Predicting the Wear Rate of Aluminum Alloy AA2024-T351 using Hybrid Linear function and Radial Basis Function

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Abstract. AA2024 is one of the heat treatable Al-Cu alloys with good strength to weight ratio and fracture resistance. It finds application mainly in aircraft and structural applications. In T351 tempered condition, AA2024 has improved hardness and strength. However, the softness of the matrix leads to high wear rate. In this study, tribological characteristics of AA2024-T351 is determined using a pin-on-disc tribometer by varying the sliding velocity, sliding distance and axial load as per face centered central composite design. A hybrid linear – radial basis function model is developed to explore the effect of normal load, sliding distance and sliding velocity on the wear rate of AA2024-T351 alloy. The predominant wear regimes in AA2024-T351 alloy is understood from the characterization study on the surface morphology of the worn specimens.

1. Introduction

The huge demand for the reduction of weights in aerospace and automobile industries has forced industries to choose materials with high strength to weight ratio. Aluminum and aluminum alloys have good formability and good strength to weight ratio. These properties enabled aluminum alloys as candidate material for wide applications in automotive structures and aircraft fuselage [1]. Aluminum alloys with copper as major alloying element are classified as 2xxx series. Among the Al-Cu alloys, AA2024 has better fracture resistance [2]. However, contact-motion results in high wear rate even at low loads and makes its industrial applications limited [3-6]. Elimination of wear problems could save $100 million in US and 1.6% GNP in developing countries like India [7,8]. There are various ways to enhance the wear resistance of AA2024 such as heat treatment, directional solidification, deformation processing, surface modification, surface coating etc.

Halkaci et al., [9] studied the effects of the solution temperature, heating rate and quenching delay on the mechanical properties of AA2024 alloy. Chao et al., [10] studied the effect of friction stir welding on dynamic properties of AA2024-T3 and AA7075-T351. The study explored the dynamic compressive flow behavior, its relation to yield stress and strain hardening. The experimental results indicated that friction stir welding reduces the yield stress of the weld material, lower than that of the base material. Lee et al., [11] studied the thermomechanical behavior for AA2024 alloy under uniaxial tensile loading. With increase in stress and elastic deformation, a quasi-linear decrease in temperature is observed.

However, temperature began to increase once the material starts to deform plastically. The temperature change was attributed to the dissipation of heat in the plastic state.

Hudaa et al., [12] characterised 2024-T3 aluminium alloy after heat treatments (solution heat treatment, cold working and tempering). In addition to α-Al, and θ-Al2Cu phases, θ’ was finely dispersed in the solution heat treated specimens. The average grain size of 19.6 μm with fine
dispersion of θ’ improved the yield strength of the alloy. Presence of Al-Cu-Mg i.e. Al2CuMg secondary phases improves the strength of alloy by precipitation hardening. Kaçar et al.,[13] studied the effect of precipitation-hardening conditions on wear behaviour of wrought AA2024. The specimens were aged at 5 different temperature for 5 different time periods (room temperature for 168 h, 120°C for 24 h, 150°C for 18 h, 160°C for 16 h, 200°C for 2 h). The wear rate of the specimens was measured at various sliding velocity (0.0708 m/s, 0.156 m/s, 0.338 m/s) and loads (6.45 N, 9 N, 9.3 N, 11N). Hardness increases with increase in temperature, because of better solubility of copper. The rapid quenching retains Cu in the matrix in supersaturated [14,15]. Artificial aging increases the precipitation behaviour of AA2024 alloy that increases the hardness of the specimens. Hence, the wear resistance of artificially aged specimens were higher than that of the naturally aged specimens.

Campestrinia et al., [16] studied the correspondence between AA2024 alloy’s corrosion behaviour and its microstructural aspects using atomic force microscopy scanning potential technique. The results show the formation of shell shaped secondary phase particles with gradient chemical composition, after homogenization treatment and delayed quench. Galvanic coupling occurs because of large potential difference between the outer shell and the core that causes pitting corrosion. Zhiqiang et al., [17] studied the microstructures and mechanical characteristics of electromagnetic cast (EMC) and direct-chill cast (DCC) AA2024. The results demonstrated that the EMC specimens had small and equiaxed grains at edge and center, compared to DCC. In EMC stirring causes fast loss of superheat, breaks dendrites, and makes grain even smaller. The presence of long grains and segregation was because of slow loss of superheat in DCC specimens. Hardness test showed EMC specimens had hardness two times more than that of the DCC specimens. Hence, the wear resistance of EMC specimens were higher than that of the DCC specimens.

In this research work, the wear rate of AA2024-T351 is studied using pin on disc wear test by varying the wear test parameters sliding distance (m), sliding velocity (m/s) and applied load (N). Response surface methodology (RSM) is one of the conventionally used techniques to develop empirical relationships between input parameters and desirable responses [21]. However, RSM is incompetent to map the non-linear robust relationship between the process parameters. Soft computing is preferred for non-deterministic polynomial problems, for which no known algorithm can compute an exact solution. Soft computing uses a combination of five main complementary techniques namely fuzzy logic, neural networks, evolutionary computation, learning theory and probabilistic methods. Among these methods, we have followed radial basis functions (mono-layered neural network) for function approximations. A statistical regression model was developed using linear function and radial basis function to explore the influence of wear test parameters on the wear rate of AA2024 alloy.

2. Materials and Methods
2.1 Materials
The composition of the wrought AA2024-T351 alloy that is used in the study is stated in the Table 1.

| Element | Al  | Cu  | Mn  | Mg  | Si  | Fe  | Cr  | Zn  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Composition | Balance, 4.65, 0.60, 1.24, 0.50, 0.50, 0.10, 0.25 |

2.2 Microstructure
The base material was cut into a specimen of dimension 10mm×10 mm. The specimen was molded using a cold setting compound and the metal pieces were finely polished for analyzing the microstructure, as per the standard ASTM E3-11. The microstructure was observed after etching the surface with the Kroll’s Reagent for 15 seconds, which was prepared by mixing 92 ml of distilled water, 6 ml of nitric acid, and 2 ml of hydrofluoric acid.

2.3 Microhardness
Vicker’s microhardness test was used to determine the hardness of the alloy. Specimens were prepared by polishing the surface as described in the microstructure section. A diamond indenter was used to make the indentations on the surface with an axial load of 100 gram force, which was loaded for 15
seconds.

2.4 Wear test

2.4.1 Specimen preparation

Specimens of size 10 mm × 10 mm were cut from the plate and were polished as per the standard metallographic preparation techniques. The cold setting compound was used to hold the workpiece in the stainless steel tube of inner diameter 10 mm, outer diameter 11 mm, and length 50 mm. The specimen is placed in such a way that one of its edges acted as the region of interest (contact surface).

2.4.2 Experimental designs

Face-centered central composite design was utilized to prepare an experimental layout with variations in sliding velocity (SV), sliding distance (SD) and applied load (AL). The chosen level of process parameters and the layout of the experimental trials are given in Table 2 and Table 3 respectively.

| Sl.No. | Sliding Velocity (m/s) | Sliding Distance (m) | Applied Load (N) |
|--------|------------------------|----------------------|------------------|
| 1      | 0.5                    | 300                  | 1                |
| 2      | 1.0                    | 600                  | 2                |
| 3      | 1.5                    | 900                  | 3                |
| 4      | 2.0                    | 1200                 | 4                |
| 5      | 2.5                    | 1500                 | 5                |

2.4.3 Wear Trials

In this study, wear test was performed using a pin-on-disc tribometer apparatus. The specimens were carefully degreased and cleaned using acetone. A precision balance with a readability of 0.0001 g was used to measure the mass of the specimens. The specimens were worn against a disc made of EN316 steel at various process parameters as described in Table 3. Calculation of the wear rate is done by using equation (1).

\[
\text{Wear rate} = \frac{\Delta M}{AL \times SD}
\]  

(1)

Where \(\Delta M\) is the mass loss, \(AL\) is the applied load, and \(SD\) is the sliding distance.

2.4.4 Surface Morphology analysis

The worn surface morphologies of the specimens with maximum and minimum wear rates were analyzed using field emission scanning electron microscope (SIGMA HV – Carl Zeiss).

2.5 Development of Hybrid Model integrating the radial basis function and linear function

A hybrid model was developed to relate the response variables (wear rate) and predictor variables (wear test parameters). Radial Basis Function (RBF) returns real values and any function, which satisfies the equation (2) is called as an RBF.

\[
(x,c) = (||x-c||)
\]  

(2)

where \(x\) is a variable and \(c\) is the center point. There are many types of RBF namely gaussian, multi-quadratic, inverse quadratic, inverse multi quadratic, polyharmonic spline, and thin plate spline. In this research, we have used a multi-quadratic type RBF. Equation (3) gives the characteristic equation for function approximation using the RBF network.

\[
RBF = y(x) \Sigma_{i=1}^{n} w_i \times \phi(||x - x_i||)
\]  

(3)

Where \((x)\) is the approximant and \(w_i\) is the weights that can be calculated by iterative methods. The characteristic equation for a linear – radial basis function is given by equation (4).
\[ z = LF + RBF \]  

(4)

where \( z \) is the liable variable, \( LF \) is linear function, and \( RBF \) is radial basis function.

3. Results and Discussions

3.1 Microstructure

Figure 1 Microstructure of AA2024-T351 at 500x magnification

Microstructure analysis revealed that the alloy has two phases (\( \alpha \)-Al and \( \theta \)-Al\(_2\)Cu), as shown in the Figure 1. The primary phase is the white colored/light patches in the image and the secondary phases are the dark black spots. We observed that the secondary phase alloys (Al\(_2\)Cu) are heterogeneously distributed.

3.2 Microhardness

The specimen was subjected to ten indentations and the corresponding microhardness values are noted. The average Vicker’s microhardness of the alloy was found to be 145.54 HV.

3.3 Wear rate

Wear tests were performed on AA2024-T351 alloy specimens. The wear test parameters and corresponding wear rate of the specimens are given in the Table 3. The results indicate that the wear rate obtained was in the order of \( 10^{-7} \) g/Nm for the tested parameter conditions. It is observed that specimen BM10 had a minimum wear rate of \( 1.61399\times10^{-7} \) g/Nm and specimen BM14 had a maximum wear rate of \( 12.9497\times10^{-7} \) g/Nm. Specimens with the same process parameters showed almost same wear rate with insignificant deviations.

| Sl. No. | Specimen number | Sliding velocity (m/s) | Sliding distance (m) | Applied load (N) | Wear rate (g/Nm) \( \times 10^{-7} \) |
|---------|-----------------|------------------------|----------------------|-----------------|-------------------------------------|
| 1       | BM01            | 1                      | 600                  | 2               | 3.31294                             |
| 2       | BM02            | 2                      | 1200                 | 2               | 3.39789                             |
| 3       | BM03            | 2                      | 600                  | 4               | 1.74142                             |
| 4       | BM04            | 1                      | 1200                 | 4               | 3.01563                             |
| 5       | BM05            | 1.5                    | 900                  | 3               | 2.45403                             |
| 6       | BM06            | 1.5                    | 900                  | 3               | 3.0581                              |
| 7       | BM07            | 2                      | 600                  | 2               | 2.97315                             |
| 8       | BM08            | 1                      | 1200                 | 2               | 3.35541                             |
| 9       | BM09            | 1                      | 600                  | 4               | 4.37478                             |
| 10      | BM10            | 2                      | 1200                 | 4               | 1.61399                             |
| 11      | BM11            | 1.5                    | 900                  | 3               | 3.51115                             |
| 12      | BM12            | 1.5                    | 900                  | 3               | 3.17135                             |
| Sl. No. | Specimen number | Sliding velocity (m/s) | Sliding distance (m) | Applied load (N) | Wear rate (g/Nm) x 10^{-7} |
|--------|-----------------|------------------------|---------------------|------------------|-----------------------------|
| 13     | BM13            | 0.5                    | 900                 | 3                | 2.41627                     |
| 14     | BM14            | 2.5                    | 900                 | 3                | 12.9497                     |
| 15     | BM15            | 1.5                    | 300                 | 3                | 11.213                      |
| 16     | BM16            | 1.5                    | 1500                | 3                | 2.44648                     |
| 17     | BM17            | 1.5                    | 900                 | 1                | 3.9642                      |
| 18     | BM18            | 1.5                    | 900                 | 5                | 2.80892                     |
| 19     | BM19            | 1.5                    | 900                 | 3                | 3.13361                     |
| 20     | BM20            | 1.5                    | 900                 | 3                | 2.90708                     |

3.4 Surface Morphology Analysis

Figure 2 exhibits the surface morphology of the specimen BM10 which had the minimum wear. Cracks, scoring and small scratches were observed on the wear tracks of the specimen. In Fig. 2 (a) the debris and cracks were observed on the specimen. Figure 2 (b) exhibits the cracks and pits on the surface of the specimen. Cracks, debris and few chips were spotted on the specimen, as shown in Fig. 2 (c). In the Fig. 2 (d), shallow grooves and scratches were spotted on the worn specimen BM10.

![Figure 2](image1.png)

Figure 2. Surface morphology of specimen BM10

Figure 3 exhibits the surface morphology of specimen BM14 with high wear rate due to the presence of many deep and shallow grooves. Formation of debris and delamination was observed in Fig. 3 (a). In Fig. 3 (b), scoring and delamination was observed. In Fig. 3 (c), many deep and shallow grooves are observed. More delamination and galling are spotted in Fig. 3 (d).

![Figure 3](image2.png)
3.5 Linear - Radial Basis Function model

A linear-radial basis function model was developed using MATLAB. AL, SD and SV are the predictor variables and wear rate is the response variable. The predictor variables are coded such that the minimum real value corresponds to -1 and maximum real value corresponds to +1. The RBF was developed using a multi quadratic kernel with 5 centers and a global width of 0.00011911.

\[
\text{Wearrate} = 4.8884 + 2.4353 \times AL + 1.4767 \times SD + 2.8246 \times SV + RBF
\]  

(5)

The analysis of variance for the developed model is given in Table 4. The statistical parameters were used to test the efficacy of the developed model. It was found that the coefficient of determination (R2) was approximately equal to 1 and RMSE value was less (0.564). This indicates higher prediction efficiency of the developed model.

|                      | SS     | DF | MS   |
|----------------------|--------|----|------|
| Regression           | 153.99 | 7.99| 19.25|
| Error                | 2.22   | 7  | 0.31 |
| Total                | 156.27 | 15 | 0    |

3.5.1 Analysis of Transition Load

Figure 4 shows the variation in wear rate at various loads with respect to change in SV. It is observed that wear rate increases with increase in SV, irrespective of the AL. Among the tested specimens, specimens worn at SV of 0.5 m/s and axial load of 1 kg exhibited the least wear rate. Among the wear test specimens, specimens worn at AL of 3 kg and SV of 2.5 m/s exhibited high wear rate. Specimens worn at AL of 5 kg exhibited the highest wear rate at SV of 0.5 m/s, while the Specimens worn at AL of 5 kg exhibited the least wear rate at SV of 2.5 m/s. The formation of oxide layers at high axial load and high SV increased the wear resistance of AA2024-T351 alloy.
Figure 4. Relation between wear rate and SV for different AL.

Figure 5. Relation between wear rate and SD for different AL.

Figure 5 illustrates the variation in wear rate at various loads with respect to change in SD. It is observed that the wear rate decreases with increase in SD, irrespective of the AL. Among the tested specimens, specimens worn for a SD of 1200 m at an axial load of 4 kg exhibited the least wear rate. Among the wear test specimens, specimens worn at AL of 3 kg and SD of 300 m exhibited a high wear rate. Specimens worn at AL 1 kg exhibited minimal decrement in wear rate with increase in SD from 300 m to 1500 m. The formation of oxide layers with increasing SD increased the wear resistance of AA2024-T351 alloy.

3.5.2 Effect of Process parameters
3.5.2.1 Sliding velocity and Sliding distance

Figure 6 shows the influence of SD and SV on the wear rate of AA2024-T351 alloy. A high wear rate is observed in the specimens worn at SV between 2.25 and 2.5 m/s and SD between 600 and 1200 m. Specimens worn at SV between 1.25 and 1.75 m/s and SD between 600 and 1200 m exhibits a high wear rate. A lesser wear rate is in the specimens worn at SV between 0.5 and 1 m/s and SD between 1000 and 1500 m. It is observed that the wear rate of the specimens decreases with increase in SD for SV between 0.5 and 1.1 m/s. At SV between 2 and 2.5 m/s, the wear rate increases up to a SD of 900 and then decreases. We observe that at higher SD and lesser SV the wear rates are minimum.
3.5.2.2 Sliding distance and Applied Load

Figure 7. Influence of SD and AL on wear rate

Figure 7 shows the influence of SD and axial load on the wear rate of AA2024-T351 alloy. A high wear rate has been noticed in the specimens which have worn at SD between 300 and 500 m and at AL between 2 and 4 kg. A less wear rate is observed in the specimens worn for a SD between 900 and 1400 m and at AL between 3.5 and 4.75 kg. It is observed that the wear rate of the specimens decreases with increase in SD. We observe that at higher SD and higher AL the wear rates are minimum. The formation of oxide layers increases the wear resistance of AA2024-T351 specimens that were slid for longer distances.

3.5.2.3 Load and Sliding velocity

Figure 8. Influence of SV and AL on wear rate

Figure 8 shows the influence of SV and applied on the wear rate of AA2024-T351 alloy. A high wear rate is observed in the specimens worn at SV between 2.25 and 2.5 m/s and AL between 2 and 4 kg. A lesser wear rate is in the specimens worn at SV between 0.5 and 1.75 m/s and AL between 3.5 and 4.5 kg. Also lesser wear rate is observed in the specimens were SV is between 0.5 and 1.75 m/s and AL between 1 and 2 kg. Specimens worn out at SV between 2 and 2.5 m/s, wear rate increases up to AL of 3 kg and then decreases. We observe that at lesser SV and at all AL the wear rates are minimum.

6. Conclusion
AA2024-T351 alloy was characterized for microstructure and microhardness. The microstructure results revealed that the alloy has two phases (Al and Al2Cu), with coarse grains and heterogeneous distribution of Al2Cu secondary phase. The average microhardness of the specimen was found to be
Wear rate of the specimens was tested at various levels of wear test parameters as per face-centered central composite design. A hybrid model were developed to determine the relationship between wear rate and the wear test process parameters used in the wear test.

The results demonstrated the following.
- Wear rate increases with increase in SV
- Wear rate decreases with increase in SD
- Wear rate increases up to AL of 3 kg and then decreases.

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