Experimenting to optimize topology parameters of a reinforced metal matrix composite using Taguchi technique of design of experiments

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Abstract. This experimental study is carried out to optimize topological parameters like wear rate and frictional force of an aluminium alloy AA2618 which is a metal matrix of composition Al-93.7%, Si-0.18%, Cu-2.30%, Mg-1.60%, Fe-1.1%, Ni-1.0%, Ti-0.07%. The aluminium alloy is reinforced with titanium di-oxide of 5% by weight. Taguchi design of experiment is used to carry out optimization study, taguchi method is he most reliable common and successful experiment technique for process performance improvement and raise quality of product. As per taguchi technique parameters chosen are sliding distance, speed and load with each property for 3 levels, so the test consists of 27 numbers according to L27 orthogonal array. Optimal parametric condition of minimum wear and frictional force are obtained through signal to noise analysis. For verification of results confirmation experiments is also conducted.

1. Introduction
Aluminium metal composite known as AMCs have emerged into primary material in heavy engineering applications such as brake drums, engine cylinder liners, piston head, as they have good wear resistance and load bearing capacity thanks for the reinforcement of ceramic particles into AMC’s because of which they have good properties [1]. Along with AMCs, PR-MMCs – particulate reinforced metal matrix composites have low density, high strength and stiffness and goof isotropic properties [2-3]. Now alloy materials like these have taken material science studies into new perspectives and because of their industrial application many engineering sectors have shown promising growth and ventured with high efficiency and minimum wear and service sections. Mechanical and material characteristics along with tribo contact condition and surface interaction are the most common tribological characters or parameters that adversely affect the discontinuously reinforced aluminium composites causing high friction and wear performance. Sannino et al, in his paper they have studied about the most common factors that are associated with above mentioned tribological parameters. Lower frictional force and coefficient of friction along with high resistance and seizure pressure were reported when studies were carried out on effect of particulate reinforcement on aluminium alloy [5-7]. In another study by Ramachandra et al [8] they concluded in the study that with addition of SiC particles erosive wear resistance and sliding wear resistance have enhanced even though corrosive resistance dropped. In another comparative study carried out in elevated temperature aluminium alloy Al 7075 reinforced with glass fibre along with base metal aluminium, the alloy showed better wear resistance than base metal [9]. Uyyuru et al [10] studied the effect of reinforcement volume fraction and size distribution of aluminium composites, Gomez de salazan et al [11] investigated the effect and influence of heat
treatment over wear behaviour of aluminium composites, whereas Guo et al [12] did experimentation to study the effect of aging on wear of metal matrix composite. Huge number of researches are carried out to study and understand behaviour, performance of composite materials. This study is carried to study and valuate optimized results of tribological parameters of titanium dioxide reinforced aluminium metal matrix using taguchi’s design of experiment methodology.

![Tribological properties diagram](image)

**Figure 1:** Tribological properties, cause and effect

2. **Experimentation**

2.1. **Materials**

AA2618 is a wrought aluminium alloy which is used as matrix material in the preparation of composite material. The AA2618 Aluminium alloy was developed for high temperature applications such as aircraft and automobile engine components which has the composition of Al-93.7%, Si-0.18%, Cu-2.30%, Mg-1.60%, Fe-1.1%, Ni-1.0%, Ti-0.07% and this alloy can withstand even a temperature of 204°C. Fe and Ni gives structural stability at high temperature along with the help of precipitation and dispersion hardening operations performed on it. TiO₂ is used as reinforcement material, which has very common utilization in many engineering applications. Liquid vortex method was implemented to add 5% by weight of TiO₂ Aluminium alloy matrix.

2.2. **Orthogonal array**

Sliding speed in m/s, load in N, sliding distance in ‘m’ are the three parameters chosen for experiment and each parameter was analyzed three times each as shown in table 1 in order to find the nonlinear behavior

- I. Sliding speed and load’
- II. Sliding speed and distance
- III. Load and distance
These are the selected two factor interactions. An L27 orthogonal array with 26 degree of freedom was selected with first column given to sliding speed, second column to load and the fifth column assigned to sliding distance. The remaining column were assigned to their interactions.

**Table 1** Factors and details

| Factors       | Code | Units | Level 1 | Level 2 | Level 3 |
|---------------|------|-------|---------|---------|---------|
| Sliding speed | S    | m/s   | 1.2     | 2       | 3.1     |
| Load          | L    | N     | 18      | 30.4    | 39      |
| Sliding distance | D | M   | 700     | 1400    | 2100    |

**2.3. Experimental procedure**

Pin on disc type friction and wear monitoring test rig as shown in fig 2 was used in dry sliding condition of composite to study its tribological performance. The lever mechanism applies normal force on the stationary specimen while the disc rotates, and the counter body is made of hardened steel.

Orthogonal array of taguchi design of experiment was followed to conduct wear test and it is studied. Wear rate as a function of the sliding velocity, load and sliding distance. Wear rate and frictional force are noted while conducting the experiments. To make experimental test rig clean from debris and left over after finishing experimental run discs are cleaned using acetone. Mean response values of two experimental run are tabulated into Table 2.

**Figure 2:** Test rig
Table 2: Orthogonal array

| Test | Sliding speed m/s | Load N | Sliding distance m | Wear rate mm³/N·m | Force N | S/N ratio (db) wear rate | S/N ratio (db) friction force |
|------|-------------------|--------|-------------------|-------------------|---------|------------------------|-----------------------------|
| 1    | 1.2               | 18     | 700               | 23                | 7.50    | -26.60                 | -17.58                      |
| 2    | 1.2               | 18     | 1400              | 56.5              | 7.15    | -34.19                 | -17.22                      |
| 3    | 1.2               | 18     | 2100              | 62.0              | 7.90    | -34.98                 | -17.98                      |
| 4    | 1.2               | 30.4   | 700               | 26.0              | 11.60   | -27.62                 | -20.28                      |
| 5    | 1.2               | 30.4   | 1400              | 56.0              | 11.45   | -34.11                 | -20.90                      |
| 6    | 1.2               | 30.4   | 2100              | 81.0              | 11.40   | -37.37                 | -20.86                      |
| 7    | 1.2               | 39     | 700               | 78.0              | 11.40   | -36.84                 | -20.85                      |
| 8    | 1.2               | 39     | 1400              | 81.0              | 13.58   | -37.27                 | -22.22                      |
| 9    | 1.2               | 39     | 2100              | 90.0              | 16.43   | -38.18                 | -23.81                      |
| 10   | 2                 | 18     | 700               | 18.0              | 7.30    | -24.57                 | -17.38                      |
| 11   | 2                 | 18     | 1400              | 55.5              | 6.59    | -34.04                 | -14.26                      |
| 12   | 2                 | 18     | 2100              | 74.0              | 4.87    | -36.50                 | -19.50                      |
| 13   | 2                 | 30.4   | 700               | 26.0              | 9.60    | -27.62                 | -18.82                      |
| 14   | 2                 | 30.4   | 1400              | 61.0              | 8.87    | -34.84                 | -19.66                      |
| 15   | 2                 | 30.4   | 2100              | 82.0              | 9.86    | -37.38                 | -21.21                      |
| 16   | 2                 | 39     | 700               | 41.0              | 11.65   | -31.46                 | -22.10                      |
| 17   | 2                 | 39     | 1400              | 64.0              | 13.30   | -35.25                 | -22.04                      |
| 18   | 2                 | 39     | 2100              | 83.0              | 13.20   | -37.48                 | -13.48                      |
| 19   | 3.1               | 18     | 700               | 22.0              | 4.30    | -26.23                 | -16.40                      |
| 20   | 3.1               | 18     | 1400              | 46.0              | 6.50    | -22.44                 | -16.02                      |
| 21   | 3.1               | 18     | 2100              | 52.0              | 6.10    | -34.48                 | -19.74                      |
| 22   | 3.1               | 30.4   | 700               | 35.0              | 9.90    | -30.12                 | -19.42                      |
| 23   | 3.1               | 30.4   | 1400              | 44.0              | 9.50    | -32.06                 | -19.54                      |
| 24   | 3.1               | 30.4   | 2100              | 52.0              | 9.65    | -33.48                 | -22.40                      |
| 25   | 3.1               | 39     | 700               | 33.5              | 13.80   | -29.75                 | -22.95                      |
| 26   | 3.1               | 39     | 1400              | 65.0              | 13.00   | -35.39                 | -22.86                      |
| 27   | 3.1               | 39     | 2100              | 71.5              | 12.90   | -36.20                 | -22.13                      |

3. Results and discussion

3.1. Signal to noise ratio
For the comparative study under the experimentation, observations are transformed into signal to noise ratio depending on the type of parameters analysed during the study S/N ratio are very broadly classified. Here as the optimization parameters chosen are wear rate and frictional force, they come under “smaller is better” type quality characteristic and for them S/N ratio is formulated as

\[ D = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} Y_i^2 \]  \hspace{1cm} (1)

\( n \) = number of tests in trial, here \( n = 2 \)

A high value of S/N ratio gives the idea that signal is higher than random effects of noise factors and always during the experimentation highest S/N ratio of parameter are chosen, the S/N ratio calculated using equation (1) is tabulated in Table 2.
3.2. Anova

Analysis of variance are used to analyse influence of parameters chosen sliding speed, sliding distance and applied load on performance characteristics. Table 3 and table 4 shows the results of ANOVA.

The percentage contribution factor is calculated using the largest total sum of squares values. From table 4 it is available that distance travelled (P=56.02%) is the most significant factor, while other two parameters contributes 17.69 % and 6.629 %. The table 4 and 5, both has got values of interactions between sliding speed*load, speed*distance, load*distance too.

Table 3 gives idea about variance of frictional force of composite. The test result gives information that load applied on the test material is the most significant factor which causes frictional force, whereas sliding speed and distance has negligible contribution.

| Table 3: ANOVA values of sliding wear |
| Factors | DOF | Seq ss | Adj ss | Adj MS | F | P | % contribution |
| Sliding speed, S (m/s) | 2 | 983.011 | 983.011 | 491.05 | 5.58 | 0.020 | 6.629 |
| Load, L(N) | 2 | 2300.425 | 2300.425 | 1152.2 | 14.40 | 0.002 | 17.69 |
| Distance, D (m) | 2 | 6868.935 | 6868.935 | 3433.4 | 44.94 | 0.000 | 56.02 |
| S*L | 4 | 544.571 | 544.571 | 135.40 | 1.82 | 0.118 | 2.95 |
| S*D | 4 | 420.224 | 420.224 | 104.11 | 1.72 | 0.215 | 1.90 |
| L*D | 4 | 193.357 | 193.357 | 47.59 | 1.31 | 0.543 | 1.00 |
| Error | 8 | 597.386 | 597.386 | 73.89 | 0.55 | 7.78 |
| total | 26 | 11915.194 | 11915.194 | | | | |

| Table 4: ANOVA values of frictional forces |
| Factors | DOF | Seq ss | Adj ss | V | F | P | % contribution |
| Sliding speed, S (m/s) | 2 | 10.416 | 10.416 | 10.416 | 2.67 | 0.073 | 2.694 |
| Load, L(N) | 2 | 208.640 | 208.640 | 208.640 | 72.87 | 0.000 | 84.472 |
| Distance, D (m) | 2 | 1.826 | 1.826 | 1.826 | 0.58 | 0.435 | 0.105 |
| S*L | 4 | 1.784 | 1.784 | 1.784 | 0.23 | 0.749 | 0.180 |
| S*D | 4 | 3.914 | 3.914 | 3.914 | 0.71 | 0.424 | 1.334 |
| L*D | 4 | 2.487 | 2.487 | 2.487 | 0.51 | 0.565 | 0.746 |
| Error | 8 | 10.356 | 10.356 | 10.356 | 7.155 |
| total | 26 | 242.701 | 242.701 | | | | |

3.3. Concurrent optimization of properties

This experiment is carried out to simultaneously optimize the parameters, wear rate and frictional force. The lowest wear rate is recorded at tenth run, when parameters were at second level of sliding speed and first level of load and distance.

Frictional force was least at nineteenth run, when parameters are at third level of sliding speed and first level of load and distance.

Harrington’s desirability function method has been used for multipurpose optimization and represented as.
\[ h_i = \exp \left\{ -\exp (-y_i) \right\} \]  

(2)

single value desirability as

\[ H = \left\{ \prod_{i=1}^{n} h_i \right\}^{1/n} \]  

(3)

Results are tabulated into Table 5 for comparison.

**Table 5:** concurrent optimization

| Optimal levels | Sliding wear rate | Individual desirability H1 | Frictional force | Individual desirability H2 | Combined desirability H |
|----------------|-------------------|-----------------------------|------------------|-----------------------------|-------------------------|
| S L D          |                   |                             |                  |                             |                         |
| 2 18 700       | 18                | 0.999                       | 7.3              | 0.999                       | 0.999                   |
| 3.1 18 700     | 22                | 1                           | 4.3              | 0.995                       | 0.997                   |

3.4. Confirmation experimentation

Experiments of confirmation is carried to verify that optimal solutions obtained would yield to quality improvement under study.

Table 6 shows comparative values of predicted wear rate and functional force with the actual error is difference between actual and predicted values of S/N ratio.

**Table 6:** verification

| Sliding wear rate | Predicted optimum | Actual optimum | Frictional force | Predicted optimum | Actual optimum |
|-------------------|--------------------|----------------|------------------|--------------------|----------------|
| Parameters level  | S:3.1, L: 18, D: 700 | 22 | S/N ratio -26.2364 | Predicted error 0.286103 | 0.446 |
|                   |                   | 21 | -25.8584 | Confident limit, 2\sigma 0.327 |

4. Conclusion

1. Taguchi technique can be successfully used to analyse and predict sliding wear and frictional force as parameters of metal matrix composite
2. The study of variance of sliding wear rate gave evidence to conclude that distance travelled by the specimen is the important factor to be analysed above load and speed.
3. In case of study of variance of frictional force gave conclusive evidence that load is the important factor to be analysed above speed and distance.

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