Development of a Novel Wear Equation by Comparing the Wear Behaviour of Hard (AA7075) and Soft (AA6063) Hybrid Composite Materials

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In this research, aluminium alloys AA7075 and AA6063 were reinforced with aluminium oxide and titanium oxide particles fabricated through stir casting. The Archard equation was used to model wear behavior, with the wear rate and hardness ratios determined experimentally. The addition of reinforcing particles improves hardness and wear resistance by impeding dislocation movement and refining grain size. At higher temperatures, a protective oxide layer forms, reducing wear. The wear rate decreases with increasing reinforcement percentage and increases with sliding distance. AA7075 exhibits lower wear rates than AA6063, especially at higher temperatures, due to its higher hardness. The developed wear equation in this study relates the wear rates of harder (AA7075) and softer (AA6063) composite materials by considering factors such as % reinforcement, load, sliding distance, velocity, and temperature. The equation considers the change in the wear rate of aluminium composites with respect to temperature, represented by dv/dT and accounts for the effect of temperature on wear behavior through the temperature coefficients (α and β). The equation takes into deliberation the impact of these parameters on wear behavior, offering a mathematical foundation for understanding and comparing wear performance across different materials.

Keywords: relative wear equation, hardness, tribology, composites, high temperature application.

1. INTRODUCTION

Aluminium alloys find extensive application in aerospace, automotive, and structural engineering owing to their impressive strength-to-weight ratios and resistance to corrosion. To enhance the strength of the composites, it was reinforced with particles, fibres, and whiskers utilizing powder metallurgy, casting, and in-situ fabrication techniques. Of distinct techniques stir casting proffers uniform dispersion and is suitable for mass production. Increasing reinforcement content reduced the density of the composites but increased their hardness and wear resistance [1]. Wear rates increase with higher loads but decrease with added TiC content, results in a 20 % reduction in the coefficient of friction [2]. Increased sliding speed reduces wear by forming a tribo layer on worn surfaces [3]. Suresh et al reinforced AA7075 with nano Silicon carbide particles and revealed that 4 % SiC proffers optimal wear resistance and increasing applied load and sliding distance can lead to a linear increase in wear [4]. The dry sliding wear behavior of AA7075 revealed that a composite with 4 wt.% TiC, 9.81 N load, 3 m/s sliding velocity, and 1500 m sliding distance exhibited the lowest wear rate [5]. AA7075 reinforced with Al_2O_3 exhibited an increase in wear resistance, with particles acting as dislocation barriers, enhancing the wear resistance [6]. Reena Roy et al. examined the wear behavior of AA6063/ZrO_2 composites and concluded that hardness increases whereas COF decreases with increasing ZrO_2 content, leading to improved wear resistance [7]. The wear resistance of the composites is attributed to increased friction force, surface oxidation, and material mixing under high loads, along with the high interfacial binding strength between the Al matrix and reinforcing grains [8].

The effective performance and potential applicability of a $Cr_2O_3 - 40\ \%\ TiO_2$ coating processed through plasma spray to grey cast iron improves resistance to wear and corrosion [9]. The tribological characteristics of brake discs coated with $Cr_2O_3 - 40\ \%\ TiO_2$ by plasma spraying showed notable enhancements and improves the durability of the braking system [10]. The impacts of $Cr_2O_3 - 2TiO_2$ and $55TiO_2 - Cr_2O_3$ coatings on braking performance are evaluated, indicating their potential to increase braking efficiency [11]. The solid particle erosion wear behaviour of AA7075 alloys study offers significant insights for developing a unique wear equation that takes changing material hardness in hybrid composites into account and for comprehending wear behaviour [12, 13]. Studies on the wear behaviour of precipitation-strengthened nickel-copper-based K-500 alloy and the effects of T5 and T6 heat treatments on AA6063 alloy have important ramifications for the development of novel materials and coatings that will improve wear resistance in hybrid composite materials [14]. The research was performed on numerical wear calculation

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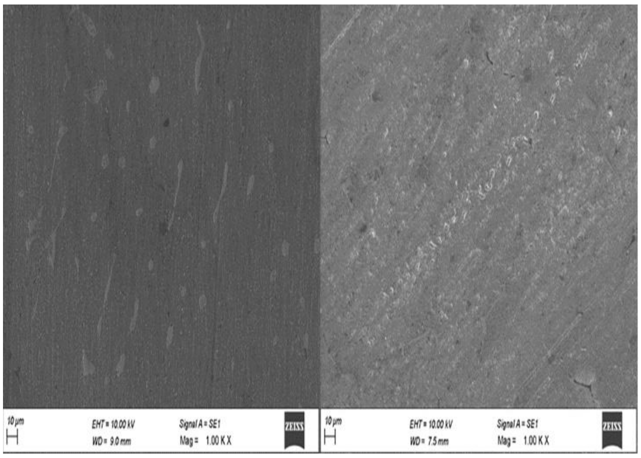
in rolling contact based on the Archard equation and correction of the Archard equation for assessing the wear behaviour of modified pure titanium [15, 16]. Abrasive wear is found to be linearly related to the inverse of Vickers hardness values, indicating adherence to Archard's law of wear [17]. From the literature survey, it was evident that a lot of works were reported on AA7075 and AA6063 composites by reinforcing with distinct particles. Even though work related to comparing the wear behavior of harder and softer alloys and developing a wear equation was scarcely available. Hence in this work, the research gap was addressed by relating the wear behavior of harder and softer alloys, thereby developing a wear equation to predict wear rates aiding in the selection of materials for specific applications.



a b

Fig. 1. SEM of hybrid composites: a – AA7050; b – AA6063

2. EXPERIMENTAL WORK

Aluminium alloys AA6063 and AA7075 were heated to the temperature of 700 °C and 850 °C utilizing the electric furnace. Preheated Al_20_3 and TiO_2 particles of 2.5 weight percentage were added to the charge and stirred for 300 sec and 2.5 % of magnesium flux was added to improve wettability after that the mixture was mixed once again for 240 sec. The mixture was bottom poured into the mild steel mould and allowed to cool for 24 hrs. The specimen was turned and faced to eliminate surface defects and the same technique was repeated for the manufacturing of composites of distinct reinforcement percentages. The uniform dispersion of reinforcement over matrix material was confirmed through SEM. The Rockwell hardness tests were performed on the specimens as per standard ASTM E-18. Pin-on-disc wear experiments were conducted on a Ducom tribometer by varying temperature, % reinforcement, load, sliding velocity, and distance.

Table 1. Process parameters and their levels

Process parameters	Levels
% reinforcement	406.77 ± 0.25
Load, N	423.24 ± 0.28
Temperature, °C	439.79 ± 0.44
Sliding velocity, m/s	433.00 ± 2.78
Distance, m	422.64 ± 2.78
Matix material	AA6063, AA7075

Experiments were planned utilizing Taguchi L25 orthogonal array. Each parameter was varied for 5 different levels as depicted in the Table 1, weight loss after sliding was taken as wear rate. The wear rate of AA6063 and AA7075 was contrasted and it is utilized for the development of wear equation.

3. RESULTS AND DISCUSSION

The examination of the microstructure, as illustrated in Fig. 1, demonstrated a consistent dispersion of the reinforced particles within the matrix material. During the casting process, the magnesium (Mg) flux was noted to undergo a reaction with oxygen, resulting in the formation of magnesium oxide (MgO), which was evident in the composites. These MgO particles contributed to enhancing the wettability of the composites. Furthermore, the inclusion of magnesium as a flux was effective in purging impurities, which were subsequently eliminated as slag.

From the results it was revealed that the load, sliding temperature, distance, hardness and velocity influence the wear rate of composites [18], hence Archard equation can be written as Eq. 1.

$$V = k \cdot F \cdot s \cdot H \cdot \upsilon, \tag{1}$$

where $H_{6063/7075}$ is the hardness ratio of AA6063 to AA7075; k_{6063} and k_{7075} are the wear coefficients for AA6063 and AA7075 respectively; F is the normal applied force; s is the sliding distance; υ is the sliding velocity.

In this study wear experiments were conducted on two materials, AA6063 and AA7075, of two AA6063 was softer material. By relating wear volume can be calculated by Eq. 2. The wear coefficient k_{6063} and k_{7075} for AA6063 and AA7075 and the hardness ratio $(\frac{AA6063}{AA7075})$ can be obtained through experimental testing.

$$V = k_{6063} \cdot k_{7075} \cdot F \cdot s \cdot H_{6063/7075} \cdot \upsilon. \tag{2}$$

When these materials were reinforced utilizing the Al_2O_3 and TiO_2 particles, improvement in hardness was observed as portrayed in Fig. 2. The dislocations that cause plastic deformation in metals are impeded by the tougher reinforcing particles when they are distributed throughout the matrix material [19]. As a result, there is an overall improvement in hardness as the deformation process is slowed down and the resistance to indentation was increased. With regards to the hardness, the equation was modified as per Eq. 3:

$$H_{composite} = \frac{H_{6063/7075} + \Delta H_{6063}}{1 + \frac{\Delta H_{7075}}{H_{6063/7075}}}, \tag{3}$$

where ΔH_{6063} is the increase in hardness for AA6063 due to reinforcement materials; ΔH_{7075} is the increase in hardness for AA7075 due to reinforcement materials.

For AA6063 wear rate decreases with an increase in reinforcing percentage, at 0 % wear rate of 0.0176 mg and it was decreased to 0.0130 mg for 10 %, representing a reduction of approximately 26 % as shown in Fig. 1. This reduction in wear rate can be attributed to the strengthening effect of the reinforcement particles [20]. As the percentage of reinforcement increases, the hardness of the composite material increases, leading to improved resistance to wear. The reinforcement particles act as barriers to the movement of dislocations, the presence of reinforcement particles refined the grain size, and enhanced the hardness and wear resistance.

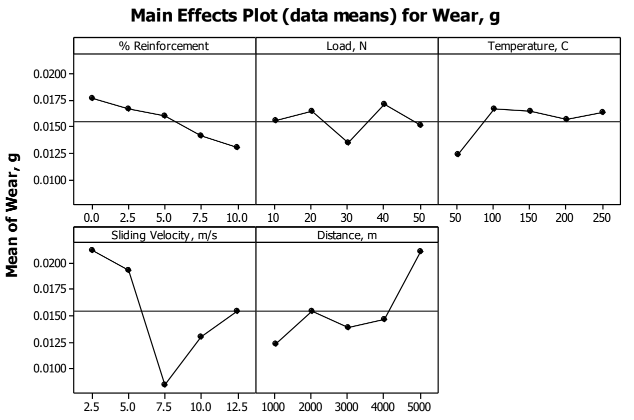


Fig. 2. Wear behaviour of AA6063 hybrid composites

Magnesium added as a flux in aluminum matrix composites reacts with oxygen to form magnesium oxide (MgO) particles. These MgO particles act as nucleation sites for new grains and as pinning points for grain boundaries, inhibiting grain growth and resulting in a finer grain structure in the composites. The findings reveal a 35 % rise in wear rate, which begins at 0.0123 at 50 °C and climbs to 0.0166 at 100 °C. However, the wear rate drops to 0.0155 at 150 °C, then increases slightly to 0.0163 at 250 °C. The initial increase in wear rate can be attributed to the softening of the alloy at higher temperatures, leading to increased plastic deformation and wear [21]. However, the subsequent decrease in wear rate at 150 °C could be due to the formation of a protective oxide layer on the surface of the alloy, which reduces wear. This oxide layer may become less effective at higher temperatures, reducing of wear resistance when temperature exceeds 150 °C.

At the load of 30 N, the reinforcing particles detached resulted in third body abrasion and the applied load was sufficient for the formation of a Mechanical Mixed Layer (MML). The MML acts as a protective layer, reducing direct contact between the mating surfaces and minimizing wear. At lower loads, the applied force was not sufficient to fully develop the MML [22]. As a result, the wear rate is relatively high as the contact surfaces experience direct interaction. At higher loads, these MMLs break down and paves the wave for the delamination wear results. The wear rate reduces with a raise in sliding speed and reaches a minimum wear of 0.008 g for 7.5 m/s, thereafter increases. At lower sliding velocities attributed to the longer contact time between the mating surfaces, leading to increased material removal through adhesion and abrasion processes [23]. At 7.5 m/s wear resistance increases owing to the formation of tribo layer which acts as a protective barrier and reduces wear. At higher sliding velocities, composite pin attains its deformation temperature and generates significant frictional heat, causes plastic deformation and leads to delamination wear. The wear rate upsurges with an increase in distance and transits from mild to severe wear when the sliding distance exceeds 4000 m. The transition was ascribed by the following factors: 1) the accumulation of wear debris between the mating surfaces can lead to increased abrasive wear [24]; 2) the composite pin experiences cyclic loading, leading to surface fatigue and the formation of microcracks results in higher wear rate [25].

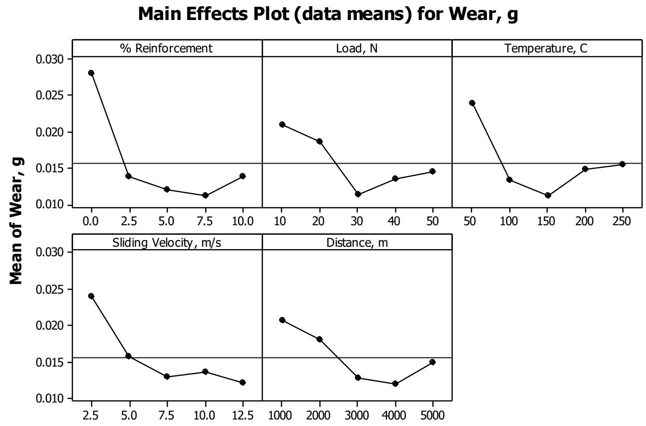


Fig. 3. Wear behaviour of AA7075 hybrid composites

AA7075 exhibits lower wear rates compared to AA6063 across all reinforcement percentages. This can be attributed to the higher hardness of AA7075, which provide better resistance to wear. The wear rate of AA7075 decreases more rapidly with increasing reinforcement percentage, indicating that harder alloys benefit more from the addition of reinforcement particles in terms of wear resistance compared to AA6063 as portrayed in Fig. 3. At elevated temperatures, the wear resistance of AA7075 hybrid composites increases until 150 °C, thereafter increases attributed to the softening of the material at higher temperatures, leading to increased plastic deformation [26]. AA7075 exhibits a wear rate of 0.011 at 150 °C which was lower than AA6063. The findings imply that AA7075 outperforms AA6063 in terms of wear resistance at higher temperatures. At 250 °C, the wear rate of AA7075 increases marginally to 0.0148 whereas AA6063 has a much greater wear rate of 0.0210 at 250 °C. This indicates that AA7075 maintains a relatively constant wear resistance at higher temperatures in contrast to AA6063, which exhibits a more pronounced increase in wear rate [27]. The results revealed that the higher strength and hardness of AA7075 make it more resistant to wear, as temperatures increase. At lower loads, AA7075 exhibits lower wear rates compared to AA6063, indicating superior wear resistance [28]. However, at higher loads, AA6063 shows lower wear rates than AA7075, suggesting better performance under heavier loading conditions. When it comes to sliding distance and velocity, AA7075 often shows lower wear rates than AA6063, and showes stronger wear resistance over longer distances and at higher velocities.

$$V_{6063} = k_{6063-TiO2} + k_{6063-Al2O3} \cdot F \cdot s \cdot H_{6063/7075} \cdot \upsilon \cdot (1 + \alpha_{6063} \cdot T), \quad (4)$$

where $k_{6063-Al2O3}$ and $k_{6063-TiO2}$ are the wear coefficients for AA6063 reinforced with Al_2O_3 and TiO_2, respectively; α_{6063} and α_{7075} represents the temperature coefficient of the softer and harder material below 150 °C.

With respect to the above results, the wear behavior for the softer material can be written as per Eq. 4.

Wear behavior for the harder material can written as Eq. 5:

$$V_{7075} = k_{7075-Al2O3} + k_{7075-TiO2} \cdot F \cdot s \cdot H_{6063/7075} \cdot \upsilon, \qquad (5)$$

where $k_{7075-Al2O3}$ and $k_{7075-TiO2}$ are the wear coefficients for 7075 reinforced with Al_2O_3 and TiO_2, respectively.

When the temperature exceeds 150 C, the equation can be modified as Eq. 6:

$$V_{7075} = k_{7075-Al2O3} + k_{7075-TiO2}.F.s.H_{6063/7075}.\upsilon.\left(1 - \frac{T-150}{\beta_{7075}}\right), \qquad (6)$$

where β_{6063} and β_{7075} represents the temperature coefficient of the softer and harder material above 150 °C.

Hardness relatives index is the common term for both materials hence Eq. 4 can modified as Eq. 7.

$$H_{6063/7075} = \frac{V_{6063}}{(k_{6063-Al2O3} + k_{6063-TiO2}).F.s.\upsilon.(1+\alpha_{6063}.T)}. \qquad (7)$$

Now, we can substitute this expression into the equation V7075 as shown in Eq. 8:

$$V_{7075} = k_{7075-TiO2} \cdot F \cdot s \cdot \upsilon \left(1 - \frac{T-150}{\beta_{7075}}\right) \cdot \frac{V_{6063}}{(k_{6063-Al2O3} + k_{6063-TiO2}) \cdot F \cdot s \cdot \upsilon (1+\alpha_{6063} \cdot T)}. \qquad (8)$$

Hardness increases with the addition of particles in the case of both materials, hence the term can be eliminated and Eq. 4 can written as Eq. 9 and Eq. 10:

$$V_{7075} = \frac{k_{7075-TiO2}}{(k_{6063-Al2O3} + k_{6063-TiO2})} \cdot \frac{V_{6063}}{(1+\alpha_{6063} \cdot T)} \left(1 - \frac{T-150}{\beta_{7075}}\right); \qquad (9)$$

$$V_{6063} = (k_{6063-Al2O3} + k_{6063-TiO2}) \cdot F \cdot s \cdot \upsilon (1 + \alpha_{6063} \cdot T) \qquad (10)$$

Now, let's differentiate both equations with respect to temperature as portrayed in Eq. 11 and Eq. 12.

$$\frac{dV_{7075}}{dT} = \frac{k_{7075-TiO2}}{(k_{6063-Al2O3} + k_{6063-TiO2})} \cdot \frac{V_{6063} \cdot \beta_{6063}}{(1+\alpha_{6063} \cdot T)^2} \cdot \left(1 - \frac{T-150}{\beta_{7075}}\right) - \frac{k_{7075-TiO2}}{(k_{6063-Al2O3} + k_{6063-TiO2})} \cdot \frac{V_{6063}(1+\beta_{6063} \cdot T)}{(1+\alpha_{6063}.T)} \cdot \frac{1}{\beta_{7075}}; \qquad (11)$$

$$\frac{dV_{6063}}{dT} = (k_{6063-Al2O3} + k_{6063-TiO2}) \cdot F \cdot s \cdot \upsilon \cdot \alpha_{6063}. \qquad (12)$$

To isolate α_{6063} on one side of the equation and all other terms on the other side, we'll rearrange the equation for $\frac{dV_{6063}}{dT}$ as follows Eq. 13:

$$\alpha_{6063} = \frac{\frac{dV_{6063}}{dT}}{(k_{6063-Al2O3} + k_{6063-TiO2}).F.s.\upsilon}. \qquad (13)$$

Now substitute α_{6063} in $\frac{dV_{7075}}{dT}$ as in Eq. 14:

$$\frac{dV_{7075}}{dT} = \frac{k_{6063-Al2O3} + k_{6063-TiO2}}{k_{7075-TiO2}} \cdot \frac{V_{6063} \cdot \beta_{6063}}{\left(1 + \frac{\frac{dV_{6063}}{dT}}{(k_{6063-Al2O3} + k_{6063-TiO2}).F.s.\upsilon} \cdot T\right)^2} \cdot \left(1 - \frac{T-150}{\beta_{7075}}\right) - \frac{k_{6063-Al2O3} + k_{6063-TiO2}}{k_{7075-TiO2}} . V_{6063} . \frac{1}{\beta_{7075}}. \qquad (14)$$

The relationship between harder and softer composite material with respect to wear Eq. 15 can be given as

$$\frac{dV_{7075}}{dV_{6063}} = \frac{k_{7075-TiO2}}{(k_{6063-Al2O3} + k_{6063-TiO2})} \cdot \left(1 + (k_{6063-Al2O3} + k_{6063-TiO2}) \cdot F \cdot s \cdot \upsilon \frac{dT}{dV_{6063}} \cdot T\right)^2 V_{6063} \cdot \beta_{6063}\left(1 - \beta_{7075} \cdot (T - 150)\right) - \frac{k_{7075-TiO2}}{(k_{6063-Al2O3} + k_{6063-TiO2})} \cdot V_{6063} \cdot \beta_{7075}. \qquad (15)$$

The equation relates the wear rates of harder (AA7075) and softer (AA6063) composite materials by relating their response to factors like % reinforcement, load, sliding distance, velocity, and temperature. It can direct material selection for certain applications and aid in understanding the relative wear performance of various materials.

A sensitivity analysis was performed to validate the wear equation under the assumption that all parameters values were equating to 1. The equation simplifies as shown in Eq. 16. This method emphasises the necessity for experimental validation and is in line with studies on adhesive wear mechanisms [29]. To further improve the prediction ability of the equation, future research can take into account the impacts of adhesion force, as investigated by Mishinaa and Hase [30]. The study offers a strong foundation for predicting wear rates in hybrid composite materials, facilitating material selection and design for diverse applications.

$$\frac{dV7075}{dV6063} = \frac{1}{(2)^2 * 1 * (149)^2} - \frac{1}{2} = -0.4998. \qquad (16)$$

The negative value indicates that the wear rate of AA7075 is lower than that of AA6063. However, the magnitude of the negative value is not significant (-0.4998), suggesting that the wear rate of AA7075 is approximately half that of AA6063, it was well correlated with the experimental results.

4. CONCLUSIONS

1. The addition of Al_2O_3 and TiO_2 particles improved the hardness of AA6063 and AA7075 composites, enhancing wear resistance. This improvement was attributed to the hindrance of dislocations by the reinforcing particles, slowing down the deformation process and increasing resistance to indentation.
2. Wear rate increases as load and sliding distance increases. On the other hand, wear rate reduced at higher sliding speed, load, and temperature owing to the formation of protective MML and oxide layer on worn surfaces. When load and temperature exceed saddle point, MML and oxide layer broke down resulting in delamination wear, hence wear increased.
3. The wear equation relates the wear rates of AA6063 and AA7075 composites based on factors like % reinforcement, load, sliding distance, velocity, and temperature. This equation can guide material selection and provide insights into the relative wear performance of different materials.

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