Property analysis and mathematical modeling of machining properties of aluminium alloy hybrid (Al-alloy/SiC/flyash) composites produced by liquid metallurgy and powder metallurgy techniques

S Charles & V P Arunachalam*
Department of Mechanical Engineering, Government College of Technology, Coimbatore 641 013, India

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Aluminium hybrid composites reinforced with silicon carbide and flyash particulates were fabricated by stir casting and powder metallurgy methods. Different volume fractions of SiC particles (10, 15 and 20 vol%) and constant volume fraction of flyash (10 vol%) were used for the synthesis. Wear, micro hardness, tensile and microstructural properties were studied. Results of the investigations indicated that wear resistance and hardness were enhanced on increasing the vol% of SiC. The tensile strength was high at 10 vol% of SiC and it decreased as the vol% increased. Microstructure showed a fairly uniform distribution of the dispersoids. Electric discharge machining was done on the composite specimens and mathematical models were developed for predicting the material removal rate and tool wear rate using design of experimentation with current, pulse duration and vol% of SiC as the process variables. Curves describing the direct and interaction effect of the process variables were drawn. It was found that the material removal rate and tool wear rate increased with increase in current and decreased with increase in pulse duration and vol% of SiC. The behaviour of the composites was similar both for powder metallurgy and stir casting, except the fact that stir cast specimens exhibited higher hardness, wear resistance and tensile strength. This increase can be attributed to the close interfacial bonding of stir cast specimens.

Composite materials are exponentially growing up and rapidly gaining importance because of their potential to produce components that features low density while maintaining high stiffness, strength, thermal stability, improved fatigue properties and wear resistance. Among the various discontinuous dispersoids used, flyash is one of the cheapest and low-density reinforcements obtained in large quantities as a waste-by-product during combustion of coal in thermal power plants. Addition of flyash particles imparts dimensional and thermal stability, improves hardness, wear resistance, stiffness and reduces the density of the matrix material. Silicon carbide and aluminium have very different mechanical properties: Young’s moduli of 400 and 70 GPa, coefficients of thermal expansion of 4×10^{-6} and 24×10^{-6} /°C, and yield strengths 600 and 35 MPa, respectively. By combining these materials e.g. A 6061/SiC/17p, an MMC with a Young’s modulus of 96.6 GPa and a yield strength of 510 MPa can be produced. Hence, SiC and flyash were selected as the dispersoids.

*For correspondence (E-mail: arunachalam_vp@rediffmail.com)
Composite preparation procedure

Liquid metallurgy

In this process, the matrix alloy was stirred in a furnace above liquidus temperature using a mechanical impeller and the dispersoids added while stirring\(^2\) the molten metal. LM10 aluminium alloy was first melted in a graphite crucible, which had the provision of bottom pouring. A servomotor operated mechanical impeller was used to stir the molten metal and create vortex\(^3,23\) motions. The depth of the immersed impeller was approximately one third of the height of the molten metal from the bottom of the crucible and the speed of the impeller was maintained at 760 rpm. Preheated SiC and flyash particles at a temperature of 350°C and size varying from 30 µm to 100 µm were added into the melt. The dispersoid being added ranged from 10-20 vol%. Stirring produces uniform suspension of solid particles in the melt\(^24\) due to centrifugal acceleration. After completion of particle addition the mixture was degassed\(^25, 26\) with nitrogen. A holding time of 10 min at a maximum temperature of 750°C was given to get maximum dissolution of particulates in the alloy. Now, the crucible containing the melt and dispersoids was taken out and placed in a hot refractory brick. The melt was hand stirred with a graphite rod and then tapped into permanent steel moulds through bottom pouring. The castings were prepared according\(^27,28\) to AFS standards. The procedure was repeated for increasing sizes of SiC dispersoids (10, 15 and 20 vol%). Flyash was maintained at 15 vol%.

Powder metallurgy

In powder metallurgy, weighed amount of metal powders were mixed thoroughly in a pestle and mortar with stearic acid as the blending agent and compacted under suitable pressures in a hydraulic press. The green compacts were sintered\(^29\) at vacuum in a tubular sintering furnace by holding at 550°C for one hour, to assist out gassing, followed by a further hold at a temperature suitable of producing full density without forming an over-sintered structure with coarse grain boundary carbides. Similar compositions were used as in stir casting method.

Results and Discussion

Tensile strength

Tensile specimens were machined according\(^30\) to ASTM D3552-77 and the test results given in Table 1. The tensile strength reaches a peak value for 10 vol% and then decreases\(^31\) for further increase in vol% of SiC. This is because the tensile behaviour is profoundly influenced by the reinforcement volume fraction and particle size. Following tensile loading, where a significant fraction of the stress is initially borne by the reinforcement, the composite undergoes micro plastic yielding\(^32\). Microplasticity in the composite takes place at stress concentrations in the matrix at the poles of the reinforcement\(^33\) or at sharp corners\(^34\) of the reinforcing particles. With an increase in the applied strain, the particles are loaded to a higher stress. Due to much lower strain-to-failure of the SiC particles, compared to the matrix, the particles will generally begin to fracture prior to ultimate tensile strength of the composite. It can be seen that the tensile property of the specimens prepared by powder metallurgy is less than the liquid metallurgy specimens. This is because of the good interfacial bonding of the cast specimens.

Hardness

Vickers microhardness measurements were done on both the specimens with a loading of 0.5 kg and speed 50 µm\(^1\). The loading time was maintained as 10 s. Four readings were taken at different points in each specimen and the average of the readings were calculated and given in Table 2. It can be observed that liquid metallurgy specimens are harder than the specimens prepared by powder metallurgy. This may also be due to the fine dispersion of the reinforcements in the matrix.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Compositions</th>
<th>SC (MPa)</th>
<th>PM (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>LM10 Aluminium alloy</td>
<td>392.6</td>
<td>230.8</td>
</tr>
<tr>
<td>B</td>
<td>10% SiC + 10% Flyash + LM10 Aluminium alloy (rest)</td>
<td>419.4</td>
<td>243.2</td>
</tr>
<tr>
<td>C</td>
<td>15% SiC +10% Flyash + LM10 Aluminium alloy(rest)</td>
<td>378.8</td>
<td>212.6</td>
</tr>
<tr>
<td>D</td>
<td>20% SiC +10% Flyash + LM10 Aluminium alloy(rest)</td>
<td>342.9</td>
<td>201.2</td>
</tr>
</tbody>
</table>

SC – Stir Casting; PM – Powder Metallurgy
Wear

Dry sliding wear testing\textsuperscript{35-37} was conducted in accordance with ASTM G99 Standards using a pin-on-disc type wear-testing machine. The wear pins of dimensions 6 mm diameter and 20 mm length were held against the rotating steel disc (EN24) of 200 mm diameter. The specimens were tested twice at each condition for wear and the average value was taken. Wear measurements were done by weight loss technique\textsuperscript{38-40} using an electronic weighing balance with an accuracy of ± 0.1 mg. Before each wear and weighing exercise the specimens were cleaned with acetone and dried. The wear rate was calculated for increasing sliding distances and loads.

**Effect of sliding distance with wear volume**

Variations in wear volume with sliding distances ranging from 600 to 3000 m in steps of 600 m at a load of 2 kg and sliding speed 2 m/s are represented in Figs 1 and 2. It is observed that the wear rate increases linearly (a steady state) with the sliding distance. The wear rate of non-modified LM10 Aluminium alloy is higher than the reinforced composites. There is a decrease in the wear rate as the percentage composition of the dispersoids increases. The specimens produced by stir casting offer better wear resistance than the powder metallurgy specimens. This may be due to the formation of pores during sintering operation, which paves way for crack formation and propagation.

**Effect of load with wear volume**

Variations in wear volume with loads ranging from 0.5 to 2.5 kg in steps of 0.5 kg are represented in Figs 3 and 4. At lesser loads it could be seen that the wear rate is less. But as the load increases there is an increase in the wear rate and the wear is abrasive. This effect is more pronounced at higher loads. This severe wear may be due to the high strain developed in the region. Under low loads the wear resistance is mainly due to the matrix properties which contain SiC and flyash particulates. The surface gets worn out on increasing the load and hence reduces the wear resistance.

**Microstructure**

Microstructural examination of the samples provided useful evidence on the distribution of the reinforcement in the matrix. A fairly uniform distribution

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Powder metallurgy</th>
<th>Stir casting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 Avg.</td>
<td>1 2 3 4 Avg.</td>
</tr>
<tr>
<td>A</td>
<td>94.2 95.6 96.8 96.8</td>
<td>95.85 96.7 97.2 97.8 96.8 97.12</td>
</tr>
<tr>
<td>B</td>
<td>108.2 114.6 109.4 112.4</td>
<td>111.5 118.2 124.6 128.4 126.2 124.3</td>
</tr>
<tr>
<td>C</td>
<td>122.4 125.4 128.7 127</td>
<td>125.8 138.4 132.6 134.4 136.8 135.5</td>
</tr>
<tr>
<td>D</td>
<td>128.4 133.4 136 132.4</td>
<td>132.5 142.2 144.4 146.8 147.8 145.5</td>
</tr>
</tbody>
</table>

![Graph 1](image1.png)

**Fig. 1**—Effect of sliding distance on wear for the specimens by stir casting

![Graph 2](image2.png)

**Fig. 2**—Effect of sliding distance on wear for the specimens by powder metallurgy
of the dispersoid particles in the matrix with no apparent segregation was observed. Fig. 5 shows particles of eutectic silicon and sledges of flyash in a matrix of aluminium solid solution. Fig. 6 shows the microstructure of powder metallurgy specimens. Little micro porosity is observed in the matrix of powder metallurgy specimens.

**Electric discharge machining**

Electric discharge machining was done on the composite specimens to evaluate the material removal rate (MRR) and the tool wear rate (TWR). The process parameters such as current, pulse duration and grit size of SiC were identified as the main factors influencing the responses MRR and TWR. The working
The range of those factors was set at three levels. For this a three level three-factor full factorial design matrix was selected to conduct the experiments. The selected factors and their levels are shown in Table 3. Experiments were conducted by machining composite specimens using a copper electrode for 30 min duration for each trial run selected at random. The MRR and TWR were obtained using an electronic balance. The design matrix and the results are shown in Table 4.

### Development of mathematical model

The response function representing any of the process parameters can be expressed as

\[ \text{Response} = \text{f}(\text{Factor 1}, \text{Factor 2}, \text{Factor 3}) \]
\[ Y = F (G, I, T), \] the relationship selected being a second degree response surface expressed as follows:
\[ Y = b_0 + b_1 G + b_2 I + b_3 T + b_{11} G^2 + b_{22} I^2 + b_{33} T^2 + b_{12} G I + b_{13} G T + b_{23} I T \]

Any mathematical model developed should be studied of its direct and interaction effects of the variable on the responses. The magnitude of the regression coefficient is a good indication of the significance of the parameters. To determine the significant direct and interaction effects precisely, a statistical analysis software package, namely, ‘DOE – PC IV’ was used. For the required response, from the 27 observed values and the second order general mathematical model for the three factors, the significant effects of the parameters together with their magnitudes (based on ANOVA) were obtained. Regression by backward elimination technique was adopted with a probability criterion of 0.75. This involves an interactive series of regressions, starting with the initial interaction array. At each step the significance of the \(t\)-statistic for each remaining parameter is compared to the specific probability criterion. The lowest parameter is discarded; any interaction with that factor meeting the criterion will remain.

Mathematical models having the significant direct and interaction effects only with calculated regression co-efficients are as follows:

- **MRR\(_1\) (LIQUID METALLURGY)**
  \[ \text{MRR\(_1\) = } 225.358 - 0.359 A - 0.046 A^2 + 1.615 B - 0.099 B^2 - 0.05 AB - 0.096 C \]

- **TWR\(_1\) (LIQUID METALLURGY)**
  \[ \text{TWR\(_1\) = } 24.694 - 0.119 A - 0.002 A^2 + 0.147 B + 0.012 B^2 - 0.006 AB - 0.011 C \]

- **MRR\(_2\) (POWDER METALLURGY)**
  \[ \text{MRR\(_2\) = } 263.035 - 0.403 A - 0.053 A^2 + 1.935 B + 0.116 B^2 - 0.061 AB - 0.112 C - 0.002 AC + 0.002 BC \]

- **TWR\(_2\) (POWDER METALLURGY)**
  \[ \text{TWR\(_2\) = } 26.605 - 0.011 A - 0.006 A^2 + 0.242 B + 0.011 B^2 - 0.008 AB - 0.011 C \]

**Machining characteristics**

Figs 7 and 8 show the direct effect of vol\% of SiC and current on MRR\(_1\), TWR\(_1\), MRR\(_2\) and TWR\(_2\). It can be observed from Fig. 7 that the material removal decreases on increasing the dispersoid content. The tool wears proportionately with the material removal. The MRR and TWR are higher for the powder metallurgy specimens. Fig. 8 shows the effect of current on material removal and tool wear. The material removal and tool wear increase on increasing the current. Higher current produces higher material removal and hence the tool wear. Excess tool wear may also be due to the presence of hard reinforcements in the debris. It can be seen from Figs 9 and 10 that increasing pulse duration decreases the material removal and also the tool wear. This is because of the reduction in the frequency of the sparks. Figs 11 and 12 show the interactive effects of vol\% of SiC and current on MRR and TWR for the specimens produced by powder metallurgy. The MRR increases with increase in current and for all levels of vol\% of SiC; however the increase in vol\% of SiC decreases the MRR, probably due to the presence of abrasive particles in the matrix which decreases the conductivity of the work mate-
Fig. 10—Interactive effect of vol% of SiC and pulse duration on TWR when current is at '0' level.

Fig. 11—Interactive effect of vol% of SiC and current on MRR when pulse duration is at '0' level.

Fig. 12—Interactive effect of vol% of SiC and current on TWR when pulse duration is at '0' level.

(i) Addition of dispersoid particles resulted in an increase in hardness and wear resistance. The composite specimens by liquid metallurgy can be attributed to lower amount of porosity and hence they possess higher hardness and improved wear resistance. Addition of vol% of SiC resulted in an increase in tensile strength to a peak value and then the strength decreases for further increase in volume fraction of SiC. Microstructures of the specimens show a fairly uniform distribution of the reinforcements in the matrix.

(ii) The three-level full factorial technique can be successfully employed to develop mathematical models for predicting the MRR and TWR. The MRR increases with increase in the current and decreases with an increase in vol% of SiC and the pulse duration, whilst the TWR increases with an increase in the current and vol% of SiC, but decreases with an increase in the pulse duration.

(iii) The MRR and TWR are high for powder metallurgy compared to liquid metallurgy specimens. This implies that strong interfacial bonding is produced as a result of stir casting.

(iv) Optimization can also be done for the process parameters; maximizing the material removal rate and minimizing the tool wear.

Conclusions
The following are the conclusions arrived from the experimental analysis:

(i) Addition of dispersoid particles resulted in an increase in hardness and wear resistance. The composite specimens by liquid metallurgy can be attributed to lower amount of porosity and hence they possess higher hardness and improved wear resistance. Addition of vol% of SiC resulted in an increase in tensile strength to a peak value and then the strength decreases for further increase in volume fraction of SiC. Microstructures of the specimens show a fairly uniform distribution of the reinforcements in the matrix.

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References