Investigations on Dry Sliding Wear Behaviour of LM13/SiC/Gr Hybrid Composites 
by Response Surface Methodology 

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Abstract

The present investigation focuses on the effect of graphite (Gr) particulates as the second reinforcement on the wear behaviour of LM13/SiC aluminium hybrid metal matrix composites. The reinforcement silicon carbide (SiC) was varied from 0 to 12 wt% in a step of 3 and graphite (Gr) particulate was maintained at 4 wt% in all the composites. The composite was fabricated using compocasting technique by conventional stir casting method. The Scanning Electron Microscope (SEM) and Energy Dispersive Spectrum (EDS) were used for the characterization of composites. The experiments were conducted by four-factor, five-level central composite rotatable design which minimizes the number of experiments. The factors considered are sliding velocity, sliding distance, normal load and wt% of SiC and Gr particles with five levels. The experiments were conducted using a pin-on-disc apparatus. Response Surface Methodology (RSM) was used to develop the statistical model to predict the wear rate and optimize the process variables for a minimum wear rate using Design Expert v10 software. Results showed that normal load is the most influential and sliding velocity is the least influential factors. It is found that increase in SiC and Gr content has increased the wear resistance which resulted in low wear rate when compared with unreinforced aluminium alloy. 

Key words: Hybrid metal matrix composites, silicon carbide, graphite, wear, Response Surface Methodology, optimization.

1. Introduction

Aluminium Metal matrix composites (AMMCs) is considered to be a potential alternative material with conventional monolithic aluminium alloys in many applications owing to its high specific strength and stiffness, low density, low thermal expansion coefficient and high wear resistance (1-3). AMMCs are widely used in many industries that are not limited to aerospace, automotive, defense, naval, electronic packaging, thermal and sports (4). LM13 aluminium alloy containing 12% silicon is widely used in manufacturing internal combustion engines parts such as pistons, cylinder blocks, cylinder heads due to its high resistance to wear, corrosion & thermal conductivities (5). AMMCs reinforced with SiC particulates exhibit higher modulus, strength and wear resistance than conventional alloys. SiC is known to have better chemical compatibility with aluminium as it doesn’t form any inter-metallic phases during its interaction, thus it is a very common type of reinforcement used in Al-MMCs (6). V.D. Londhe et al. have observed the wear increases with increase in normal load at ambient temperature and the wear decreases with increase in normal load at elevated temperature (125°C) of LM 13-SiC10% composite (7). S.Das has conducted a sliding wear, abrasive wear, erosion-corrosion wear study on LM13/SiC composites and concluded the wear rate increases beyond the seizure pressure and addition of SiC particles leads to improvement in seizure pressure with that of unreinforced aluminium alloy. The wear rate of composites decreased with increase in wt% of SiC particles. The alloy exhibited greater wear rate compared to the composite in acidic medium and sand (8). Both mechanical strength and wear resistance of composites increases with addition of SiC particulates but increase in hardness leads to decrease in tribo layer results in increased counter face wear (9–11). Graphite acts as a solid lubricant wherever the liquid lubricant cannot play a role, which prevents metal to metal contact by forming a thin layer of Gr particles (12). Composites reinforced with graphite is used in manufacturing components such as valves, bushes, bearing, pistons, piston rings, cylinder liners which requires resistance to tensile and wear loads (13). Al–Gr composites have better wear resistance than conventional aluminium alloy (14). Rohatgi et al. have reported that reduction in friction coefficient in Al–10SiC–6Gr composite is due to increase in bulk mechanical properties of addition of SiC and formation of graphite film layer due to Gr particulates (15). Ted Guo et al. have observed that wear of Al–10SiC–Gr (Gr 2-8%) hybrid composite increases up to 5% Gr addition which is due to the
reduction in fracture toughness. The wear decreases above 5% Gr addition because of the formation of thick solid lubricant film which overrides the effect of fracture toughness (16). Basavarajappa et al. have investigated the effect of sliding speed on the subsurface deformation on Al2219/15SiCp and Al2219/15SiCp-3Gr composites and have indicated the degree of subsurface deformation. The results reveal increase in sliding speed in mild wear region leads to increase in degree of subsurface deformation. The graphite reinforced composite resulted in less degree of subsurface deformation compared to the graphite free composite (17). These investigations emphasize on the use of Gr particulates as secondary reinforcement in aluminium matrix composites for better tribological properties. An attempt is made here to study the dry sliding wear behaviour of LM13/SiC/Gr hybrid aluminium metal matrix composite using statistical tools. The Design of Experiments (DoE), Analysis of Variance (ANOVA), regression analysis, prediction and optimization are carried out by RSM method using Design Expert v10 software.

2. Experimental Investigations

2.1. Production of Composite by Compocasting Process

Al-SiC-Gr hybrid AMMCs with different weight percentage (0, 3, 6, 9 and 12 wt %) of SiC and 4wt% Gr particulates were produced by compocasting technique using liquid stir casting process (18,19). LM13 aluminium alloy is used as metal matrix. SiC and Gr are used as reinforcements. In the first step 1 kg of aluminium alloy was measured and melted at 800°C in a graphite crucible using a stir casting furnace. According to the wt% SiC and Gr particulates were measured and preheated at a temperature of 400°C for about 30 min in the preheating furnace. The preheating was done to remove the surface impurities and reduce the oxide formation by absorption of gases. Once the metal is melted it was continuously stirred at 600–800 rpm to create a vortex with the help of a mechanical stirrer for 10 mins during which a hexachloroethane tablet (C6Cl6) was added to the melt to degas and liberate any unwanted gases generated during the melting of the aluminum. The preheated SiC and Gr particles were added slowly and continuously into the vortex of the molten metal. To improve wettability 1 wt. % of Mg metal powder was added to the molten metal (20). The stirrer was frequently moved vertically up and down within the mixture to ensure uniform distribution of the added particles. After all the particulates were added into the molten metal the temperature of the furnace was set to 550°C and the composite mixture was allowed to attain the solidus state in the crucible. In the second step the slurry mixture was reheated and melted again at 750°C. The molten metal was again stirred at 300 rpm for about 2 mins. Finally it was cast into a 100 x 100 x 10 mm preheated m.s mould. The composite was allowed to solidify in the atmospheric air and was removed from the mould after solidification.

2.2 Wear Test

The wear test specimens 10 mm x 10 mm x 50 mm are obtained from the cast hybrid composites by machining. The end surface of the specimens are cleaned and polished with 600 grade followed by 1000 grade abrasive paper. The dry sliding wear test was conducted on pin-on-disc wear apparatus (DUCOM TR20-LE) at room temperature according to ASTM G9905 standard. A gray cast iron disc with micro hardness 246 (HV) and surface roughness 0.0001 microns was used to conduct the test. A computer aided data acquisition records the height loss in microns.

2.3 Development of Design Matrix

The most popular design in response surface methodology is central composite design (CCD). The design matrix for experimentation is developed using rotatable central composite design with 31 set of experimental trial runs with input variables and its response results. The literatures of the design matrix are available elsewhere (21, 22).

3. Response Surface Methodology (RSM) for Prediction of Wear Rate

In the traditional experimental design one factor is varied at a time by keeping the other factors constant to find the output response which results in more number of experiments for various factors and levels. It is also very difficult to find the combined effect of the input factors on the response in the experiment. Response surface methodology (RSM) is one of the popular design which simplifies and reduces the number of experiments as well as it helps to find the combined effect of input parameters on the output responses. In this study a RSM with full factorial design of experiments consisting of four factors (sliding velocity, sliding distance, normal load and reinforcement content) and five levels (-2,0,2,4) was used. The experiment results were statistically analyzed by RSM technique using Design Expert v10 software which is widely used in many engineering research fields. Analysis of variance (ANOVA) is performed to check the statistical significance of the quadratic model of wear rate.

The results are analysed with confidence level 95% or p-value of 0.05. This implies that any factor with p-value equal to or less than 0.05 is significant and greater than 0.05 is termed non-significant. ANOVA shows the “Model” is “Significant” while the “Lack of fit” is “Not significant”, which are desirable for a
model. The “Prob. > F” column indicates the significance and non-significance of the factors and its interactions. The Model F-value is 5.46 and Prob. > F value is 0.0009 implies the model is significant and is important. There is just a 0.01% chance that an F-value could occur due to interference or noise. Values greater than 0.1000 indicate the model terms are not significant. Table 5 also shows the other adequacy measures of R², Adj R², and Pred R² are nearer to 1 which means the regression model indicates the goodness of fit between input variables (wear parameters) and output response (wear rate). The regression equation is obtained from the Design Expert v10 software in terms of actual factors is used to predict the wear rate with a reasonable accuracy is given below

\[
W = -10.27678 + 616.16071 \times V + 0.47793 \times D + 47.93809 \times F - 167.27182 \times S + 0.03359 \times V \times D - 11.18750 \times V \times F + 1.04166 \times V \times S + 6.84375 \times 10^{-3} \times D \times F + 5.31249 \times 10^{-3} \times D \times S - 0.19166 \times F \times S - 240.19717 \times V^2 - 2.61290 \times 10^{-4} \times D^2 - 1.81547 \times 10^{-3} \times F^2 + 9.11871 \times S^2
\]

4.2 Optimization of Wear Parameters

The objective of optimization is to provide the optimum wear parameters which give the minimum wear rate. This analysis is based on “smaller is better” concept. It means low wear rate is considered as optimum. The ramp function (optimal solution) is obtained for minimum wear rate with a desirability of 1. The optimal values of the input parameters are; sliding velocity is 1.585 m/s, sliding distance is \( m \), normal load is 11 N and SiC-4Gr is 5.3625 wt%. The desirability varies from 0 to 1 depends on the nearness of the response toward the objective input. The wear parameters are selected based on desirability close to 1, but in this case desirability of 1 is achieved which is said to be proficient.

4.3 Validity of the Wear Model and Confirmation of Experiments

The validity of the dry sliding wear model was evaluated by conducting dry sliding wear test on composites at different values of the experimental factors such as sliding speed (V), sliding distance (D), normal load (F), silicon carbide (S) wt% and graphite (G) 4wt%. As the equation of response for the model is derived from quadratic regression, confirmation test must be conducted in order to confirm their validity. The independent variable selected for the confirmation experiments must lie within the ranges for which equations were derived. It is inferred that the error between experimental and predicted values is within ±5% for the response. All the experimental values of each run are within the 95% prediction interval. This shows the quadratic model obtained is accurate which confirms the experimental conclusion.

5. Conclusions

In the present experimental work LM13/SiC/4Gr hybrid metal matrix composites were successfully fabricated by compocasting process and dry sliding wear tests were conducted on pin-on-disc apparatus and the following conclusions are drawn.

1. The micro and macro hardness of composite increased when compared with base metal matrix. The hardness of the composite increased with increase of SiC and Gr wt%.
2. The wear resistance of the composite increased when compared to conventional metal matrix. The wear resistance of the composite increased with the increase of hardness of the composite.
3. The wear rate of composites decreased with increase in sliding speed, sliding distance and...
reinforcement’s wt % and decreased with the increase in normal load.

4. The wear resistance of developed composites was higher than that of cast metal matrix. This is due to the formation of MML on the worn surface of the composite which played a key role in controlling the wear properties of the composites.

5. The ANOVA indicated that normal load is the most influential factor followed by reinforcement wt %, sliding distance and load on the wear rate of composites.

6. The optimized wear parameters are sliding velocity is 1.585 m/s, sliding distance is 1115 m, normal load is 11 N and SiC-4Gr is 5.9625 wt% respectively.

7. The confirmation experiments showed that the error between experimental and predicted value of wear rate lies within the range of ±5% for the response.

8. Due to less amount of wear Al–SiC–Gr hybrid composites are best suited for tribological applications.

References


