CHAPTER 6

RESULTS AND DISCUSSION

6.1 INTRODUCTION

The results obtained from the experiments and analyse on microstructure, hardness, wear, heat treatment and machining characteristics of hybrid composites are presented in the following sections.

6.2 HARDNESS STUDY

The results of hardness studies on both as cast and heat treated composites are presented in the following sections.

6.2.1 Hardness of as Cast Composites

The Rockwell hardness values of the un heat treated composites with variation in the reinforcement content is shown in Table 6.1. It is observed that the Rockwell hardness of Al 6061 composites increases significantly with increasing content of the reinforcements. Further, it can also explained based on the dislocation densities. Increased content of reinforcement in the matrix alloy leads to increased dislocation densities during solidification arising from a thermal mismatch of the matrix alloy and the reinforcement. The mismatch of the thermal expansion between matrix and reinforcement due to temperature change results in large internal stresses and mismatch strain that affects the microstructure and mechanical properties of the composites. The matrix deforms plastically to accommodate the smaller
volume expansion of the reinforcement particles. Enhancement in dislocation densities results in higher resistance to plastic deformation, leading to improved hardness (Prabhu swamy et al 2007a). The measurements shows that an increase in graphite content for same amount of SiC reduces hardness of the composite. The improvement in the hardness of the composites with increased content of the reinforcements can therefore be mainly attributed to higher hardness of only SiC and not graphite. It can be noted that with increasing content of SiC particles in the matrix alloy, there is a significant improvement in the Rockwell hardness of the composites. An increase of around 65% is observed in the composites compared to the unreinforced matrix alloy.

Table 6.1 Hardness of as cast composites

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Specimen Composition</th>
<th>Rockwell Hardness (HRB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al6061</td>
<td>46.25</td>
</tr>
<tr>
<td>2</td>
<td>Al6061+4%SiC+3%graphite</td>
<td>65.0</td>
</tr>
<tr>
<td>3</td>
<td>Al6061+6%SiC+2%graphite</td>
<td>64.0</td>
</tr>
<tr>
<td>4</td>
<td>Al6061+6%SiC+4%graphite</td>
<td>62.0</td>
</tr>
<tr>
<td>5</td>
<td>Al6061+8%SiC+1%graphite</td>
<td>70.5</td>
</tr>
<tr>
<td>6</td>
<td>Al6061+8%SiC+3%graphite</td>
<td>64.0</td>
</tr>
<tr>
<td>7</td>
<td>Al6061+8%SiC+5%graphite</td>
<td>61.5</td>
</tr>
<tr>
<td>8</td>
<td>Al6061+10%SiC+2%graphite</td>
<td>68.5</td>
</tr>
<tr>
<td>9</td>
<td>Al6061+10%SiC+4%graphite</td>
<td>68.0</td>
</tr>
<tr>
<td>10</td>
<td>Al6061+12%SiC+3%graphite</td>
<td>67.7</td>
</tr>
</tbody>
</table>

6.2.2 Hardness of Heat Treated Composites

The variation of hardness with increased content of graphite particles in the matrix Al 6061 alloy after heat treatment with different ageing durations is shown in Table 6.2.
Table 6.2 Hardness of heat treated unreinforced matrix alloy and composite specimens

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Specimen composition</th>
<th>After heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rockwell hardness value (HRB)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aged at 4h</td>
</tr>
<tr>
<td>1</td>
<td>Al 6061</td>
<td>61.5</td>
</tr>
<tr>
<td>2</td>
<td>Al 6061+8%SiC+1% graphite</td>
<td>92.0</td>
</tr>
<tr>
<td>3</td>
<td>Al 6061+8%SiC+3% graphite</td>
<td>77.0</td>
</tr>
<tr>
<td>4</td>
<td>Al 6061+8%SiC+5% graphite</td>
<td>74.0</td>
</tr>
</tbody>
</table>

The hardness values were obtained by taking the average of three indentations. It is observed that with increase in ageing duration, the hardness of both unreinforced alloy and composite increased. Heat treatment has a profound influence on the hardness of the unreinforced matrix alloy as well as its composites. For a solutionising temperature of 803K, and a duration of 1h, ageing temperature of 448K, quenching in water, ageing duration significantly alters the hardness of both unreinforced matrix alloy as well as the composites. The maximum hardness was observed for both the matrix alloy and the composites for ageing duration of 8h when the quenching media is water. For all ageing time studied, composites exhibited higher hardness when compared with the base alloy. On water quenching and ageing for 8h, the matrix Al 6061 alloy exhibited a maximum improvement of around 51.3% and Al 6061+8%SiC+5%graphite composite exhibited maximum improvement of around 50% in the Rockwell hardness value. On water quenching and ageing for 6h, the matrix Al 6061 alloy exhibited a maximum improvement of around only 27.8% and Al 6061+8%SiC+5% graphite composite exhibited
maximum improvement of around 63% (in BHN value). Improved hardness of the matrix alloy Al 6061 and its composites on heat treatment can be due to the formation of intermetallic precipitates during the ageing process of heat treatment. The amount of precipitates and the size of precipitates are the deciding factors for the observed improvement in mechanical properties. These factors are dominantly controlled by cooling during quenching which will promote more formation of intermetallic precipitates with controlled size of the intermetallic precipitates (Prabhuswamy et al 2007b, Kiourtsidis et al 2002).

6.3 WEAR STUDY

The micrographs of particle distribution, wear surfaces of as cast composites and the effect of wt.% of SiC particles, wt.% of graphite particles, applied load and sliding distance on dry sliding wear behaviour of aluminium composites reinforced with SiC and graphite particles are discussed in the following sections.

6.3.1 Micrographs of Particle Distribution and Wear Surfaces of as Cast Composites

Micrographs of as cast composites (Figure 6.1) showed that the reinforcement particles are uniformly distributed within the matrix material. The wear surface of the un heat treated Al 6061 hybrid composite specimens is shown in Figure 6.2 (a-d). After wear of the composite specimen, a non-uniform wear consisting of grooves, micro cutting and scratch marks have been formed by the reinforcing materials were observed. This shows that the wear of the composite is due to abrasion wear. Delamination is also observed on the wear surface of the composite which induces sub surface cracks that gradually grow and eventually shear to the surface, forming long thin wear sheets.
Figure 6.1 Micrograph of particle distribution in as cast composite

(a) Al 6061+4%SiC+3%graphite composite  (b) Al 6061+6%SiC+2%graphite composite

(c) Al 6061+6%SiC+4%graphite composite  (d) Al 6061+8%SiC+1%graphite composite

Figure 6.2 (a-d) Scanning electron micrographs of the wear surface of composites when the sliding distance is 1250m and applied load of 30N
6.3.2 Effect of Influencing Factors on Weight Loss

The developed mathematical model obtained from the wear test data is given in 5.8. This can be used to predict the weight loss of composite by substituting the coded values of the respective influencing factors. The responses calculated from this model for each set of coded factors are represented in graphical form in Figure 6.3-6.9. Effect of influencing factors such as weight percentage of SiC particles, weight percentage of graphite particles, applied load and sliding distance on weight loss are discussed in the following sections.

6.3.2.1 Effect of wt% of SiC particles on weight loss

Figure 6.3 depicts the effect of weight percentage of SiC particles on weight loss. It is observed that the weight loss of the composites decreases linearly with increasing content of silicon carbide particles in the matrix. This is similar to the observation made by other researchers (Sahin and Acilar 2003, Tham et al 2002, Tjong et al 1997). The reduction in weight loss of composites can be attributed to the following factors:

(a) SiC particle, a hard reinforcement, in a soft and ductile matrix increases the hardness and hence reduces the weight loss of the matrix alloy

(b) The thermal mismatch between the matrix alloy and the SiC particles the dislocations density is increased. The increased levels of dislocations increase the resistance of the materials to plastic deformation.

(c) Good bond between the matrix and reinforcement
(d) The SiC particles form a mixed layer at the interface of the composite pin and the steel disc. This layer was found to be composed of oxides of aluminium and iron which were scuffed off from the steel counterface by SiC particles.

![Figure 6.3 Effect of wt.% of SiC particles on weight loss](image)

6.3.2.2 Effect of wt% of graphite particles on weight loss

It can be observed from Figure 6.4 that the weight loss decreases on increasing the weight percentage of graphite particles.

![Figure 6.4 Effect of wt.% of graphite particles on weight loss](image)
The coefficient ($\beta_2$) associated with weight percentage of graphite particles ($X_2$) in the mathematical model (Equation 5.8) is seen to be negative, suggesting that the weight loss increased with decreasing weight percentage of graphite particles. This can be attributed to the lubricating effect of the graphite particles. Addition of graphite to the matrix reduces the friction during sliding motion. A similar observation was agreed in the previous studies carried out by the researchers (Basavarajappa et al 2007c, Gonzalez et al 2005, Akhlaghi and Pelaseyyed 2004a) during the investigation on aluminium based hybrid composites reinforced with graphite as a second reinforcement.

6.3.2.3 Effect of applied load on weight loss

The coefficient ($\beta_3$) associated with the applied load ($X_3$) in the mathematical model (Equation 5.8) is noted to be positive (Figure 6.5).

![Figure 6.5 Effect of applied load on weight loss](image)

This means that the weight loss increased with increase in applied load and can be attributed to the extensive plastic deformation at higher load. Greater the extent of plastic deformation, higher the probability of sub-surface cracking which in turn leads to larger volume of material removal. This has
been confirmed by Basavarajappa et al (2007d) in the case of hybrid Al 2219 alloy composite. He reported that with increasing applied load the weight loss (wear) of the composite increased.

6.3.2.4 Effect of sliding distance on weight loss

The variation of weight loss of the composites with sliding distance is shown in Figure 6.6. The coefficient ($\beta_4$) in the mathematical model (Equation 5.8) associated with the sliding distance ($X_4$) is observed to be positive indicating that the weight loss of the composite increases with increase in sliding distance. An increase in weight loss with increase in sliding distance can be mainly attributed to increased surface temperature. As the sliding distance increases, the surface temperature increases which promotes softening of the surface leading to higher surface and subsurface damage eventually resulting in higher weight loss as observed by Ramesh and Mirsaifiulla (2007c).

![Figure 6.6 Effect of sliding distance on weight loss](image)

It can be noted from the mathematical model that sliding distance has more effect on weight loss followed by weight percentage of graphite.
particles and applied load while the weight percentage of SiC particles had the least effect compared to other parameters, which could be possible due to the coarse particle size (75 microns). This is opposite to the previous study carried out on aluminium composites (Lin et al 1998a, Ranganath et al 2001a). They observed that weight percentage of SiC particles greatly influence the weight loss (wear) of the composites. They used 10-40 microns silicon carbide particles in an aluminium matrix to produce the composites.

6.3.3 Interaction Effects of Influencing Factors on Weight Loss

The interaction effects of influencing factors such as wt.% of SiC particles, wt.% of graphite particles, applied load and sliding distance on weight loss were discussed in the following sections.

6.3.3.1 Interaction effects of wt% of SiC and graphite particles on weight loss

The coefficients associated with applied load and sliding distance in Equation 5.8 are positive and the coefficients associated with weight percentage of SiC and graphite particles are also positive. Figure 6.7 depicts the interaction effects of weight percentage of SiC particles and graphite particles on weight loss of the composite. It is evident that the weight loss decreases with increase in weight percentage of SiC particles when the weight percentage of graphite particles is from 1% to 4%. But when weight percentage of graphite particle is 5% weight loss increases with increase in weight percentage of SiC particles. This is possibly due to the reduction in hardness with increase in graphite particle content. This observation is opposite to the previous study carried out by Lin et al (1995), who have stated that with increasing graphite content the wear resistance of the composites increases due to the lubricity of graphite particles.
Figure 6.7 Interaction effect of wt.% of SiC particles and graphite particles on weight loss

6.3.3.2 Interaction effects of wt% of SiC particles and sliding distance on weight loss

Figure 6.8 shows the interaction effects of weight percentage of SiC particles and sliding distance on weight loss of the composite. The interaction coefficient between weight percentage of SiC particle and sliding distance is positive.

Figure 6.8 Interaction effect of wt.% of SiC particles and sliding distance on weight loss
It is clear that weight loss decreases with increasing weight percentage of SiC particles when the sliding distance is from 500 to 1625m. A similar observation was observed by the researcher (Sahin 2005b), who has stated that weight loss of the aluminium composites increases with increasing sliding distance. But when the sliding distance is increased to 2000m, the weight loss slightly increases with increase in weight percentage of SiC particles. This can be due to increase in contact temperature with increase in sliding distance.

6.3.3.3 Interaction effects of applied load and sliding distance on weight loss

Figure 6.9 shows the interaction effects of applied load and sliding distance on weight loss. The interaction coefficient between applied load and sliding distance is negative.

![Interaction effect of applied load and sliding distance on weight loss](image)

**Figure 6.9 Interaction effect of applied load and sliding distance on weight loss**

It can be concluded that weight loss increases with the increase in applied load when the sliding distance is 500m. This is similar to the
observation made by Sahin (2005c), who has reported that the wear (weight loss) of the composite increases with increase in applied load. However, when the sliding distance is increased from 875 to 2000m, the weight loss decreases with increase in applied load. This signifies that the effect of sliding distance is more predominant than that of the applied load.

6.4 ARTIFICIAL NEURAL NETWORK MODELLING

The ANN was trained and implemented using a fully developed feed forward back propagation neural network. Absolute percentage errors were used to evaluate the performance of the developed ANN. It was found that the predicted and experimental values were very fairly close to each other. This is in agreement with the previous researchers (Kexing Song et al 2005a, Cook et al 1990, 1995). The variation of Mean Squared Error (MSE) with the number of epochs is depicted in Figure 6.10. In the present study, the desired MSE achieved after 20 epochs. Figure 6.11 represents the error profile of weight loss for both training and testing patterns and the maximum percentage of error was found to be around 6%. However, these levels of error are satisfactory and smaller than the errors that normally arise due to experimental variation and instrumentation accuracy. A comparison of the measured and predicted values of weight loss for the training and testing stage is given in Figure 6.12 and 6.13. From these comparison charts, it can be clearly seen that the developed ANN model is properly trained and shows a consistent weight loss values. Weight loss at testing stage indicates that there is a high correlation between them. Figure 6.14 and 6.15 represent the scatter diagram of experimental and predicted values of weight loss for training and testing data. The prediction can be seen as fairly close to the corresponding experimental values of weight loss. For trained data, it can be observed that a maximum and minimum absolute percentage error of 6.28% and -1.27% respectively was obtained for weight loss prediction. For tested data, it can
also be observed that a maximum and minimum absolute percentage error of 5.48% and -1.64% respectively was obtained for weight loss prediction. These results indicate that the well trained proposed network model has great accuracy in predicting the weight loss.

Figure 6.10 Variation of mean squared error (MSE) with number of epochs

Figure 6.11 Error profile of weight loss for training and testing patterns
Figure 6.12 Comparison for the training stage of weight loss

Figure 6.13 Comparison for the testing stage of weight loss

Figure 6.14 Scatter plot for the training stage of weight loss
6.5 HEAT TREATMENT STUDY

The micrographs of wear surfaces and dry sliding wear behaviour of heat treated composite specimens are discussed in the following sections.

6.5.1 Micrographs of Wear Surfaces of Heat Treated Composites

Scanning Electron Microscopic examinations of the wear surfaces of heat treated composites identified different wear mechanisms. They are abrasion, delamination and adhesion. It is evident from Figure 6.16 (a) that, the number of grooves, mostly parallel to the sliding direction were formed on all the wear pins. Grooving and scratch marks on the wear surface of the pin indicating the abrasion wear of the composite. Grooving and scratching appear more severe at the lower ageing duration Figure 6.16 (b). Grooves were less severe for higher ageing duration. Such features are characteristics of abrasion, in which hard asperities of the steel counter face, or hard reinforced particles in between the contacting surfaces, plough or cut into the pin, causing wear by the removal of small fragments of material. The abrasion
took place primarily via ploughing, in which material is displaced on either side of the abrasion groove without being removed, or through wedge forming, where tiny wedge shaped fragments are worn only during the initial contact with an abrasive particle (Wilson and Alpas, 1996b). Figure 6.16 (c-e) shows delamination in the wear surface of Al6061+8%SiC+5%graphite composite aged at 8h, 6h and 4h respectively. Delamination is fatigue related wear mechanism in which repeated sliding induces sub surface cracks that gradually grow and eventually shear to the surface, forming long thin wear sheets (Alpas and Zhang 1992b). Delamination is observed to be more extensive under the ageing duration of 4h. Since delamination involves subsurface deformation, crack nucleation and crack propagation, a decrease in ageing duration will hasten these processes and produce greater wear. The pivotal role of crack formation and growth in delamination also accounts for the higher wear of the composites. In the present tests, wear rates for the composites are higher under the ageing duration of 4h where delamination is significant.

Wear test the graphs obtained (Figure 6.17,6.18 and 6.19) show that the wear of composite reinforced with 8%SiC and 5% graphite particles was reduced for increasing ageing duration. SEM photo micrographs of the above composition have confirmed the wear test results. SEM photo micrograph Figure 6.16 (a-e) show relatively shallow grooves due to ploughing indicating that heat treatment has improved the resistance of composite to delamination.
(a) Grooves formation on the wear surface indicating abrasion wear
(b) Deep and large grooves on the wear surface
(c) Delamination in the wear surface of Al6061+8%SiC+5%graphite composite aged at 8h
(d) Delamination in the wear surface of Al6061+8%SiC+5%graphite composite aged at 6h
(e) Delamination in the wear surface of Al6061+8%SiC+5%graphite composite aged at 4h

Figure 6.16 (a-e) Scanning electron micrographs of the heat treated composite wear surfaces after wear testing
6.5.2 Effect of Reinforcement Particles Percentage on Wear Behaviour

Figure 6.17, 6.18 and 6.19 show graphs of wear curves of composite specimens with 1, 3 and 5% graphite particle content and 8% SiC particle content for aging durations of 4, 6 and 8h as well as that of unreinforced Al 6061 alloy. The wear curves of unreinforced Al alloy and composite specimens with 2, 4% graphite and 10% SiC particles for aging durations of 4, 6 and 8h are shown in Figure 6.20, 6.21 and 6.22. The tests were conducted by keeping the sliding distance and normal load at 1250m and 30N respectively. It is observed that the wear of composite specimens was less as compared to the Al 6061 alloy. The wear resistance of the metal matrix composites shows an increase with increase in reinforcement particle content. Similar trend of wear behaviour has been reported by Ma et al (1996). This is because of the presence of lubricating film formed by the graphite particles and hardness of the silicon carbide particles during sliding motion. The amount of wear has decreased with increase in ageing duration.

Figure 6.17 Wear behaviour of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 4h
It was observed from Figure 6.17 that the wear resistance of composites reinforced with 8% SiC and 5% graphite improved nearly nine times than the matrix material and nearly three times than the Al 6061 alloy reinforced with 8% SiC and 1% graphite particles. The wear curve of Al6061+8%SiC+1%graphite showed a very small initial nonlinear wear regime. After a certain sliding distance, the wear has increased linearly with time indicating steady state wear regime. The transition from initial wear regime to steady state wear regime occurs within few minutes (2-3min) of commencement of the test. The wear curve of Al6061+8%SiC+5%graphite showed an initial nonlinear wear regime and after a certain time the wear has increased very slowly.

![Wear curve comparison](image)

**Figure 6.18 Wear behaviour of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 6h**

It is evident from Figure 6.18 that the wear of composites reinforced with 8% SiC and 3% graphite particle shows a decrease of nearly four times than the matrix material. From the plot it can be observed that the maximum amount of wear of Al 6061 for sliding distance of 1250m is around 850 microns and the amount of wear of Al 6061 composite reinforced with
8%SiC and 5%graphite particle for the same sliding distance is 150 microns, indicating that wear resistance of the composite has increased more than five times than the matrix alloy. The wear resistance of the 8%SiC and 5%graphite particle composite aged at 6 h duration is more than the wear resistance of 8%SiC and 5%graphite particle composite aged at 4h duration.

Figure 6.19 shows the wear behaviour of hybrid Al 6061 composite aged at 8h duration. It was observed that upto 40 seconds the wear of all the composite specimens are almost uniform. Beyond this time the amount of wear is varying with percentage of graphite particle present in the composites. The initial wear of Al6061 composite reinforced with 8wt.% SiC and 5wt.% graphite particle is more (Upto 140 seconds) and increases very slowly. The wear curve of the unreinforced alloy shows that the wear increased linearly with time.

![Figure 6.19 Wear behaviour of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 8h](image)

It is evident from Figure 6.20, 6.21, 6.22 that the wear of composites reinforced with 10%SiC and 4% graphite particle decreases
compared with unreinforced alloy and the composite reinforced with 10% SiC and 2% graphite particles and also the wear of composites increases at the ageing duration of 8h.

Figure 6.20 Wear behaviour of Al 6061, Al 6061+10%SiC+2.4% graphite composites under an ageing duration of 4h

Figure 6.21 Wear behaviour of Al 6061, Al 6061+10%SiC+2.4% graphite composites under an ageing duration of 6h
From the above graphs it was observed that the amount of wear of the composites reinforced with 1, 3 and 5 wt.% of graphite particles are 225, 160 and 140 microns respectively when the composites are aged at 8h duration. For an ageing duration of 6h the observed amount of wear of the composites reinforced with 1, 3 and 5 wt.% of graphite particles are 245, 175 and 150 microns respectively and the amount of wear observed for the composites reinforced with 1, 3 and 5 wt.% of graphite particles are 650, 200 and 180 microns respectively when the composites are aged at 4h duration. The wear of heat treated unreinforced alloy reduced from 850 microns (Figure 6.18) to 675 microns (Figure 6.19). This can be due to the formation of more intermetallic precipitates when the ageing duration was increased. A similar observation was reported by Prabhuswamy et al (2007c) who have stated that the wear of the composite was reduced as ageing duration increases.

From these graphs it is clear that, the metal matrix composites with low weight fractions of graphite particle underwent large wear at all ageing durations. Base metal showed higher wear and metal matrix composites with
8wt.% SiC and 5wt.% graphite particle showed lower wear aged for 8h duration. In the initial wear regime, the reinforced particles act as a load carrying elements and as inhibitors against plastic deformation and adhesion of matrix material. In the later stages of wear regime, the worn particles get dislodged from their positions in the matrix and get mixed with the wear debris. The similar observation was observed by Ramachandra and Radhakrishna (2007d) who observed this behaviour is due to the wear debris containing matrix material and worn particles get pushed into the craters formed by dislodging of particles and acts as a load bearing elements. The amount of wear has decreased with increase in weight percentage of reinforcement particles.

6.5.3 Effect of Ageing Duration on Frictional Force

Figure 6.23 depicts the variation of frictional force of Al 6061+8%SiC+1%Gr composites for different ageing duration.

![Figure 6.23](image)

**Figure 6.23 Variation of frictional force of Al 6061+8%SiC+1%Gr composite with variation in ageing duration**

Frictional force varies between 11.0 to 39.0N for a variation of ageing duration from 4 to 8h. The range of variation of frictional force for
entire test duration for an ageing duration of 4h was between 17.5 to 39.0N. After 320 seconds sudden drop of the frictional force was observed. This can be possible due to lubricity of the graphite particles. For an ageing duration of 8h frictional force fluctuates in the range of 12.5 to 17.5N. Due to the large value of frictional force of the composite aged at 4h, the wear of this composite was more as compared to the composite aged at 8h.

Figure 6.24 shows the frictional force variation of Al 6061+8%SiC+3%Gr composites for different ageing time. The amount of frictional force varies between 6.0 to 18.0N. The amount of fluctuation of the frictional force is maximum for the composites aged at 8h. The value of frictional force lies between 7.0 to 12.0N for the composites aged at 6 and 4h. The lower value of the frictional force indicates that the amount of wear of the composites was less. When the frictional force generated in between the pin and disc surface is high then the wear of the material is more due to delamination.

Figure 6.24 Variation of frictional force of Al 6061+8%SiC+3%Gr composite with variation in ageing duration
Figure 6.25 shows the frictional force curves of Al 6061 composites reinforced with 8wt.% SiC and 5 wt.% graphite particle aged at 4 to 8h. The range of frictional force varies in between 4 to 20N. The composite aged at 8h is having the lowest frictional force. It indicates that the wear of this composite is very less compared to the composites aged at 4 and 6h. The amount of fluctuation of frictional force is also very less. The fluctuation of frictional force is maximum for composites aged at 6h.

Figure 6.25 Variation of frictional force of Al 6061+8%SiC+5%Gr composite with variation in ageing duration

Figure 6.26 and 6.27 shows the frictional force curves of Al 6061 composites reinforced with 10% SiC +2% graphite particles and 10%SiC +4% graphite particles aged at 4 to 8h. Frictional force varied between 10.0 to 28.0N. Lower values of the frictional force indicated that the amount of wear of the composites was less. When the frictional force generated between the pin and disc surface is high the wear of the material is more due to delamination.
6.5.4 Effect of Weight Percent of Reinforcement Particles on Coefficient of Friction

Figure 6.28 shows the variation of coefficient of friction of hybrid composites under an ageing duration of 4 h. The coefficient of friction value
lies between 0.4 to 0.55 for hybrid composites reinforced with 5 wt.% graphite particles and 0.6 to 0.9 for unreinforced alloy. It is clear that, the coefficient of friction has decreased with increasing graphite particle content. During the test a normal load of 30N and sliding distance of 1250m were used. Hybrid composites with 5wt.% graphite particles reinforcement showed lowest average coefficient of friction of 0.45. It was found that in all the composites aged at 4h, the composite reinforced with 5wt.% graphite is having the minimum value of the coefficient of friction, and hence the wear of the composite also lower.

![Figure 6.28 Variation in coefficient of friction of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 4h](image)

Figure 6.28 Variation in coefficient of friction of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 4h

Figure 6.29 depicts the variation of coefficient of friction of composites with varying percentage of graphite particles aged at 6h. The fluctuation of coefficient of friction for the unreinforced alloy is maximum and the value lies in between 0.3 to 0.9 while the value lies in between 0.3 to 0.4 for composites reinforced with 5wt.% of graphite particles. This trend in the variation of coefficient of friction may be due to the presence of graphite
particles. This will reduce the friction by providing point of contact between counter face and the pin.

Figure 6.29 Variation in coefficient of friction of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 6h

It is evident from Figure 6.30 that, the increased content of graphite particle has decreased the coefficient of friction. Composite with 5wt.% of graphite particle reinforcement showed lowest average coefficient of friction 0.1 and the base material exhibited an average coefficient of friction in the range of 0.6 to 0.75. It was found that the composites reinforced with 5wt.% of graphite content aged at 8h has lower wear due to the lower value of the coefficient of friction. The fluctuation of coefficient of friction of the composites reinforced with 3wt.% of graphite particle reinforcement lies between 0.5 to 0.6 and 0.4 to 0.6 for composites reinforced with 1wt.% of graphite particle. The range of variation of coefficient of friction is more for composites reinforced with 1 wt.% of graphite particles.
Figure 6.30 Variation in coefficient of friction of Al 6061, Al 6061+8%SiC+1,3,5% graphite composites under an ageing duration of 8h

Figure 6.31, 6.32 and 6.33 shows the variation of coefficient of friction of hybrid composites under an ageing duration of 4, 6 and 8 h. The coefficient of friction value lies between 0.28 to 0.55.

Figure 6.31 Variation in coefficient of friction of Al 6061, Al 6061+10%SiC+2,4% graphite composites under an ageing duration of 4h
It is clear that, the coefficient of friction has decreased with increasing graphite particle content. The fluctuation of coefficient of friction for the unreinforced alloy is maximum and the value lies in between 0.6 to 0.9.

Figure 6.32 Variation in coefficient of friction of Al 6061, Al 6061+10%SiC+2.4% graphite composites under an ageing duration of 6h

Figure 6.33 Variation in coefficient of friction of Al 6061, Al 6061+10%SiC+2.4% graphite composites under an ageing duration of 8h
6.6 MACHINING CHARACTERISTICS STUDY

The micrographs of electric discharge machined composite specimen surfaces and effect of process parameters on Metal Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness (SR) are presented in the following sections.

6.6.1 Micrographs of Electric Discharge Machined Composite Surfaces

Figure 6.34 (a-d) shows the SEM photograph of electric discharge machined surface of the composite. When the discharge current increases from 3A to 15A, electric discharges strike the surface of the work piece more intensely. Due to this the diameter and the depth of craters of electric discharge machined surface increases, and hence the surface roughness consequently increases. Owing to the insulating nature of reinforcement particles, abnormal arcing and random spark discharges occur in the region where micron-sized reinforcements are seen. Fall out of particles can be observed due to the impact of spark. Bands and craters observed at the machined surfaces of composites as shown in Figure 6.34 c and d confirm the irregular spark discharges during machining. In general, at low discharge energy the craters are shallow and the surface irregularities are smooth, shallow and less frequent. At high discharge energy the craters are deeper and surface irregularities are larger and more pronounced. When the flushing pressure was increased, the rate of solidification of debris scattered over the electric discharge machined surface by molten material droplets from the tool and work piece electrodes also increased. Because of this the surface roughness of the machined work piece was decreased. The obtained variation in surface roughness of the composite (Ra = 4–11 μm) for all the selected experimental conditions is also minimal due to the flushing of debris.
Figure 6.34 (a-d) SEM photograph of electric discharge machined surface of Al 6061 composites reinforced with SiC and graphite particles at a voltage 50V and a flushing pressure 3psi: a) 3A,400µs, b) 15A,400µs, c) 9A,200µs, d) 9A,600µs

6.6.2 Effect of Process Parameters on MRR, TWR and SR

The mathematical models developed shown in Equations 5.12, 5.13 and 5.14 can be used to predict the response variables by substituting the coded values of the respective process parameters. The responses calculated from these models for each set of coded machining parameters are represented in graphical form in Figure 6.35-6.38. In addition, by substituting the values of desired response variables, the values of the machining parameters in coded form can be obtained. The influence of process parameters such as the current, pulse on time, voltage and the surface roughness were analyzed based
on mathematical models. Direct effect of influencing factors such as current, pulse on time, voltage and flushing pressure on metal removal rate, tool wear rate and surface roughness are discussed in the following sections.

### 6.6.2.1 Effect of current on MRR, TWR and SR

Figure 6.35 depicts the direct effect of current on the response variables. It can be observed that the metal removal rate and tool wear rate of the composites increases linearly with increasing the value of current. The increase in metal removal rate and tool wear rate is due to the fact that the spark discharge energy increases to facilitate melting and vaporization and promoting the large impulsive force in the spark gap. High current values results in higher thermal loading on both tool and work piece electrode lead to high metal removal rate and tool wear rate. The surface roughness value also slightly increases with increase in current. This is similar to the observation made by other researchers (Narender singh et al 2004c) who have stated that increase in current results in increasing metal removal rate, tool wear rate and surface roughness.

![Figure 6.35 Effect of current on the response variables](image-url)
6.6.2.2 Effect of pulse on time on MRR, TWR and SR

It can be observed from the effect pulse on time (T) on MRR and SR shown in Figure 6.36, the metal removal rate and surface roughness increases with increasing the value of pulse on time while the tool wear rate shows a decrease. The increase in the pulse on time means applying the same heating temperature for longer time. This will cause an increase in the evaporation rate and the number of gas bubbles, which explode with high ejecting force when the discharge ceases, causing removal of bigger volume of the molten metal. Increase in the discharge current strengthens the pulsation energy, so that the material is removed more easily at higher current densities. In addition, increasing the pulse on time possibly results in the expansion of the discharge column, promoting the material removal rate and surface roughness.

The coefficient ($\beta_z$) associated with pulse on time (T) in the developed mathematical model for metal removal rate and surface roughness (Equations 5.12 and 5.14) is seen to be positive while for tool wear rate shown in Equation 4.13, it is negative. This suggests that the metal removal rate and surface roughness are directly proportional to the pulse-on-time whereas the tool wear rate is just the opposite. Reduction in tool wear rate can be attributed to the fact that rate of evaporation from tool is lower. A similar observation for the effect of pulse on time on metal removal rate and surface roughness was observed in a study carried out on the machining of composites using electric discharge machining (Kao et al 2009) where copper was used as the tool material. However, the effect of pulse on time with tool wear rate is in disagreement with another work (Narender singh et al 2004d) where it has been stated that an increase in pulse on time results in increasing the tool wear rate due to the presence of SiC particles only in aluminium matrix.
6.6.2.3 Effect of voltage on MRR, TWR and SR

The variation of machining parameters of the composites with voltage during EDM is shown in Figure 6.37. The coefficient ($\beta_v$) in the developed mathematical model for tool wear rate and surface roughness associated with the voltage shown in Equations 5.13 and 5.14 is seen to be positive, while for that metal removal rate shown in Equation 5.12 is negative. This suggests that the tool wear rate and surface roughness are directly proportional to the voltage whereas the metal removal rate is inversely proportional. It can be observed from Fig.6.37 that low values of voltage can give rise to increase in metal removal rate. However, application of very low values promotes arcing tendency. Higher values of gap voltage can cause relatively lower removal rates. This is in opposition to the previous study carried out on electric discharge machining of mixed alumina based ceramic with titanium carbide composites (Ko-Ta Chiang 2008a), where it was stated that increase in voltage leads to increase in metal removal rates. However the
effect of voltage on tool wear rate and surface roughness is in agreement with yet another study carried out on the electric discharge machining of composites (Narender singh et al 2004e).

![Graph showing the effect of voltage on MRR, TWR, and SR](image)

**Figure 6.37 Effect of voltage on the response variables**

### 6.6.2.4 Effect on flushing pressure on MRR, TWR and SR

In electric discharge machining, flushing is very important, since the dielectric flushing of the spark gap keeps the gap clean and removes spark eroded particles continuously from the gap. It has a significant influence on machining stability, which in turn affects the removal rate and tool wear rate. From Figure 6.38, it is found that the dielectric flushing pressure has positive effect on metal removal rate and surface roughness. The metal removal rate and surface roughness increases with increase in dielectric flushing pressure. This is because when the flushing pressure is low, flushing cannot remove the gaseous and solid debris adequately after each discharge and the dielectric is increasingly unable to clear away the molten material, causing it to build upon
the surface of the parent material. Further, an increase in the flushing pressure decreases the tendency for arcing and increases the metal removal rate. The tool wear rate decreases with increasing flushing pressure. This is possibly due to the increase in cooling rate of the tool with increase in flushing pressure. A similar observation has been reported by Narender singh et al 2004f, El-Taweel 2009a.

![Figure 6.38 Effect of flushing pressure on the response variables](image)

**Figure 6.38 Effect of flushing pressure on the response variables**