CHAPTER 8

COMPARATIVE STUDIES

Aluminium alloy 356 and 413 were chosen as the matrix material, boron carbide, fly ash and hybrid of boron carbide and fly ash were chosen as the reinforcement material. The reinforcements were in the form of particles and were added in 3%, 6% & 9% by weight. Six sets of composites and two aluminium alloys (356 & 413) were fabricated using stir casting technique. WEDM experiments and pin on disc wear tests were conducted using Taguchi’s L$_{27}$ orthogonal array for all six sets of composites. WEDM and wear tests were also conducted on the 356 & 413 aluminium alloys. The results of the comparative studies were discussed in the following sections.

8.1 COMPARISON OF MRR

The Material Removal Rate (MRR) must be more for any type of machining and material. Wire EDM is used to study the machinability, the experiments were conducted based on Taguchi’s DOE and analyzed using S/N ratio analysis. The Taguchi technique optimizes the input parameters to obtain the required output. The optimum machining parameters for obtaining larger MRR using Wire Electric Discharge Machining of 356 & 413 aluminium alloy and six sets of composites along with their confirmation experimental values were presented in Table 8.1 and Figure 8.1.
Table 8.1 Optimum Parameters and their MRR values

<table>
<thead>
<tr>
<th>Material</th>
<th>Gap Voltage (V)</th>
<th>Pulse on Time (µs)</th>
<th>Pulse off Time (µs)</th>
<th>Wire Feed (m/min)</th>
<th>Reinforcement (wt %)</th>
<th>MRR (mm³/min)</th>
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<td>356 Al alloy</td>
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<td>10</td>
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</tr>
<tr>
<td>356 + B₄C composites</td>
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<td>2</td>
<td>4</td>
<td>3</td>
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</tr>
<tr>
<td>356 + Fly ash composites</td>
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<td>36.96</td>
</tr>
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<td>-</td>
<td>37.97</td>
</tr>
<tr>
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<td>9</td>
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<td>413 + Hybrid composites</td>
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<td>2</td>
<td>4</td>
<td>6</td>
<td>38.01</td>
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</table>

Figure 8.1 Comparison of optimum MRR values
Table 8.1, first row and fifth row shows the optimum input parameters in WEDM for obtaining maximum MRR in 356 Aluminium alloy and 413 Aluminium alloys respectively. This was obtained using Taguchi’s L9 OA. The Taguchi’s L27 OA was used for WEDM of composites. Totally six sets of 27 experiments were conducted. The second row shows the optimum input parameters for obtaining maximum MRR in 356 + Boron Carbide (3%, 6% & 9%) composites. The third row shows the optimum input parameters for obtaining maximum MRR in 356 + Fly ash (3%, 6% & 9%) composites. The fourth row shows the optimum input parameters for obtaining maximum MRR in 356 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The sixth row shows the optimum input parameters for obtaining maximum MRR in 413 + Boron Carbide (3%, 6% & 9%) composites. The seventh row shows the optimum input parameters for obtaining maximum MRR in 413 + Fly ash (3%, 6% & 9%) composites. The eighth row shows the optimum input parameters for obtaining maximum MRR in 413 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The gap voltage, pulse on time and pulse off time are the most significant factors for obtaining maximum MRR. The wire feed and reinforcement are neutral parameters. Interestingly gap voltage of 30 V, pulse on time of 10 µs and pulse off time of 2 µs gives the maximum MRR for all six sets of composites (18 composites) and 2 aluminium alloys.

While comparing among 356 alloy and composites, 356 aluminium alloys have maximum MRR followed by 356 + Boron Carbide composites, 356 + Fly Ash composites and 356 + Hybrid Composites.

While comparing among 413 alloy and composites, 413 + Fly Ash composites have maximum MRR followed by 413 + Boron Carbide composites, 413 + Hybrid Composites and 413 aluminium alloys.
8.2 COMPARISON OF SR

The Surface Roughness must be less for any type of machining and material. The optimum input parameters for obtaining lesser SR using Wire Electric Discharge Machining of 356 & 413 aluminium alloy and six sets of composites along with their confirmation experimental values were presented in Table 8.2 and Figure 8.2.

Table 8.2 Optimum Parameters and their SR values

<table>
<thead>
<tr>
<th>Material</th>
<th>Gap Voltage (V)</th>
<th>Pulse on Time (µs)</th>
<th>Pulse off Time (µs)</th>
<th>Wire Feed (m/min)</th>
<th>Reinforcement (wt % )</th>
<th>SR (µm)</th>
</tr>
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<td>413 Al alloy</td>
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<td>6</td>
<td>4</td>
<td>-</td>
<td>2.95</td>
</tr>
<tr>
<td>413 + B4C composites</td>
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<td>6</td>
<td>6</td>
<td>3</td>
<td>2.75</td>
</tr>
<tr>
<td>413 + Fly ash composites</td>
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<td>6</td>
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<td>3</td>
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</table>
Figure 8.2 Comparison of Optimum Surface Roughness values

Table 8.2, first row and fifth row shows the optimum input parameters in WEDM for obtaining minimum SR in 356 Aluminium alloy and 413 Aluminium alloys respectively. This was obtained using Taguchi’s L_9 OA. The Taguchi’s L_{27} OA was used for WEDM of composites. Totally six sets of 27 experiments were conducted. The second row shows the optimum input parameters for obtaining minimum SR in 356 + Boron Carbide (3%, 6% & 9%) composites. The third row shows the optimum input parameters for obtaining minimum SR in 356 + Fly ash (3%, 6% & 9%) composites. The fourth row shows the optimum input parameters for obtaining minimum SR in 356 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The sixth row shows the optimum input parameters for obtaining minimum SR in 413 + Boron Carbide (3%, 6% & 9%) composites. The seventh row shows the optimum input parameters for obtaining minimum SR in 413 + Fly ash (3%, 6% & 9%) composites. The eighth row shows the optimum input parameters for obtaining minimum SR in 413 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The reinforcement and gap voltage are the most
significant factors for obtaining minimum SR. The interactions of parameters play important role in obtaining minimum SR. It has been observed that the combination of factors for optimization of Surface Roughness for each set of composites were different.

While comparing among 356 aluminium alloy and composites, 356 aluminium alloy have minimum SR followed by 356 + Fly Ash composites, 356 + Hybrid Composites and 356 + Boron Carbide composites.

While comparing among 413 alloy and composites, 413 + Fly Ash composites have minimum SR followed by 413 + Boron Carbide composites, 413 aluminium alloy and 413 + Hybrid Composites among the 413 composites.

8.3 COMPARISON OF WEDM RESULTS WITH OTHER RESEARCHES

A comparison of the optimization results obtained in this work with those reported in the literature is difficult because different materials, WEDM machines of different manufacturers and different machining parameters have been used by others. Scott et al. 1991 used Robofil 100 machine and identified 32 non-dominated combinations of process parameters. However, the discharge currents and pulse durations used in the investigations are very much lower than the values used in the present work. Spedding and Wang worked on Robofil 300, machining was done on AISI 420 steel workpiece of 31.5-mm height using a brass wire electrode with four setting parameters.

Effect of Pulse on Time on Material Removal Rate

The experiment results indicate that MRR increases with increase in pulse on time, and that the fly ash reinforced 413 Aluminium alloy
exhibited the highest MRR (40.75 mm\(^3\)/min), followed by 356 Al alloy (39.79 mm\(^3\)/min) the lowest among these materials is 356 Hybrid composites (36.96 mm\(^3\)/min). Optimum pulse on time for all the materials are interestingly 10 micro seconds, which is the maximum of the three levels chosen and also maximum of the CNC Eco cut WEDM. The same trend was reported by Biing Hwa Yan et al 2005.

At longer pulse on time, more discharge energy, which subsequently causes a more powerful explosion and results in deep craters on the surface of the work piece. Deep craters indicate high rates of metal removal and poor surface finish. It is desirable to use higher values of pulse-on time to obtain higher rates of metal removal (Kapil Kumar & Sanjay Agarwal 2012).

It could be inferred from the results that higher pulse on time leads to increase in cutting velocity due to higher thermal energy which transfers from wire to workpiece (Bagherian Azhiri et al 2014).

**Effect of Pulse off Time on Material Removal Rate**

The experiment results indicate that MRR increases with decrease in pulse off time. Optimum pulse off time for all the materials are interestingly 2 micro seconds, which is the minimum of the three levels chosen. Increase in pulse off time leads lower cutting velocity due to increase in non-cutting time (Bagherian Azhiri et al 2014).

A larger pulse off time result in a small gap width, but it also offers a longer flushing time to clean the debris in the gap. A longer pulse off time is always adopted for wire rupture prevention or for the elimination of the abnormal process. It is noted that the increase of pulse off time leads to the decrease of gap voltage. Hence, the feed rate is reduced, and the gap width
becomes larger accordingly. This action allows a better flush of the debris in
the gap, and the process is improved. Off-time should be increased and table
feed should be reduced for a high risk of wire rupture. A larger on-time
produces more instantaneous metal removal, which leads to a high
instantaneous slag concentration, and the gap becomes easy to ionize (Liao &
Woo 1997).

At shorter pulse off time, more number of discharges in a given
time during machining led to an increase in cutting rate, resulting to large
craters and micro-damage on the surface. The formation of the craters in the
WEDMed surface is also due to sparks that form at the conductive phase,
generating melting or possible evaporation. It is obvious that large crater sizes
result in a rough surface (Kapil Kumar & Sanjay Agarwal 2012).

**Effect of Voltage on MRR**

Result indicates that the MRR increases with decrease in gap
voltage. The same trend is followed by Bagherian Azhiri et al, 2014 also.30 V
is the optimum gap voltage for obtaining larger MRR. It’s interesting that 30
V is the optimum voltage for all the six sets of composites and two base
alloys. Actually, the increase of the voltage means that the electric field
becomes stronger and the spark discharge takes place more easily under the
same gap. Lower voltage can produce sufficient energy to melt the
surrounding dielectric particles (Guo et al 2002).The material removal rate
(MRR) directly increases with increase in pulse on time and peak current
while decreases with increase in pulse off time and servo voltage (Singh &
Garg 2009).
Effect of the Wire Feed and Reinforcement on MRR

The wire feed and percentage of reinforcement are neutral input parameters. The wire feed should be chosen so that the wire does not break. Cutting speed increases with an increase in wire speed. In the nutshell we can say that Results from this study were in agreement with findings in literature. Although those research efforts performed on different materials, the outcomes were in accordance.

Effect of Gap Voltage on SR

The surface roughness reduces as the voltage increases. This is a very interesting phenomenon. Lower voltage cannot produce sufficient energy to melt the surrounding dielectric particles, which remain on the machined surface and form many protruding peaks. In contrast, with a high voltage these grains are melted and removed, resulting in better surface roughness (Guo et al 2002). Increase in gap voltage resulting in higher electrostatic force and leads to winding of wire during discharge process. So, lower surface roughness is obtainable while gap voltage increases (Bagherian Azhiri et al 2014).

Effect of Pulse on time on surface roughness

Surface roughness decreases with decrease in pulse on time. SR is significant to the finish cut of wire electrical discharge machining (WEDM). Experiments proved that the surface roughness can be improved by decreasing both pulse duration and discharge current. Most related research found that the roughness of WEDMed surfaces increased accompanying the increase of discharge energy, since greater discharge energy would produce larger craters, thus causing a larger surface roughness value on the work piece. Furthermore, related research has indicated that the dominant factor
affecting surface roughness was pulse duration, because the surface roughness depended on the size of the spark crater. Shallow craters together with larger diameters lead to better work piece surface roughness. To obtain flat craters, it is important to control the electrical discharge energy at a lower level by setting short pulse duration (Han et al 2007).

Higher pulse on time leads to higher surface roughness due to transferring more thermal energy that induces deeper discharge craters on work piece surface (Bagherian Azhiri et al 2014).

**Effect of Pulse off time on surface roughness**

It can be inferred that higher pulse off time leads to lower surface roughness due to increasing noncutting time (Bagherian Azhiri et al 2014).

**Effect of Wire feed and Reinforcement on surface roughness**

SR decreases with increasing reinforcement particles. Wire feed is a neutral parameter. Increasing the wire feed rate may reduce the rigidity of wire during discharging process; hence, the wire wind back during the sparks and damaging power of sparks on workpiece surface decreases (Bagherian Azhiri et al 2014).

**8.4 COMPARISON OF SWR**

The Specific wear rate must be less for any material. The optimum input parameters for lower SWR in pin on disc wear testing of 356 & 413 aluminium alloy and six sets of composites along with their confirmation test values were presented in Table 8.3 and Figure 8.3.
Table 8.3 Optimum Parameters and SWR values

<table>
<thead>
<tr>
<th>Material</th>
<th>Sliding Speed, S (m/s)</th>
<th>Sliding Distance, D (m)</th>
<th>Load, L (N)</th>
<th>Reinforcement, R (wt %)</th>
<th>SWR x 10⁻⁵ (mm³/Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>356 Al alloy</td>
<td>1.5</td>
<td>500</td>
<td>45</td>
<td>-</td>
<td>6.21</td>
</tr>
<tr>
<td>356 + B₄C composites</td>
<td>2</td>
<td>500</td>
<td>45</td>
<td>3</td>
<td>5.67</td>
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<tr>
<td>356 + Fly ash composites</td>
<td>1.5</td>
<td>500</td>
<td>45</td>
<td>3</td>
<td>5.57</td>
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<td>6</td>
<td>3.52</td>
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<tr>
<td>413 Al alloy</td>
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<td>-</td>
<td>8.75</td>
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<td>45</td>
<td>6</td>
<td>5.14</td>
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Figure 8.3 Comparison of Optimum SWR values
Table 8.3, first row and fifth row shows the optimum input parameters for obtaining minimum SWR in 356 Aluminium alloy and 413 Aluminium alloys respectively. This was obtained using Taguchi’s L$_9$ OA. The Taguchi’s L$_{27}$ OA was used for WEDM of composites. Totally six sets of 27 experiments were conducted. The second row shows the optimum input parameters for obtaining minimum SWR in 356 + Boron Carbide (3%, 6% & 9%) composites. The third row shows the optimum input parameters for obtaining minimum SWR in 356 + Fly ash (3%, 6% & 9%) composites. The fourth row shows the optimum input parameters for obtaining minimum SWR in 356 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The sixth row shows the optimum input parameters for obtaining minimum SWR in 413 + Boron Carbide (3%, 6% & 9%) composites. The seventh row shows the optimum input parameters for obtaining minimum SWR in 413 + Fly ash (3%, 6% & 9%) composites. The eighth row shows the optimum input parameters for obtaining minimum SWR in 413 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The load is the most significant factor for obtaining minimum SWR followed by sliding speed, sliding distance and reinforcement.

While comparing among 356 aluminium alloy and composites, 356 + Hybrid Composites have minimum SWR followed by 356 + Fly Ash composites, 356 + Boron Carbide composites and 356 aluminium alloys.

While comparing among 413 alloy and composites, 413 + Fly Ash composites have minimum SWR followed by 413 + Boron Carbide composites, 413 + Hybrid Composites and 413 aluminium alloys.

8.5 COMPARISON OF COF

The COF must be less for materials like piston, cylinder, cylinder liner, etc. The optimum input parameters for lower COF in pin on disc wear
test of 356 & 413 aluminium alloy and six sets of composites along with their confirmation test values were presented in Table 8.4 and Figure 8.4.

Table 8.4 Optimum Parameters and COF values

<table>
<thead>
<tr>
<th>Material</th>
<th>Sliding Speed, S (m/s)</th>
<th>Sliding Distance, D (m)</th>
<th>Load, L (N)</th>
<th>Reinforcement, R (wt %)</th>
<th>COF</th>
</tr>
</thead>
<tbody>
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<td>356 + B$_4$C composites</td>
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Figure 8.4 Comparison of Optimum COF values
Table 8.4, first row and fifth row shows the optimum input parameters for obtaining minimum COF in 356 Aluminium alloy and 413 Aluminium alloys respectively. This was obtained using Taguchi’s L9 OA. The Taguchi’s L27 OA was used for WEDM of composites. Totally six sets of 27 experiments were conducted. The second row shows the optimum input parameters for obtaining minimum COF in 356 + Boron Carbide (3%, 6% & 9%) composites. The third row shows the optimum input parameters for obtaining minimum COF in 356 + Fly ash (3%, 6% & 9%) composites. The fourth row shows the optimum input parameters for obtaining minimum COF in 356 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The sixth row shows the optimum input parameters for obtaining minimum COF in 413 + Boron Carbide (3%, 6% & 9%) composites. The seventh row shows the optimum input parameters for obtaining minimum COF in 413 + Fly ash (3%, 6% & 9%) composites. The eighth row shows the optimum input parameters for obtaining minimum COF in 413 + Boron Carbide (1.5%, 3% & 4.5%) + Fly ash (1.5%, 3% & 4.5%) hybrid composites. The load is the most significant factor for obtaining minimum COF followed by sliding distance, sliding speed and reinforcement.

While comparing among 356 aluminium alloy and composites, 356 + Fly Ash Composites have minimum COF followed by 356 aluminium alloy, 356 + Hybrid composites and 356 + Boron Carbide composites.

While comparing among 413 alloy and composites, 413 + Boron Carbide composites have minimum SWR followed by 413 + Hybrid Composites 413 + Fly Ash composites and 413 aluminium alloys among the 413 composites.
8.6 MICRO GRAPHS OF WORN PINS (356 AMCs)

The SEM micrograph of worn pins of 356 aluminium alloy and its composites with lesser wear rate with optimum parameter using the Taguchi S/N ratio analysis are shown in Figure 8.5 to Figure 8.8.

An examination of worn surface of aluminium alloy 356 reveals ploughing of material from the surface. Micrograph of 356+3% B₄C composite reveals mild patches, 3% B₄C reinforcement has less wear rate compared to 6% and 9% B₄C reinforced composites. The worn surface of 356+ 3% flyash indicates the presence of debris of oxides which are present in the fly ash. The worn surfaces of 356 + 6% hybrid composites show severe patches and grooves.

Figure 8.5 Micrograph of worn pin of 356 Al Alloy

Figure 8.5 & 8.6 shows the SEM images of the wear test pins of virgin 356 alloy and 3% B₄C metal matrix composite. Figure 8.5 shows broad
grooves with long deformed grains. The surface also shows the effect of ploughing. On the other hand alloy 356 with 3% addition of $\text{B}_4\text{C}$ shows smooth fine finished surface with least crest and troughs. Only the particles of $\text{B}_4\text{C}$ from the metal matrix are seen after wear test.

![Figure 8.6 Micrograph of worn pin of 356 +3 % $\text{B}_4\text{C}$](image)

Figure 8.5 & 8.7 shows the wear test pins surfaces of 356 aluminium alloy with 3% fly ash addition. Comparison of virgin 356 alloy with 3% fly ash show that 3% addition of fly ash shows improved wear resistant behavior as per the SEM images taken.
Similarly 6% hybrid composite shows lesser wear rate compared to the other percentages of hybrid composites with virgin 356 alloy. The hybrid composite of 3% $B_4C$ & 3% Fly ash show improved wear resistant properties due to $B_4C$ addition. It is evident that the addition of $B_4C$ with fly ash contributed to the lesser wear rate showing the wear resistant properties of $B_4C$. This reduction in severity of the worn surfaces is due to the presence of hard boron carbide particles which has the direct contact of the material with the harder counter face material. The wear test experiment values are in tandem with the SEM images recorded. These results match with the trend reported by earlier researchers (Kenney & Courtois 1998, pasto et al 1999, Shorowordi et al 2003, Sajjadi et al 2012). They observed that increasing the wt% of $B_4C$ in composites, up to 15% increases the wear properties of the composites.

**Figure 8.7 Micrograph of worn pin of 356 +3% Fly Ash**
8.7 MICROGRAPHS OF WORN PINS (413 AMCs)

The SEM micrograph of worn pins of 413 aluminium alloy and its composites with lesser wear rate with optimum parameters using the Taguchi S/N ratio analysis are shown in Figure 8.9 – Figure 8.12.

The SEM images of the 413 virgin aluminium alloy worn surface shows smaller grooves and broad patches along the sliding direction indicating a greater degree of wear and localized adhesion between the pin surface and the counter body probably due frictional heat.

Figure 8.8 Micrograph of worn pin of 356 +6% Hybrid
Figure 8.9  Micrograph of worn pin of 413

Micrograph of 413 + 9% B₄C reveals lesser wear rate due to the presence of hard B₄C particles.

Figure 8.10  Micrograph of worn pin of 413 +9% B₄C
SEM images of 413+9% fly ash shows ploughing of fly ash particles, because the fly ash particles are smaller in size and softer than boron carbide. Hence 413+9% fly ash comparing with virgin 413 alloys show lesser wear rate. The presence of fly ash particles at the interface could have caused the lower friction and lower wear rate.

Figure 8.11 Micrograph of worn pin of 413 +9% Fly Ash

413+ 6% hybrid composites shows lesser wear rate compared to 3% & 9 % hybrid composites. This reduction in severity of the worn surfaces is due to the presence of hard boron carbide particles which presents the direct contact of the matrix material with the harder interface material. The presence of fly ash decreases the wear rate.
8.8 COMPARISON OF WEAR RESULTS WITH OTHER RESEARCHES

The wear results are discussed in comparison with other researches based on the input parameters: sliding speed, reinforcement percentage, applied load and sliding distance.

Effect of Sliding Speed

The sliding wear decreases with increasing the sliding speed for the tested range. This has been attributed to the increased extent of oxidation of the Al alloy as a result of higher interfacial temperatures. The thicker oxide present helps to protect the sliding interfaces by lowering the wear rate. This may as well be the reason for the decrease in wear rate with increasing sliding speed in the present case too (Basavarajappa & Chandramohan 2005).
With increase in sliding speed, there will be less time for material to escape from the wear track. Indirectly this will imply that with increase of the sliding speed, tribolayer thickness increases and will be relatively thicker for longer durations. Thus both the wear rate and the friction coefficient decrease with increase of the sliding speed (Uyyuru et al 2007).

It is observed that higher sliding velocity leads to lower wear rate and lower friction coefficient for both MMCs. It is suggested that the transfer layer on MMC acts as a protective cover and helps reduce both wear rate and friction coefficient (Shorowordi et al 2004). The wear rate decreases as the sliding speed increases (Daoud & Abou El-khair 2010, Radhika et al 2011).

The reason for the decrease in the wear rate with increasing sliding speed at low speeds is based on the competing effects of the temperature rise and strain rate. It is well known that the hardness of a material depends on the rate of indentation. An increase in the sliding speed will increase the strain rate which, in turn, increases the hardness or flow strength. This increase in the flow strength will reduce the true area of contact and thus result in a lower wear rate. Another important effect of the increasing sliding speed is the rise in temperature due to frictional heat, which softens the material. This will, in turn, result in a higher wear rate owing to increased true area of contact (Subramanian 1991, 1992).

**Effect of Reinforcement Percentage**

The reinforcement did not appear to influence the wear rate and the wear rate for the composites and matrix alloy was similar at low sliding velocities. In steady state sliding the choice of reinforcement type had no influence on the wear rates of the composite (Deuis et al 1997).
The wear rate decreases with the increase in reinforcement percentage. The projected ceramic particles in the pin will plough the surface of the counter face. The ploughed surface of the counter face that is Fe will react with aluminium of the pin and form Fe$_2$O$_3$, and ceramic particles will crush to very minute particles and form a layer designated as mechanically mixed layer (MML). The MML forms a layer between the workhardened pin and the counter face and reduce the sliding wear. The quantity of increase in wear resistance with the further increase in reinforcement from 3 to 9 wt pct in steps of 3% is less because it will only increases the thickness of the MML.

The various researchers have the opinion that as the reinforcement content increases, the dry sliding wear resistance increases. The quantity of increase in wear resistance will be less with further increase in reinforcement content. Sannino and Rack (1995) recognized that an increase in hard ceramic reinforcement in discontinuously reinforced aluminium (DRA) composites up to approximately 20 vol. pct improves the abrasion and fretting wear resistance (Basavarajappa & Chandramohan 2005). The wear is found to be low, because of the presence of the hard ceramic particles present in the MMC which acts as the load bearing member and abrasive nature (Natarajan et al 2006).

Some studies report that the wear and friction behaviour of aluminium-based MMC, strongly depends on the reinforcement’s particle, particle size and rate. If the rate of reinforcement particle in MMC is low, the coefficients of friction of the composites were high. Besides these, the wear resistance increases with increasing volume fraction of reinforcing particulates. If the reinforcement particle is well bonded to the matrix, the composite wear resistance increases continuously with increasing volume fraction of ceramic particles. This critical volume fraction depends on the load applied during the wear test (Ipek 2005).
Particle additions have reduced the wear rates of the composites and have delayed the transition with load from low wear coefficients to higher wear coefficients, low wear rates were characterized by thin stable transfer layers and an almost uniform wear coefficient (Shipway et al 1998).

The wear resistance of the MMCs has increased with increase in flyash content. This is because of the presence of hard flyash particles which will increase the overall bulk hardness of the material. The MMCs with low weight fractions of flyash underwent large wear and wear increased almost linearly with time (Ramachandra & Radhakrishna, 2007).

The wear of composites was less than that of the unreinforced aluminum alloy due to the addition of hard fly ash particles. An increase in the percentage of fly ash decreased the wear volume at all speeds and loads. This increase may be attributed to the decrease in ductility of the composites caused by an increase in hardness due to the addition of hard fly ash particles (Ravi Kumar et al 2012).

Increasing the volume fraction of reinforcement has delayed the transition from low wear coefficients to high wear coefficients to higher applied loads. The increase in hardness of the alloy as the volume fraction of reinforcement increases also has the effect of decreasing the wear rate even when the wear coefficients are similar (Shipway et al 1998).

**Effect of Load**

It is observed that for the matrix alloy and the composite, the SWR decreases as the load increases. The results match with the results of Rohatgi et al, 1997.
The wear rate increases with increase in load, as the load increases the penetration ability of the fractured particles, will increase and remove the material on the pin surface. The fractured small ceramic particles between the pin and the counter face form a three-body abrasion and remove the material on the surface of the pin. As the load increases the more fractured particles occur, which penetrate into the pin and flow through it (Basavarajappa & Chandramohan 2005, Uyyuru et al 2007).

The amount of wear has increased with increase in normal load (Ramachandra & Radhakrishna 2007, Daoud & Abou El-khair 2010, Radhika et al 2011). The applied load shows a direct relationship with wear volume for any percentage of fly ash. An increase in load increased the pressure, which in turn increased the abrasion and hence increased the wear volume of the composites (Ravi Kumar et al 2012).

Effects of load or contact pressure on the wear rate of MMC have been reported by various researchers. All these studies revealed that the wear rate of MMC increases as the applied load increases (Shorowordi et al 2006).

**Effect of Sliding Distance**

SWR increases with the increase in the sliding distance. This match with Basavarajappa & Chandramohan, 2005. The wear volume loss increases with the increase in the sliding distance. This may be due to cutting ability of the fractured particles trapped between pin and the counter face will not decrease with increasing the sliding distance.

Adhesive wear is dominant in unreinforced alloy, whereas abrasive wear is predominant in composites. At higher load, subsurface delamination is the main mechanism in both the alloy as well in composites (Sudarshan & Surappa 2008).
In summary, a composite material that possesses superior adhesive wear resistance is associated with a stable tribolayer. The creation of this layer depends on the magnitude of the applied load, sliding speed, operating temperature and composition of the MMC. Reinforcement volume fraction appears to be a critical parameter. Achievement of a lower wear rate for the counterface, would involve the utilization of materials exhibiting high hardness and adequate fracture toughness. The micro-machining action of the MMC’s reinforcement phase, towards the counterface, could be minimised by selecting reinforcement particles of low fracture toughness. However, the wear resistance of the composite is then reduced. Clearly, a compromise is required between wear rates expected for both the composite and the counterface materials (Deuis et al 1997).

**Influence of Parameters on Coefficient of Friction**

The friction coefficient is observed high for lower loads and reduced for increase of applied loads in 356 matrix composites and alloy. This is because at lower loads, the transfer film is found to be stable for more time and temperature rise is also low, whereas at higher loads the transfer film is destroyed at faster rate and the temperature rise is also high (Natarajan et al 2006).

COF increases with increase in applied load for 413 matrix composites and alloy. At low applied load and sliding velocity the friction coefficient is observed less due to less formation of transfer film at the interface. At higher sliding velocities, the formation of transfer film is fast. Hence the friction coefficient is found to be slightly high. But at higher velocity and at higher loads, the formation and destruction of the transfer film is fast which results in reduced friction coefficient (Natarajan et al 2006).
Generally speaking, for all sliding speeds, with the increase in the applied load, the friction coefficient decreases. It is interesting to note that the load effect on the wear rate is as intense as on the friction coefficient (Daoud & Abou El-khair 2010).

For a constant percentage of fly ash, an increase in load and speed decreased the coefficient of friction. Umanath, et al. reported a similar relation, where the coefficient of friction decreased with increased load. In summary, the coefficient of friction decreased with an increase in the percentage of fly ash, load, and speed (Ravi Kumar et al 2012).

It is observed that higher sliding velocity leads to lower wear rate and lower friction coefficient for both MMCs. It is suggested that the transfer layer on MMC acts as a protective cover and helps reduce both wear rate and friction coefficient (Shorowordi et al 2004).

Increase in sliding speed decreases the coefficient of friction (Radhika et al 2011). The coefficient of friction has decreased with increased flyash content. The coefficient of friction has decreased with increase in normal load (Ramachandra & Radhakrishna, 2007).

As the load increases, the coefficient of friction decreases for both the composite and the matrix alloy. The decrease of the coefficient of friction with the increase of the load may be attributed to increasing amounts of wear debris particles coming out from the wear surface and filling in the empty spaces between ceramic particles, thereby decreasing the effective depth of penetration (Rohatgi et al, 1997).

The decreasing specific wear rates and friction during abrasion wear with increasing load have been attributed to the accumulation of wear debris in the spaces between the abrading particles, resulting in reduced
effective depth of penetration and eventually changing the mechanism from two-body to three-body wear, which is further indicated by the magnitude of wear coefficient (Rohatgi et al, 1997).

The increase in sliding distance decreases the coefficient of friction and this can be attributed to the presence of hard ceramic particles which provides abrasion resistance, resulting in enhanced dry sliding wear performance (Radhika et al 2011).

8.9 COMPARISON OF THEORETICAL DENSITY WITH MEASURED VALUES

The theoretical density of composites was calculated using the rule of mixtures. The porosity of the composites was calculated using the formula given below.

\[
\text{Porosity} \% = \frac{\text{Theoretical Density} - \text{Measured Density}}{\text{Theoretical Density}} \times 100 \quad (8.1)
\]

Density values and porosity of the composite materials were presented in Table 8.5. The theoretical values of the densities are in agreement with the measured values. The difference is due to the porosity and it is very minimal. As seen from the results porosity percentage increases with the increase in the particle loading. It is inline with the results reported in the literature. For introducing more reinforcements in the matrix by stir casting one has to stir for longer period resulting more of gas entrapment.
Table 8.5 Density values and Porosity of Specimen

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Material</th>
<th>Theoretical Density (g/cm³)</th>
<th>Measured Density (g/cm³)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>356+3%B₄C</td>
<td>2.72</td>
<td>2.7</td>
<td>0.87%</td>
</tr>
<tr>
<td>2</td>
<td>356+6%B₄C</td>
<td>2.72</td>
<td>2.65</td>
<td>2.48%</td>
</tr>
<tr>
<td>3</td>
<td>356+9%B₄C</td>
<td>2.71</td>
<td>2.53</td>
<td>6.68%</td>
</tr>
<tr>
<td>4</td>
<td>356+3%Flyash</td>
<td>2.71</td>
<td>2.69</td>
<td>0.77%</td>
</tr>
<tr>
<td>5</td>
<td>356+6%Flyash</td>
<td>2.69</td>
<td>2.63</td>
<td>2.29%</td>
</tr>
<tr>
<td>6</td>
<td>356+9%Flyash</td>
<td>2.67</td>
<td>2.6</td>
<td>2.71%</td>
</tr>
<tr>
<td>7</td>
<td>356+3%Hybrid</td>
<td>2.72</td>
<td>2.6</td>
<td>4.32%</td>
</tr>
<tr>
<td>8</td>
<td>356+6%Hybrid</td>
<td>2.70</td>
<td>2.58</td>
<td>4.60%</td>
</tr>
<tr>
<td>9</td>
<td>356+9%Hybrid</td>
<td>2.69</td>
<td>2.56</td>
<td>4.89%</td>
</tr>
<tr>
<td>10</td>
<td>413+3%B₄C</td>
<td>2.69</td>
<td>2.69</td>
<td>0.17%</td>
</tr>
<tr>
<td>11</td>
<td>413+6%B₄C</td>
<td>2.69</td>
<td>2.62</td>
<td>2.57%</td>
</tr>
<tr>
<td>12</td>
<td>413+9%B₄C</td>
<td>2.68</td>
<td>2.5</td>
<td>6.85%</td>
</tr>
<tr>
<td>13</td>
<td>413+3%Flyash</td>
<td>2.68</td>
<td>2.65</td>
<td>1.18%</td>
</tr>
<tr>
<td>14</td>
<td>413+6%Flyash</td>
<td>2.66</td>
<td>2.41</td>
<td>9.51%</td>
</tr>
<tr>
<td>15</td>
<td>413+9%Flyash</td>
<td>2.65</td>
<td>2.34</td>
<td>11.53%</td>
</tr>
<tr>
<td>16</td>
<td>413+3%Hybrid</td>
<td>2.69</td>
<td>2.65</td>
<td>1.42%</td>
</tr>
<tr>
<td>17</td>
<td>413+6%Hybrid</td>
<td>2.68</td>
<td>2.6</td>
<td>2.85%</td>
</tr>
<tr>
<td>18</td>
<td>413+9%Hybrid</td>
<td>2.66</td>
<td>2.53</td>
<td>5.05%</td>
</tr>
</tbody>
</table>

The porosity of 413 + 9% Fly ash is maximum (11.53 %) and that of 356 + 3 % Fly ash is the minimum (0.77 %), from these observations it can be inferred that the fly ash reinforcement with 356 aluminium alloy is better than 413 aluminium alloy.