CHAPTER 4

FRICITION AND WEAR ANALYSIS OF HYBRID ALUMINIUM METAL MATRIX COMPOSITES

4.1 INTRODUCTION

Bowden and Tabor (1986) had proposed that the two main contributing factors to the friction generated during sliding wear could be described by an adhesion term and a ploughing term. A new theory for friction has been reported by Suh and Sin (1981) in which a third term has been introduced, namely deformation.

‘Wear’ may be defined as the progressive loss of material from the contacting surfaces in relative motion. The load applied to the surface will be transferred through contact points. The material intrinsic surface properties i.e. the surface finish, load, speed and temperature and properties of the opposing surfaces have been important in determining the wear rate. Wear, the progressive loss of substance from the operating surface of the mechanically interacting element of a tribo-system may be measured in terms of weight loss or volume loss. The wear rate of the composite has been measured by using the relation,

\[ K_C = \vartheta_m \cdot K_m + \vartheta_f \cdot K_f \]  \hspace{1cm} (4.1)

where, \( K_C, K_m \) and \( K_f \) - Wear rate of the composite, the matrix and the reinforcement (particulates) respectively.
\( \vartheta_m \) and \( \vartheta_f \) - Volume fraction of the matrix and the reinforcement (particulates) respectively.
The test apparatus usually available for measuring sliding friction and wear characteristics are Pin-on-Disc, Pin-on-Flat, Pin-on-Cylinder, Thrust washers, Pin into Bushing, Rectangular Flats on a Rotating Cylinder etc. In laboratories, wear tests are conducted at ambient temperature by varying load and speed under varying environmental conditions and frictional force. A small rider of the test material has been loaded against larger moving surface and the tests have been performed. The sliding has been repeated on the same counter-face or under single path conditions in which fresh tracks of the counterpart move against the loaded specimen.

In the present work, studies have been carried out to assess the friction and wear behavior of Al based composites with SiC and B₄C as reinforcements under controlled laboratory conditions. A comprehensive picture of wear under different working conditions has been presented by conducting laboratory tests in pure sliding mode using a pin-on-disc machine. Studies on microstructure, by adopting Scanning Electron Microscope (SEM) and optical microscope have also been done to know the wear mechanism.

### 4.2 MECHANISM OF WEAR TEST

Figures 4.1 shows the complete pin-on-disc wear test experimental setup. The slider disc has been made up of 0.95 to 1.20% carbon (EN31) hardened steel disc with hardness of 62 HRC having diameter of 165 mm. A track diameter of 100 mm has been used in all the experiments. The initial surface finish (Ra) of the steel disc has been 1μm. The Hybrid Aluminium Metal Matrix Composites (HAMMCs) test samples have been prepared as pins of dimensions 12 mm in diameter and 32 mm in height. It is important to ensure that the test sample’s end surfaces have been flat and are polished by using metallographic techniques prior to wear testing. Conventional aluminium alloy polishing techniques have been used to make
the contact surfaces of the monolithic composite aluminium specimen ready for wear test.

![Image of Pin-on-disc sliding wear testing machine with integrated system](image)

**Figure 4.1  Pin-on-disc sliding wear testing machine with integrated system**

The procedure involves grinding of composite aluminium surface manually by using 240, 320, 400 and 600 grit silicon carbide papers followed by polishing with 5, 1 and 0.5μm alumina using low speed polishing machine. This preparation technique has enabled to create considerable surface relief between hard and soft aluminium matrix. The polished specimens have been then cleaned ultrasonically with acetone and methanol solutions. Similarly, the counter face materials have been polished and cleaned ultrasonically with acetone and methanol solutions before each wear test. The steel slider has been polished by the above described procedure and all the tests have been conducted at room temperature. The surface roughness (Ra) of test samples have been measured using (Mitutoyo SJ-201 P, Japan) a surface roughness tester and the measured values of the tested samples of Al alloy and
HAMMCs are listed in Table 4.1. It has been observed that the test samples surface roughness increases with the increase in percentage of particulates added to the matrix.

Table 4.1 Surface roughness of samples

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface roughness in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>Al 6061</td>
<td>0.252</td>
</tr>
<tr>
<td>Al 7075</td>
<td>0.259</td>
</tr>
</tbody>
</table>

The tests have been carried out by applying normal loads such as 10, 20 and 40N at a maximum sliding distance of 4241m at different velocities such as 1.5, 3.0 and 4.5 m/s. The wear rates of test samples have been measured in weight units by weighing the specimen before and after the test and have finally been converted into volumetric wear loss. The wear losses of the specimens have been measured using a high precision (accuracy 0.001g) electronic balance.

The difference in weight loss of the entire test samples have been measured before and after the wear test under dry condition. Using this weight loss data, the composite’s volume loss has been calculated. An experimental graph showing the volume loss or wear in μm against sliding time in seconds (which has been proportional to sliding distance) obtained from wear testing machine has been shown in Figure 4.2. As it can be seen, there is scatter in the results as wear testing produces highly variable results. Hence, the wear rate corresponding to any sliding distance is evaluated as an average of values obtained during the time period. These results are discussed in chapter 4.
Finally, the micro structural investigation and semi quantitative chemical analysis on the worn surfaces have been performed with the aid of SEM.

Figure 4.2  Typical graphical results from pin-on-disc type wear testing machine (a) Wear in μm and (b) Frictional force in N

The parameters considered during the performance of wear test are, i) Applied load, ii) Sliding velocity, iii) Sliding time and iv) Volume fraction of the particulate. The corresponding input parameters are presented in Table 4.2.

Table 4.2 Parameters considered during sliding wear test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied load (L)</td>
<td>10, 20 and 40 N</td>
</tr>
<tr>
<td>Sliding velocity (S)</td>
<td>1.5, 3 and 4.5 m/s</td>
</tr>
<tr>
<td>Sliding time (t)</td>
<td>5, 10 and 15 min</td>
</tr>
<tr>
<td>Volume fraction (R)</td>
<td>5, 10 and 15 %</td>
</tr>
</tbody>
</table>
4.3 EFFECT OF PARAMETERS ON TRIBOLOGICAL CHARACTERISTICS

The wear factor, defined as the ratio of wear volume (m$^3$) to the product of applied load (N) and sliding distance (m) has been an important parameter, which quantifies the wear resistance. The entire tests have been carried out for both the Al 6061 and Al 7075 HAMMC series.

4.3.1 Effect of Sliding Distance on Wear Rate

Figures 4.3(a-c) and 4.4(a-c) clearly explain the correlation between wear rate and sliding distance at different applied load. The wear rate decreases and attains a lower steady value with the increase in sliding distance, invariably for all the samples. Test specimen’s wear rate has been obtained from the ratio between volume loss and sliding distance. The variation of wear rate against sliding distance has been calculated for three different applied loads viz., 10, 20 and 40N for unreinforced alloys and for all the samples of HAMMCs and shows a reasonable decrease of the wear rate as indicated in Figures 4.3(a-c) and 4.4(a-c). In general, at any load, the wear rate of unreinforced material decreases as the sliding distance increases and the wear rate of all composites increases with sliding distance. However, beyond the same value (around 3000m), the wear rate begins to decreases in the case of the test specimens. This is because, when the sliding distance is lower, because of asperities the contact between pin and disc remains less, leading to less wear. As the sliding distance increases the same increases which leads to more wear. On the other hand, after around 3000m, the smoothness of the contact surface becomes better and thus, wear rate attains a decreasing mode. Usually, increasing the sliding distance also increases the interface temperature. High sliding distances or high loads result in surface
frictional heating which in turn results in the formation of a thin molten layer at asperity contacts in case of low melting metals as reported by Ghazali et al (2005). This has led to the reduction in shear strength and drop in friction co-efficient. Although in these tests, a low speed has been used to minimize frictional heating, the contact temperature depends on the applied load during sliding. In the same way, the influences of oxide layer formation on wear behavior have also been observed by Wilson and Alpas (1997). The hard particles assist the retention of oxide transfer layer on sliding surfaces, which prevent metal-metal contact and thus decreases wear resistance at low sliding velocity range.

The following observations have been made during the wear analysis of HAMMCs.

i) At a constant applied load, the wear rate for the unreinforced alloy has been found to be larger than that of the reinforced HAMMCs in both the cases.

ii) The reinforced HAMMCs with higher concentration of SiC (15wt.%) possesses lower wear rate.

iii) At the maximum load of 40N, wear rate has been high as compared to other load conditions.

iv) Thus the wear rate has been low at low applied loads.

v) It leads to a conclusion that the reinforced HAMMCs of all percentage of reinforcements have been found to be better than the unreinforced alloys at all loads and sliding distances.
Figure 4.3  Variation of wear rate with sliding distance at a sliding velocity of 4.5m/s for Al 6061 HAMMCs under applied loads of (a) 10N, (b) 20N and (c) 40N
Figure 4.3  (Continued)
Figure 4.4 Variation of wear rate with sliding distance at a sliding velocity of 4.5m/s for Al 7075 HAMMCs under applied loads of (a) 10N, (b) 20N and (c) 40N
Figure 4.4  (Continued)
4.3.2   Effect of Applied Load on Wear Rate

Applied load has also been one of the major factors influencing the wear rate of the composites. Figures 4.5(a-c) and 4.6(a-c) illustrate the effect of applied load on wear rate of unreinforced Al 6061 and Al 7075 alloys along with their corresponding HAMMCs of different percentage reinforcements (5 to 15wt.% SiC and 3wt.% B₄C) speed tested for 15 minutes. At constant speed, the wear rate of the composites and the matrix increases with increase in load. The wear rate of the composites has been less than that of the matrix alloy for all loads. Similar trend has been observed by Basvarajappa et al (2006), Natarajan et al (2006), Feng et al (2008), in the study of dry sliding wear behavior of Al 2219/SiC, Al 5083/B₄C and A356/25SiCp Metal Matrix Composites (MMCs). The composites with hard particles thus exhibits better wear resistance than matrix alloys, which may be due to the fact that the surface of the matrix materials tend to get delaminated in the absence of harder reinforcement, thus increasing the wear.
Figure 4.5  Variation of wear rate with applied load for Al 6061 HAMMCs at a sliding velocity of (a) 1.5m/s, (b) 3m/s and (c) 4.5m/s
Figure 4.5  (Continued)
Figure 4.6 Variation of wear rate with applied load for Al 7075 HAMMCs at a sliding velocity of (a) 1.5m/s, (b) 3m/s and (c) 4.5m/s
Figure 4.6 (Continued)
4.3.3 Effect of Volume Fraction of Reinforcement Particulate on Wear Rate

Figures 4.7(a-c) and 4.8(a-c) illustrate the variation in wear rates of both Al alloys and their HAMMCs at different loads and sliding velocities as a function of percentage reinforcement. The comparative wear study of both Al 6061 and Al 7075 based composites have been made and the individual effects of weight percentage of particulates on their wear rate have been discussed.

In this work, wear rate has been calculated after a sliding time period of 5, 10 and 15 minutes for all the samples at three different sliding velocities. As far as the results have been concerned, the main observation being the decrease of wear rate with the increase in volume fraction of the particulate reinforcement, sliding time and sliding velocity. The reinforced HAMMCs have shown lower wear rate as compared to unreinforced Al 6061 and Al 7075 alloy. This can be attributed to the fact that an improved hardness of the composite, resulting from the incorporation of hard particles, which acts a harder phase into the matrix. Increase in hardness results in the improvement of wear and seizure resistance of the material. When the hard particles have strongly been bonded with matrix, they protect the surface against severe destructive action of the counter face, because of the strong interface bond, which plays a critical role in transferring loads from the matrix to hard particles, as observed by Al-Qutub et al (2008).
Figure 4.7  Variation of wear rate with SiC volume fraction (%) - Al 6061 HAMMCs at a sliding velocity of (a) 1.5m/s, (b) 3m/s and (c) 4.5m/s
Figure 4.7  (Continued)
Figure 4.8  Variation of wear rate with SiC volume fraction (%) - Al 7075 at a sliding velocity of (a) 1.5m/s, (b) 3m/s and (c) 4.5m/s
Figure 4.8  (Continued)
Figure 4.9 clearly explains the effect of percentage volume fraction of the harder SiC reinforcement particulate on the percentage reduction of wear rate, under maximum load and maximum sliding velocity conditions. Although both 6061 and 7075 exhibit consistent reduction in wear rate as the particulate percentage increases, the latter is found to be superior to the former from this perspective. Since the hardness of 7075 is higher than that of 6061, the effect of reinforcement of particulate is more pronounced in 7075.

Figure 4.9 Effect of volume fraction of SiC on the percentage reduction of wear rate
4.3.4 Effect of Applied Load, Sliding Distance and Volume Fraction of Reinforcement Particulate on Specific Wear Rate for Al 6061 and Al 7075 HAMMCs

Figures 4.9i(a) and 4.9ii(a) gives the specific wear rate for Al 6061 and Al 7075 HAMMCs (otherwise known as Lancaster wear co-efficient) as a function of load. The values are in the range of $1.146 \times 10^{-13}$ to $0.695 \times 10^{-13}$ m$^3$/N-m and $1.188 \times 10^{-13}$ to $0.496 \times 10^{-13}$ m$^3$/N-m respectively. The specific wear rate decreased with load for all the materials, indicating improved wear resistance at the higher loads. Figures 4.9i(b) and 4.9ii(b) indicates the specific wear rate as a function of sliding distance. The values are in the range of $1.293 \times 10^{-13}$ to $0.725 \times 10^{-13}$ m$^3$/N-m and $1.111 \times 10^{-13}$ to $0.628 \times 10^{-13}$ m$^3$/N-m respectively. The specific wear rate decreased with sliding distance for all compositions indicating improved wear resistance at the higher velocities. From figures 4.9i(c) and 4.9ii(c) it can be observed that 5 wt.% SiC HAMMCs has highest specific wear rate and 15 wt.% SiC composite exhibited lowest specific wear rate, such that 15 wt.% SiC corresponds to highest wear resistant material.
Figure 4.9i  Variation of specific wear rate with (a) Applied load (b) Sliding distance and (c) Percentage of reinforcement for Al 6061 HAMMCs
Figure 4.9i (Continued)
Figure 4.9ii Variation of specific wear rate with (a) Applied load (b) Sliding distance and (c) Percentage of reinforcement for Al 7075 HAMMCs
Figure 4.9ii (Continued)
4.3.5 Effect of Sliding Distance on Friction Co-efficient

Friction co-efficient of the test specimens obtained from the frictional force of the specimens during sliding has been plotted against sliding distance as shown in Figures 4.10(a-c) and 4.11(a-c) for three different applied loads viz., 10, 20 and 40 N. In all the Figures, friction co-efficient of the hybrid composite shows initially high value due to more frictional force and as the sliding distance increases the friction co-efficient decreases because of less frictional force between the disc and the test specimen pin. Another important characteristic observation in the unreinforced sample has been the high friction co-efficient compared to the reinforced HAMMCs. At higher load of 40 N conditions, the friction co-efficient of the hybrid composite has been reduced compared to that of the unreinforced alloy. It has been demonstrated that during the initial stages, the surfaces of both the composite specimens and the unreinforced alloy counterpart have been rough and thus strong ‘interlocking’ took place, resulting in high friction co-efficient.
Figure 4.10 Variation of friction co-efficient with sliding distance at a sliding velocity of 4.5m/s for Al 6061 HAMMCs under the applied load of (a) 10N, (b) 20N and (c) 40N
Figure 4.11 Variation of friction co-efficient with sliding distance at a sliding velocity of 4.5m/s for Al 7075 HAMMCs under the applied load of (a) 10N, (b) 20N and (c) 40N
Figure 4.11 (Continued)
As the wear process continued, the rough profiles of the Al alloy and the composite specimens have been smoothened as a result of abrasion and a transfer film has been formed on the surface of the composite specimen as well as on its counter part. Consequently, lower friction co-efficients have been achieved when a steady wear stage has reached. A decrease in the friction co-efficient with increased sliding distance can also be attributed to the fact that the brittle particulate reinforcements in the composites crack and have squeezed out onto the mating surfaces forming a thin adherent solid lubricating film. Similar results have already been reported by Al-Qutub et al (2008).

4.3.6 Effect of Applied Load on Friction Co-efficient

Figures 4.12a and 4.12b indicate that increase in friction co-efficient with increase in load has been attributed for the maximum speeds at different volume fraction of the reinforcement. It has been observed that, the value of friction co-efficient has been low at initial loads for both the matrix alloy and its composites. However, the 15wt.% of volume fraction composite possesses the lowest friction co-efficient at any particular load. It has been found that the average friction coefficients have been in the range of 0.35 and 0.33 for Al 6061 and Al 7075 HAMMCs respectively. Thus, friction co-efficient increases with increase in applied load.
Figure 4.12 Variation of friction co-efficient with applied load at a sliding velocity of 4.5m/s of (a) Al 6061 and (b) Al 7075 based HAMMCs
It has been concluded that the increase of load leads to a significant increase in the friction co-efficient as shown in Figures 4.12a and 4.12b. According to Bowden and Tabor (1986) theory, effects of normal and tangential loads have been considered separately. It has been well thought-out that the normal load determines the real area of contact and to shear over this area, tangential force has been needed. If the normal load has been increased, then the real area of contact has also been increased along with tangential force, resulting in the increase of instantaneous value of friction co-efficient. From this test, it has been confirmed that the friction co-efficient of the composite with 15wt.% SiC has been low for all loads. On the other hand, considering the different load conditions the wear rate is as intense as the friction co-efficient.

4.3.7 Effect of Volume Fraction of Reinforcement Particulate on Friction Co-efficient

Figures 4.13(a-c) and 4.14(a-c) specify the effect of reinforcement percentage on friction co-efficient. According to Rabinowicz (1995), the friction force required to start sliding has usually been greater than the force required to maintain sliding and hence, kinetic friction co-efficient generally has a positive slope at slow sliding velocity and a negative slope at high sliding velocity. Friction should have mainly occurred between the particles and the disc surface. The average friction co-efficient between disc and alloy has been 0.38 and an average friction co-efficient between disc and composites has been 0.32. Due to the formation of tribolayers, the friction co-efficient decreases as the volume fraction increases.
Figure 4.13 Variation of friction co-efficient with SiC volume fraction (%) - Al 6061 HAMMCs at a sliding velocity of (a) 1.5m/s, (b) 3m/s and (c) 4.5m/s
Figure 4.13 (Continued)
Figure 4.14 Variation of friction co-efficient with SiC volume fraction (%) - Al 7075 HAMMCs at a sliding velocity of (a) 1.5m/s, (b) 3m/s and (c) 4.5m/s.
Figure 4.14 (Continued)
4.4 ANALYSIS OF TRIBOLOGICAL CHARACTERISTICS

The wear rates of aluminium based alloys and its composites have highly been influenced by different wear mechanisms and have been controlled by applied load, percentage of reinforcement, sliding velocity and sliding time. Based on the detailed interpretation carried out on the worn surfaces and wear debris, three stages have been identified.

i) First stage: overcoming the roughness of the machine marks on the disc surface.

ii) Second stage: piling up of the tribo-layer.

iii) Third stage: dynamic competition between material transfer processes (transfer of material from pin onto disc and formation of wear debris and their subsequent removal).

All these stages have not been clearly distinguishable from each other. It might be that either one of them has been dominant at any given instant of time. At the beginning of the wear test, under actual load and speed conditions, contact area and nature of contact might change. Hence, every test has been initiated with run-in-wear stage with low loads and speeds to compensate for these changes. But under new set of test conditions, there have been some disturbances in the friction force curve. Occurrence of which can be attributed to the process of overcoming machining marks, which has been marked by the rise in frictional force.

In the next stage, frictional force tends to decrease. This has been believed to be due to gradual submerging of machining marks and/or wear debris in the pool of material transferred from the pin i.e. formation of tribo-layer. Transfer of the pin material occurs because of ploughing action of the hard asperities of the disc material against the relatively soft pin material.
Final stage of wear test has been the dynamic competition between material transfer processes. As mentioned in the earlier sections, material transfer from the pin onto disc causes submerging of machining marks/debris on the disc.

As the applied load and sliding distance increases, more material has to shear off from both pin and disc as shown in Figures 4.3(a-c) - 4.6(a-c). Thus tribo-layer thickness might have increased with increase of normal load and sliding distance, causing the wear rate of composites and matrix materials to increase.

The volumetric wear loss of matrix alloys and its composites with the increase in hard particles is revealed in Figures 4.7(a-c) - 4.8(a-c). It has been experimentally that the volumetric wear loss of the composites decrease with increased content of hard particles in the matrix alloys. However, for a given reinforcement content, the composites posses lower volumetric wear loss than the matrix alloys. It has also been observed that the HAMMCs possess lower wear rates than that of the base alloy with the increasing content of SiC. A reduction of 22.89%, 34.38% and 53.53% in wear rates has been observed for composites containing 5 wt.%, 10 wt.% and 15 wt.% SiC respectively when compared with the matrix Al 6061 alloy, under the conditions of 40 N load, 4.5 m/s sliding velocity and 15 min of sliding time. In case of HAMMCs formed from Al 7075 alloy matrix, a reduction of 7.97%, 33.75% and 55.34% in the wear rate has been observed for composites containing 5 wt.%, 10 wt.%, and 15 wt.% SiC respectively.

As the normal load increases, the real areas of contact have been increased along with tangential force leading to the instantaneous increase in the value of friction co-efficient. From the analysis of graphs, it is concluded that the increase of load leads to a significant increase in the friction coefficient. However, under identical test conditions,
Al 6061/10%SiC/3%B₄C and Al 7075/10%SiC/3%B₄C possessed better friction co-efficient.

The experimental results of friction co-efficient with normal loads and sliding distance have been shown in Figures 4.10(a-c), 4.11(a-c), 4.12a and 4.12b for Al 6061 and Al 7075 based HAMMCs respectively. It has been observed that the friction co-efficient of matrix alloy and their composites decrease with increase in sliding distance.

It had been observed that there is a significant decrease in the friction co-efficient of HAMMCs with the increasing content of SiC. A reduction of 20.54%, 31.83% and 35.22% in the friction co-efficient has been observed for composites containing 5 wt.%, 10 wt.% and 15 wt.% SiC respectively when compared with the matrix Al 6061 alloy. Similar trend has been reported by Kumar et al (2008). This can be mainly attributed to the excellent lubricating properties of SiC. In case of HAMMCs formed from Al 7075 alloy matrix, a reduction of 6.32%, 18.23% and 27.26% in the friction co-efficient has been observed for composites containing 5wt.%, 10wt.% and 15wt.% SiC respectively.

The wear resistance of the composites increases with increase in percentage of hard particles as depicted in Figures 4.7(a-c) - 4.8(a-c). Whereas, the friction co-efficient of composites decreases with increase in the content of hard reinforcement particles as indicated in Figures 4.13(a-c) and 4.14(a-c). Sudarshan and Surappa (2008) have reported similar trends in their study.
4.5 DESIGN OF EXPERIMENTS (DoE)

An experiment had been designed as illustrated in Figure 4.15 to evaluate simultaneously two or more factors which possess their ability to affect the resultant average or variability of particular product or process characteristics. The Design of Experiment (DoE) should focus on the preferred levels of influencing factors. The results of the particular test combinations have been observed and the complete sets of results have been analyzed to determine the preferred level of various influencing factors (Phillip J. Ross 1996).

![Diagram of Experimental Design]

**Figure 4.15 Experimental Design**

The Taguchi technique had been an optimization tool for the solving of design problems (Taguchi and Konishi 1987, Ross Phillip 1990 and Taguchi 1993). This method significantly reduces the number of experiments that have been required to model the response function, compared with the full factorial design of experiments. Moreover, it has a systematic and easy approach to optimize the design parameters such as quality, cost, etc., (Ross Phillip 1990 and Roy Ranjit 1990). It has a multi-step process technique to
find the possible interaction between the parameters. This approach has a factorial design approach and creates a standard orthogonal array (Paulo Davim 2000 and Paulo Davim 2003).

Graphical evaluation methods convey rapidly the relative magnitude of different factor effects and quick identification of optimum setting for each factor under experiment. They also display visually the relative effects of each of the individual design factors.

Taguchi methods also use Analysis of Variance (ANOVA) to determine the effect of a particular factor on the response or its variability with F tests on Signal- to- Noise ratios (SN) in the robust design studies. Before attempting regression exercise, cause-effect relationship between the variables by ANOVA and has been carried out.

Taguchi also formulated a simple statistics namely SN ratio, a logarithmic function. The ratio of mean performance to variation in mean performance due to uncontrollable factors has a concurrent statistics and a special kind of data summary. SN ratio has been an ideal measurement to decide the best values or levels of control factors. SN ratio has been the primary measurement used for products or process optimization and represents the ratio of sensitivity to variability, which has been used to optimize the robustness of a product or process. Table 4.3 shows the typical SN ratios used in various situations.

Based on the Taguchi technique, orthogonal arrays have been formed to reduce the number of experiments for finding out the optimum test parameters. Ross (1998) has reported in his investigation that the experimental outcomes uses SN ratio to support the determination of the finest process design. This method has effectively been used for the study of dry sliding wear behavior of composite materials (Siddhartha et al 2011). In the present work, the identified influencing parameters on the wear rate and
friction co-efficient have been applied load, sliding velocity, sliding time and percentage of reinforcement. The range of values of the above mentioned parameters have been given in Table 4.4.

**Table 4.3 Signal-to-noise ratios and its significance**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Case</th>
<th>SN ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Target is better</td>
<td>$\frac{S}{N} (\bar{\theta}) = 10 \log_{10} (\tau^2 / s^2)$</td>
</tr>
<tr>
<td>2</td>
<td>Smaller is better</td>
<td>$\frac{S}{N} (\bar{\theta}) = -10 \log_{10} (Y_i^2 / n)$</td>
</tr>
<tr>
<td>3</td>
<td>Larger is better</td>
<td>$\frac{S}{N} (\bar{\theta}) = 10 \log_{10} [(1 / Y_i^2) / n]$</td>
</tr>
<tr>
<td>4</td>
<td>Binary scale (GO/NO GO)</td>
<td>$\frac{S}{N} (\bar{\theta}) = 10 \log_{10} p / (1 - p)$ $p = \text{Proportion of good products}$</td>
</tr>
</tbody>
</table>

**Table 4.4 Process parameters with their values at three levels**

| Level | Sliding velocity, S (m/s) | Applied load, L (N) | Sliding time, t (min) | Percentage of reinforcement, R (wt.%)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
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<tr>
<td>3</td>
<td>4.5</td>
<td>40</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

For every parameter, three levels have been taken based on the earlier references (Basavarajappa et al 2006 and Venkat Prasat et al 2011) and have been assigned at levels 1, 2 and 3. The assigned values at three levels have been used in the orthogonal array.
The selection of orthogonal array has been based on the condition that the degrees of freedom for the orthogonal array should be greater than or at least equals the sum of those of wear parameters (Taguchi 1987, Phillip J Ross 1996, Hahsim 1999 and Naher 2003). In the present investigation, an L\textsubscript{27} orthogonal array has been chosen, which has 27 rows corresponding to the number of tests and 13 columns indicating the number of influencing factors. Since the wear rate and friction co-efficient have been influenced by only four factors, as explained earlier, only four columns are to be assigned these factors. To choose the exact column for each factor a linear graph applicable to L\textsubscript{27} orthogonal array has been obtained and is given in Figure 4.16.

![Figure 4.16 Linear graphs for L\textsubscript{27} array](image)

In Figure 4.16 the shaded circles indicate the numbers of the column that are to be assigned to the influencing factors. The remaining columns have been assigned to their interactions. Accordingly, columns 1, 2, 5 and 9 are the ones those correspond to applied load, sliding velocity, sliding time and percentage of reinforcement respectively. The table of orthogonal array has been presented in Table 4.5. The numbers inside the table have been indicating the levels of parameters. For instance, at experiment no.5, against column 1(sliding velocity), the number has been given as 1. This means that
the number 1 has to be replaced by the value of the factor, sliding velocity at level 1 given in Table 4.4. i.e. 1.5 m/s. The outputs to be studied such as wear rate and friction co-efficient of the samples have been repeated three times corresponding to 81 tests.

**Table 4.5 Orthogonal array L27(3^13) of Taguchi method**

<table>
<thead>
<tr>
<th>L27(3^13)</th>
<th>1</th>
<th>2</th>
<th>3</th>
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The experimental results of wear rate and friction co-efficient have further been transformed into SN ratio which has been evaluated as logarithmic transformation of loss function and the expression is as shown below

$$\frac{S}{N} = -10 \times \log \frac{1}{n} (\sum Y_i^2)$$  \hspace{1cm} (4.2)$$

where, ‘n’ is the number of observations, ‘Yi’ is the measured value of wear rate and friction co-efficient. It has been suggested that the quality characteristics have been optimized when the SN response has been as smaller as possible. In this work, the “smaller the better” quality characteristics have been taken to find the minimum wear rate and friction co-efficient.

4.6 SUMMARY

In this chapter, the effect of parameters on tribological characteristics and DoE has been dealt with. The considered parameters have been the effect of sliding distance along with applied load on wear rate. From the experimental results, it has been clearly observed that at a constant sliding distance and at higher load conditions, wear rate for unreinforced alloys has been 45 to 55 % higher compared to reinforced HAMMCs. Another significant observation is that at lower applied load and at higher volume fraction and sliding distance the wear rate has been low for both Al 6061 and Al 7075 based HAMMCs. It has also been evident that as the sliding distance and volume fraction increases, the friction co-efficient decreases due to less frictional force, whereas it has been the reverse for applied load. In DoE, the Taguchi technique has been adopted as the optimization tool for the solving of designed problem. The major advantage of this method is that it significantly
reduces the number of trial experiments. SN ratios considered for this study has been “smaller is better” concept. From this research work, it has been concluded that “smaller is better” quality characteristics have been very effective in finding the minimum wear rate and friction co-efficient.