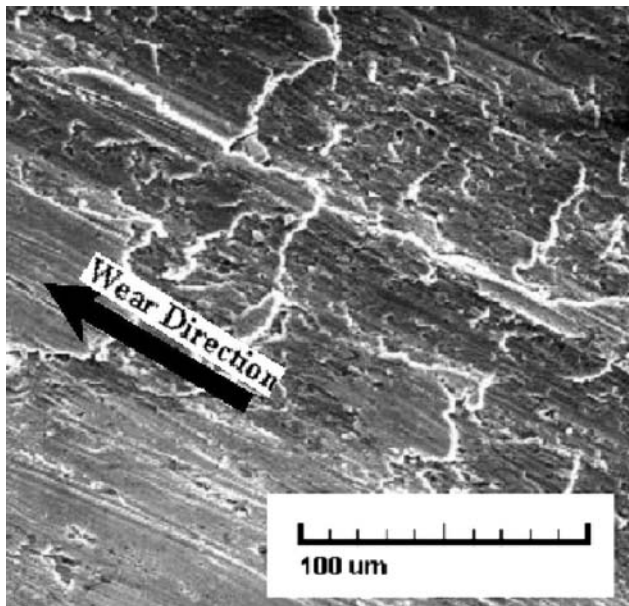


Fig. 14 Wear surface of un-reinforced A356 + 1Mg alloy

Fig. 15 Wear surface SEM images of A356/SiC_p composites (a) 5 vol.%, (b) 10 vol.%

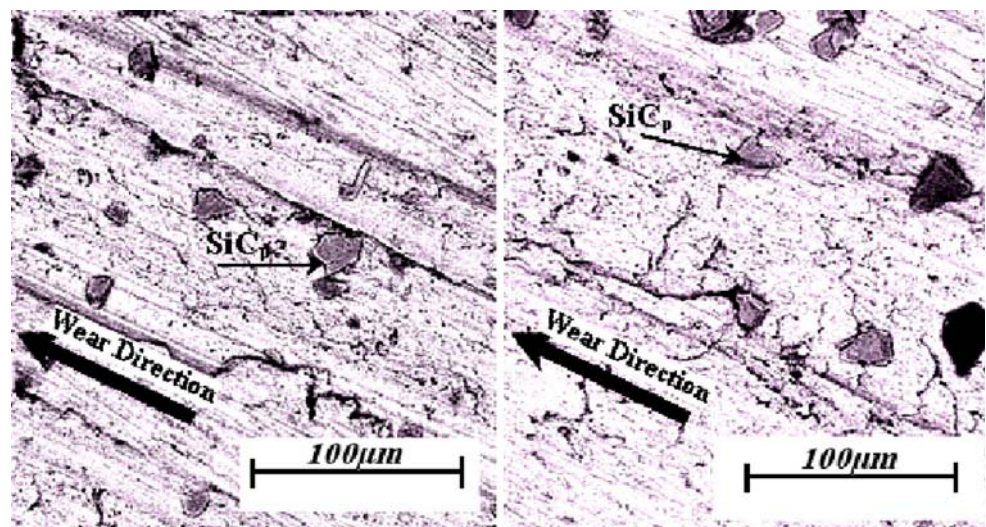


Table 1, the weight loss decreases with increasing the SiC_pvol.%, which is in agreement with the previously reported results [20, 21]. The wear rates of the A356/MMC as a function of the SiC_pvol.%, and the sliding distance are shown in Table 1. Also data of Table 1 indicate that under this production condition, the wear rate decreases by an increase in SiC_pvol.%. Shown in Fig. 16 is the profile of the weight loss contents superposed with the A356 alloy, at present SiC_p different values. The trend of wear resistance for A356/10 vol.%SiC_p composite was observed to be different from those the A356 alloy and the A356/3 vol.%SiC_p. In fact, minimum of the weight loss belongs to the A356/10 vol.%SiC_p. We modelled this trend as a function of the SiC_pvol.% using Eq. 4

$$W_{\text{loss}} = ax^2 + bx + c, \quad (4)$$

where W_{loss} is the weight loss (mg), x the sliding distance (m) and a , b , c coefficients via the SiC_p(vol.%) are as follows:

$$a = [3 (\%SiC) - 6] \times 10^{-6}$$

$$b = 7 \times 10^{-4}(\%SiC) + 0.0111$$

Table 1 The wear rate and the weight loss between the A356/SiC_p-vol.% composites and the A356 Al alloy at different conditions

Samples	Wear distance (m)							
	100		300		600		1,000	
	WL	WR	WL	WR	WL	WR	WL	WR
A356	0.6	2.2	3	3.7	4.2	2.6	5.1	1.9
A356 + 1Mg/5SiC	0.5	1.84	2.2	2.7	2.8	1.7	3.4	1.26
A356 + 1Mg/10 SiC	0.5	1.83	1.2	1.4	1.5	0.91	1.8	0.66

WL, weight loss (mg); WR, wear rate ((m³/m) × 10⁻³)

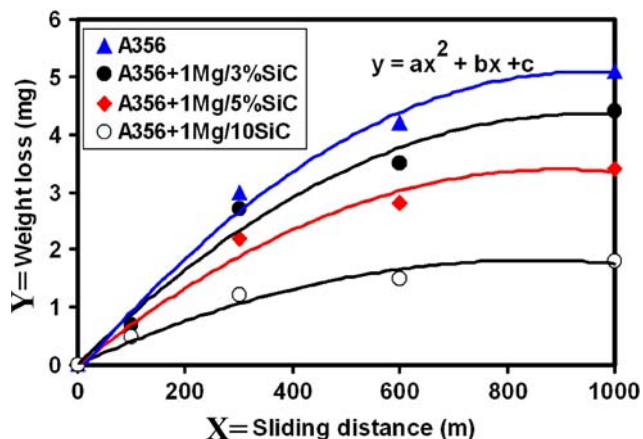


Fig. 16 Modelling of weight loss (Y) via sliding distance (X) based on experimental results obtained from the wear test (see Eq. 4)

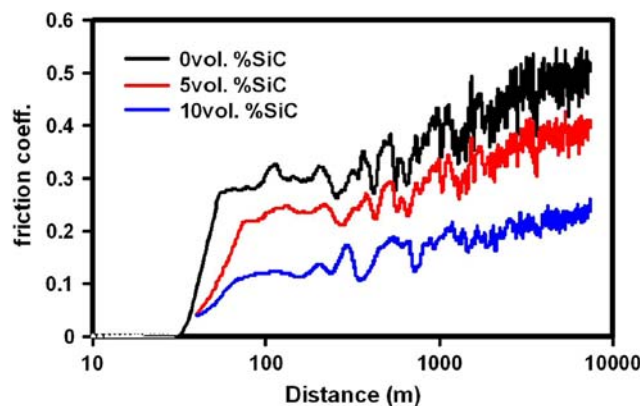


Fig. 17 Effect of SiC percentage on the wearing resistance

$$c = 7 \times 10^{-4} (\%SiC)^3 - 9.9 \times 10^{-3} (\%SiC)^2 + 0.0282 (\%SiC) - 0.012.$$

The wear behaviour of A356 alloy, A356/5 vol.%SiC_p and A356/10 vol.%SiC_p composites can be observed in Fig. 17. As shown the friction coefficient is less for composites with high SiC_p.

Conclusion

1. In this investigation a novel MMC casting technique was introduced using a foam pattern consisting of the PPS/SiC_p/CMC. Using this technique leads to more uniform distribution of SiC particles than the other casting technique. Since the contact time between SiC and matrix is much shorter than the other MMC fabrication processes, deleterious phase Al₄C₃ will be absent.
2. Processing parameters such as the SiC particles percentage, the CMC glue percentage, size of the PPS foam beads, ratio of volume to the cooling area of

the mould cavity during casting and the solidification stages are the important factors that have to be considered in the production of the A356/SiC_p using the EPS/CMC/SiC_p casting method.

3. The composite solidification time has to be less than the particles floatation time, which can be estimated based on Eq. 3. Effect of casting and solidification parameters such as the super-cooling, physical properties of the mould's material and the molten metal, and solidification rate were concluded on the thickness of the casting part by Eq. 3.
4. Wear properties of 10 vol.% SiC shows improvement, in compare to other quantities of particles.

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