Wear behavior of AA 5083/SiC nano-particle metal matrix composite: Statistical analysis

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Abstract: This paper reports study on statistical analysis of the wear characteristics of AA5083/SiC nanocomposite. The aluminum matrix composites with different wt % (0%, 1% and 2%) of SiC nanoparticles were fabricated by using stir casting route. The developed composites were used in the manufacturing of spur gears on which the study was conducted. A specially designed test rig was used in testing the wear performance of the gears. The wear was investigated under different conditions of applied load (10N, 20N, and 30N) and operation time (30 mins, 60 mins, 90 mins, and 120mins). The analysis carried out at room temperature under constant speed of 1450 rpm. The wear parameters were optimized by using Taguchi’s method. During this statistical approach, L27 Orthogonal array was selected for the analysis of output. Furthermore, analysis of variance (ANOVA) was used to investigate the influence of applied load, operation time and SiC wt. % on wear behaviour. The wear resistance was analyzed by selecting “smaller is better” characteristics as the objective of the model. From this research, it is observed that experiment time and SiC wt % have the most significant effect on the wear performance followed by the applied load.

Keywords: Metal matrix composite, 5083 Al Alloy, SiC nano reinforcement, wear test, ANOVA, Taguchi method.

1. Introduction

Aluminium alloys play a crucial role in various engineering fields due to their superiority in quality to weight proportion and other mechanical properties [1]. These alloys are used as matrix phase in aluminium matrix composites. These composites achieve enormous interest and are widely utilized in various applications of making automobile and aerospace components because of their different essential properties like light weight, bring down cost, high stiffness, easy fabrication and high dimensional stability which aided to mould the material to desired shape and size. The metal matrix composites (MMCs) are most commonly used in engineering applications due to their ease of fabrication, lower costs, recyclability and isotropic properties [2].

Aluminium alloy reinforced with particulates are a most promising way to enhance the wear properties of any metal matrix composites (MMCs). There are numerous reinforcements which have been utilized for improving the mechanical characteristics including wear properties of aluminum based alloys, but the fillers such as silicon carbide [3–9] and alumina [10–12] to aluminium alloys were also reported to enhance the tribological properties of AMCs. For determining the better reinforcement aluminum matrix composites reinforced with SiC and Al\textsubscript{2}O\textsubscript{3} are compared for wear performance. The analysis of results showed that SiC particles were more effective than Al\textsubscript{2}O\textsubscript{3} particles for the enhancement of wear resistance of aluminum matrix composites due to its property of high hardness [13, 14]. Given results expressed that SiC preferably can be used as reinforcement. It was also reported that temperature widely affects the tribological properties of the AMCs. Martin et al. [15] conducted wear test on fabricated composite and stated that at the temperature range of 20-200 Al alloy reinforced with 15 vol% SiC particles showed the transition from mild wear to sever wear with the increase in temperature. Similarly, Muratoglu et al. [16] also studied the effect of temperature on wear behavior of Al-Cu alloy reinforced...
with 25 vol% SiC. The study demonstrated that wear resistance decreases with increase in temperature for the base metal as well as reinforced composite material.

Various combinations of 5083 Al alloy and SiC have been utilized to improve the tribological properties of aluminum matrix composite. Gargatte et al. [17] fabricated AA 5083 reinforced with SiC particles using stir casting technique, where the different volume fraction of SiC particles (3, 5 and 7 wt%) were used for synthesis. The wear test was conducted on the pin-on-disc testing machine to examine the wear behavior of the aluminum alloy and its composites. It was observed that the wear rate decreased by increasing the reinforcement percentage of SiC particles. Al-5083 reinforced with 3, 5 & 7 wt % shows lesser wear rate compared with pure Al-5083 alloy. Similarly, a dry sliding wear test was performed on 5083 Al alloy composite with 10 wt.% SiC by using the pin-on-disk machine. For testing normal load (10N, 20N, 30N) was applied for constant time of 30 minutes at different sliding distance (754 m, 1131 m, 1508 m, 1885 m) and the sliding velocity (0.42 m/s, 0.63 m/s, 0.84 m/s, 1.04 m/s). It was found that applied load has the highest influence on the wear rate by Ravindra et al. [18]. Furthermore, a wide range of SiC weight percentage (5%, 10%, 20% and 25%) utilized as reinforcement by Manoj Singla et al. [19] for fabrication of composite and reported that 20% weight fraction of SiC particles has minimum wear under different applied load. The structure and properties of these metal matrix composites can be varied by the size as well as the type of the reinforcement and nature of bonding [20]. Aluminium matrix composite strengthened with micron or nano-sized particles enhanced mechanical and physical properties in composite materials. The distribution of nano-sized reinforcing particles also affects the morphology and interfacial characteristics of nano-composites as reported by Xiaoxin Y et al. [21].

For analysis of wear results statistical technique used by many researchers. S. Basavarajappa et al. [22] used Taguchi’s method for investigating the influence of wear parameters like as normal load, sliding speed and sliding distance on dry sliding wear of the composites. Prasanta [23] used L27 Taguchi orthogonal design for optimization of four process parameters, viz., concentration of reducing agent, concentration of nickel source solution, bath temperature, and annealing temperature. The wear characteristics of electroless Ni–P coatings sliding is used as the response. It is observed that annealing temperature and bath temperature have the most significant influence on wear characteristics of electroless Ni–P coating. Wear performance was also analyzed by sachin [24] for the composite and the matrix alloy size using a linear factorial design approach. The linear regression equation for the wear rate of the alloy and composite when tested against the SiC and Al2O3 emery paper expressed in term of sliding distance, applied load and abrasive size. It was observed that the wear rate increased with increasing abrasive size, applied load and sliding distance for SiC emery paper, whereas the wear rate increased with abrasive particle and applied load, and it decreased with sliding distance for Al2O3 paper.

In the light of discussed literature, an attempt is made to study the effect of applied load, experimental time and SiC wt % on wear behavior of the Al/SiC nano-composites using Taguchi design of experiments. The analysis of variance (ANOVA) was employed to determine the influence percentage of various factors and its interaction on the wear of the composites.

2. Material and method

2.1 Materials

Al 5000 arrangement is widely utilized as a part of marine and aviation applications considering their dominant corrosion resistance, formability, and great welding qualities. However, because of low strength and poor wear resistance, the utilization of this arrangement is limited. Al 5083 alloy used as a base metal for this work. It is a high Mg-Al composite with light-weight and broadly utilized for the marine and automobile applications. The composition is shown in Table 1. The aluminium alloy was strengthened by mixing nano-particles of SiC through stir casting process [25].

| Table 1. Al 5083 alloy chemical composition |
|------------------------------------------|
| **Element** | **Zn** | **Ti** | **Si** | **Cu** | **Fe** | **Cr** | **Mn** | **Mg** | **Al** |
| % Present  | 0.25   | 0.15   | 0.4    | 0.1    | 0.4    | 0.05-0.25 | 0.4-1.0 | 4.0-4.9 | Balance |

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2.2 Basic concept of Design of experiments (DOE)

The system of laying out the states of analyses including various elements was first proposed by the Englishman, Sir R.A. Fisher [26]. This technique is known as the factorial design of experiments. Taguchi developed technique for directing the design of experiments which depend on all around characterized rules. This method utilizes a set of arrays called orthogonal arrays. These standards exhibit stipulate the technique of performing the minimum number of tests which could give the full data of the considerable number of variables that influence the execution parameter [27]. The crux of the orthogonal arrays strategy lies in picking the level combinations of the input design factors for each analysis. The design of an experiment involves the following steps:

![Figure 1. Steps for design of an experiment](image)

2.3 Plan of experiments

There are numerous standard orthogonal arrays which can be implied for number of independent design factors and levels. The L27 orthogonal array is implied for understanding the impact of 3 autonomous elements each having 3 levels of value. This array has 27 rows and 13 columns. There are three parameters (applied load, time, and SiC weight percentage) which were used for performing the wear analysis furthermore three levels of these parameter were selected. The levels of these factors decided for experimentation are given in table 2.

| Level | Applied Load (N) | Experiment time (mins) | SiC (wt%) |
|-------|------------------|------------------------|-----------|
| 1     | 10               | 30                     | 0         |
| 2     | 20               | 60                     | 1         |
| 3     | 30               | 90                     | 2         |

3. Results and discussion

3.1 Results for Statistically analysis of wear rate

The experiments were directed according to the orthogonal array. For determining the effect of each variable on the output, the signal-to-noise ratio or the SN number, needs to be evaluated for each conducted experiment. The SN ratios were also obtained for various combinations of parameters by using Minitab 17 as shown in table 3. The experimental values were transformed into S/N ratios for measuring the quality attributes.

| Sr. No. | Applied Load (N) | Experiment Time (mins) | SiC wt % | Wear (gms) | SNRA1 |
|---------|------------------|------------------------|----------|------------|-------|
| 1       | 10               | 30                     | 0        | 0.02235    | 33.01445 |
| 2       | 10               | 30                     | 1        | 0.02293    | 32.79192 |
| 3       | 10               | 30                     | 2        | 0.01392    | 37.12722 |
| 4       | 10               | 60                     | 0        | 0.05312    | 25.49484 |
| 5       | 10               | 60                     | 1        | 0.04853    | 26.27979 |
| 6       | 10               | 60                     | 2        | 0.03486    | 29.15345 |
| 7       | 10               | 90                     | 0        | 0.08356    | 21.56003 |
3.2 Minitab analysis of the Taguchi design
The Influence of the control process parameters such as load, experiment time and SiC weight % on wear has been analyzed. The ranking of process parameters is obtained by Minitab using the signal to noise ratios and means for different parameter levels for wear.

| Level | Applied Load (N) | Experiment time (mins) | SiC wt(%) |
|-------|------------------|------------------------|------------|
| 1     | 28.16            | 32.76                  | 24.91      |
| 2     | 26.99            | 25.94                  | 26.25      |
| 3     | 25.87            | 22.34                  | 29.86      |
| Delta | 2.29             | 10.42                  | 4.95       |
| Rank  |                  |                        | 2          |

**Table 5. Response Table for Means**

| Level | Applied Load (N) | Experiment time (mins) | SiC wt (%) |
|-------|------------------|------------------------|------------|
| 1     | 0.04514          | 0.02424                | 0.06439    |
| 2     | 0.05143          | 0.05211                | 0.05358    |
| 3     | 0.05825          | 0.07848                | 0.03686    |
| Delta | 0.01311          | 0.05423                | 0.02754    |
| Rank  | 3                | 1                      | 2          |

Table 4 and Table 5 demonstrate the impact of elements on the different levels of trial and contribution to the general wear of Al Alloy composite. It can be comprehended that time is more critical as it has
the first rank for the fabricated composite component. The impact of SiC wt% on wear behaviour is more than the applied load however not as much as experiment time for SiC nanoparticles.

3.3 Residual Analysis
The main effect plot for mean wear and S/N ratios showed in figure 2(a) and figure 2(b) respectively. The significance of each parameter is determined from the inclination of the main effects plot. It is clear from the main effect plot for wear and main effect plot for S/N ratio that experiment time is a most significant parameter, while SiC wt% also has some considerable effect. These plots were generated based on the condition that “smaller is better” so for minimizing the wear, applied load and experiment time level should be low whereas SiC wt% level must be high. It is also observed from figure 2(a) and figure 2(b) that the parameter for which the line has the higher slope will have the most significant effect.

![Figure 2. Main effects for plot for a) Means b) SN Ratio](image)

The interaction plot between the process parameters such as applied load, experiment time and SiC wt % are also shown in figure 3. The non-parallel lines of parameter play a vital role in the study of an interaction plot means. If the lines of an interaction plot are not parallel, it suggests that there is nominal interaction occurred and if the lines interact each other, then strong interaction occurred between the parameters. Figure 3 shows that there is a substantial interaction between the experiment time and SiC wt.% while moderate interaction between the applied load and experiment time and between applied load and SiC wt.%.

![Figure 3. Interaction effect plot of process parameters on wear](image)
3.4 Results of ANOVA in Minitab

The experimental results were analyzed by analysis of variance (ANOVA) which is used to investigate the influence the wear parameters like applied load, sliding distance and sliding speed. By performing the analysis of variance, it can be decided which factor dominate over the other and the percentage contribution of that particular independent variable. The analysis of variance results for the wear rate for three factors varied at three levels and interactions of those factors. The analysis showed in table 6 was carried out for the confidence level 95%.

| Source                               | DF | Seq SS     | Contribution | Adj SS     | Adj MS     | F-Value  |
|--------------------------------------|----|------------|--------------|------------|------------|----------|
| Applied Load (N)                     | 2  | 0.000774   | 4.23%        | 0.000774   | 0.000387   | 137.19   |
| Experiment Time (mins)               | 2  | 0.01324    | 72.40%       | 0.01324    | 0.00662    | 2347.2   |
| SiC wt %                             | 2  | 0.003464   | 18.95%       | 0.003464   | 0.001732   | 614.16   |
| Applied Load (N)*Experiment Time (mins) | 4 | 0.000041 | 0.23%        | 0.000041   | 0.00001    | 3.65     |
| Applied Load (N)*SiC wt %            | 4  | 0.000223   | 1.22%        | 0.000223   | 0.000056   | 19.75    |
| Experiment Time (mins)*SiC wt %      | 4  | 0.000521   | 2.85%        | 0.000521   | 0.00013    | 46.23    |
| Error                                | 8  | 0.000023   | 0.12%        | 0.000023   | 0.000003   |          |
| Total                                | 26 | 0.018286   | 100.00%      |            |            |          |

It can be observed in table 6 that for aluminium metal matrix composites, that time and SiC wt % has the highest influence on wear.

3.5 Multiple linear regression model

A multiple linear regression model is developed using statistical software “MINITAB 17”. This model gives the relationship between an independent / predicted variable & a response variable by fitting a linear equation to observed data. The generated regression equation established a correlation between the significant terms obtained from ANOVA analysis namely applied load, experiment time and SiC wt%. The regression equation developed for wear calculation in weight (grams) as given in equation (1)

\[
\text{Wear (gms)} = -0.01585 + 0.000699 \text{Applied Load (N)} + 0.000998 \text{Experiment Time (mins)} + 0.00751 \text{SiC wt %} + 0.000006 \text{Applied Load (N)*Experiment Time (mins)} - 0.000413 \text{Applied Load (N)*SiC wt %} - 0.000217 \text{Experiment Time (mins)*SiC wt %} \ldots(1)
\]

From above equation, it is observed that the experiment time has significant role in the wear weight (grams) followed by SiC wt %.

4. Conclusions

From the Taguchi experimental design method results, it is found that the experiment time has the highest influence on wear rate followed by SiC wt % then the applied load for Al-5083 composite reinforced with SiC nano-particles. It is also clear from the ANOVA results that the contribution of applied load, experimental time and SiC wt % is 4.23%, 72.40%, 18.95% respectively in the analysis. It can be concluded from this study that for minimizing the wear, load and time level should be low whereas SiC wt% level must be high.
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