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The Effects of Titanium Dioxide (TiO_2) Content on the Dry Sliding Behaviour of AA2024 Aluminium Composite

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ABSTRACT

The low density, low expansion coefficient, and strong corrosion resistance at room temperature of Aluminium alloys have made them a popular choice for engineering applications. In this study, Aluminium AA2024 alloys are prepared with different weight contents of ceramic material, titanium oxide (TiO_2) nanoparticles (0%, 2.5%, 5%, and 7.5% wt.) of a particle size of 30 nm using the metal stir casting method. The hardness property and wear resistance with the effect of heat treatment are investigated using a pin-on-disc wear device for both the base alloy and the reinforced alloys. The result shows the prosperity of 5wt.% of TiO_2 to attain the optimum hardness and wear resistance. Using the optimum content of TiO_2 and heat treatment, the hardness and wear resistance of 5wt.% TiO_2-AA2024 nanocomposite has been significantly improved after heat treatment over the unreinforced Aluminium matrix. Statistically, the hardness and wear resistance are improved by 68% and 22%, respectively. This is due to an increased number of fine precipitates besides their uniformly distributed after heat treatment. Furthermore, casting AA2024 Aluminium alloy material mainly has S (Al_2CuMg) and Al_3TiCu phases. The appearance of a large number of S phases causes a significant improvement in the properties of the alloy.

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Introduction

Technologically advanced industries such as aerospace, automobiles, power plants, etc. have been demanding materials of high-strength, temperature-resistant with a high "strength to weight" ratio. Thus, many scholars in the area of materials science have developed materials with highly prosperous properties of strength, hardness, and toughness for a wide set of industries. This also necessitates the invention of superior cutting tool materials in order to maintain productivity. Composite materials are among the oldest and newest structural materials. The long history of composites is fascinating because it allows engineers to create completely new materials with precise combinations of properties required for specific tasks [1].

One of the most difficult aspects of producing strong, light, and low-cost engineering materials is getting a high strength-to-weight ratio suited for vehicles [2]. The global need for such products for the automobile and aerospace industries has attracted the attention of researchers in the field of composite materials [3]-[4]. Due to their excellent mechanical properties, Aluminium Matrix Composites (AMCs) are advanced materials that combine the characteristics of light and tough matrix material with hard ceramic reinforcement [5]. AMCs are able to satisfy the market need for lightweight, durable, and high-performance components. The high corrosion resistance of Aluminium and its alloys is due to the formation of an oxide layer on their surface which resists corrosion in many environments [6]-[7]. Ships, transportation, and pipes of oil, gas, or water all this structure will suffer from corrosion. Corrosion can result in structure failure and sometimes this failure is tragic. Nowadays, the prevention of corrosion becomes more important [8]. AMCs strengthened using ceramic particles have become popular for various automotive and aerospace applications because of their mechanical characteristics. The wear rate of AMCs can be improved by adding hard ceramic reinforcement. Aluminium alloy AA2024 contains Cu, Mg, Mn, and some other minor alloying elements and has good a mechanical properties ratio at elevated temperatures, high ductility, fatigue, and fracture resistance [9].

To assess Al-Si alloys, Rajaram et al. [10] examined wear related to the Al-Si alloys at different temperatures, from ambient to a temperature of 350 °C. The stir casting technique was applied to fabricate Al-Si alloys. A practically uniform distribution that is related to the silicon particles has been indicated via microstructural research. The fractography specified that the fracture behaviour regarding the Al-Si alloys has been changing from brittle to ductile modes with increasing temperature. The wear tests indicated that wear resistance regarding the Al-Si alloys has been increased with an increase in temperature. Throughout the sliding process, oxidational wear has been predominant with developed composite materials by reinforcing Aluminium metal with added silicon carbide in different weight percent ratios, followed by stir casting fabrication [11]. The distribution of SiC was observed to be intra-granular. The results showed that the SiC particles were refined to the grain size of the alloy matrix which improved the bonding in the matrix with an increase in their microhardness. An increase in SiC content shifted the fracture mode from ductile to brittle [12]-[13].

Sevik and Kurnaz [14] utilised the pressure die-casting technique to produce metal-matrix composites related to Al-Si-based alloys, as well as Al_2O_3 particles with volume fractions of 0.05, 0.10, and 0.15, and sizes 44, 85, and 125 μm. Wear, hardness, density, and tensile strength have been studied. The addition of Al_2O_3 particles has increased the density of the composite. Additionally, the composite's hardness has also increased due to an increase in particle volume fraction and a decrease in particle size. The particle volume fractions, and the size are increased by decreasing the composite’s tensile strength. There is a decrease in the composite’s wear rate with an increase in particle volume fraction, also with a decrease in particle size, yet it has been proportionally increasing with applied load. The wear mechanism with regard to the unreinforced alloy’s surface has been plastic deformation, while for composites, there has been a deformation of the layer on the composite’s surface [15]-[16].

Moy et al. [17] used solution heat treatment to prohibit corrosion. The ideal heat treatment process involved heating samples at 400 °C for 90 min, followed by cooling the samples in water. Additionally, for 120 minutes at a temperature of 200 °C, the ideal aging condition occurs in samples. The weight loss method was used to calculate the rate of corrosion of the heat-treated samples. An electron microscope has also been used to observe the microstructures of heat-treated samples. The hardness of the samples has increased with increasing the corrosion resistance of the heat-treated samples [18].

El-Mahallawi et al. [19] evaluated the effects of adding titanium dioxide (TiO_2), zirconia (ZrO_2), alumina (Al_2O_3) nanoparticles (40 nm), 0–5wt.%, at varying stirring speeds (270, 800, 1500, and 21500 rpm) to the Aluminium cast alloy A356 as a base metal matrix. According to the findings, the castings formed in the semi-solid state (600 °C) with 2 weight percent Al_2O_3 and 3 weight percent TiO_2 or ZrO_2 at 1500 rpm stirring speed has caused an increase in the mechanical properties and hardness of nano-reinforced castings manufactured with TiO_2, Al_2O_3, and ZrO_2. Several studies to improve the wear resistance of nanocomposite materials have been conducted, which include the incorporation of intragranular nanoparticles via precipitation and stir casting, as well as the development of a microstructure. Mostly, materials scientists have recently focused their attention on the utilisation of metallic materials such as nanocomposite [20]-[21].

Rao et al. [22], used the aluminium alloy 7009 and reinforced it by silica carbide (micro-particles 20-40 mm). This alloy is primarily composed of aluminium, with zinc as the main alloying element, along with smaller amounts of other elements such as copper, magnesium, and chromium. The alloy has the chemical composition of Fe-0.29%, Cu-0.01%, Mg-1.63%, Zn-5.85%, Al-rest. The study investigated the impact of varying the applied load and sliding speed on parameters such as wear rate, temperature rise, coefficient of friction, and seizure pressure. Additionally, the aging time varied between 4 to 10 hours in 2-hour increments, and the nature of the worn surface produced after wear. The results show that the coefficient of friction rises as one increase silica carbide content but falls with increasing age treatment. Heat treatment increases hardness, and particle addition in the alloy reduces wear rate and frictional heating while raising seizure pressure and temperature. The microstructure of the alloy showed primary Al dendrites and secondary intermetallic phases around the dendrites, which become more uniform with the equiaxed grain structure after heat treatment, while intermetallic precipitates are distributed both in the grain boundary and within the grains.

After reviewing the available literature, it has been found that the impact of adding titanium to Al-Cu-Mg alloys through stir casting has not been thoroughly investigated. The AA2024 aluminium alloy belongs to the Al-Cu-Mg alloy series that relies on S (Al_2CuMg) and θ (Al_2Cu) precipitates as the primary strengthening factors. Introducing titanium to this alloy group can facilitate the formation of high-strength titanium aluminides. One issue with Al-Cu-Mg alloys is their susceptibility to thermal instability at elevated temperatures. However, creating titanium aluminides, which have high thermal stability, and their even distribution throughout the aluminium matrix can enhance the thermal stability of these alloys. This study aims to fill the gap by introducing TiO_2 nanoparticles as reinforcement for aluminium AA2024 alloys.

The goal is to concurrently improve the hardness and wear resistance properties of the synthesised TiO_2-AA2024 nanocomposites. To systematically achieve this aim, a wide range of weight contents of TiO_2 are evaluated for their effects on wear resistance and hardness in the presence of heat treatment. In other words, the purpose of this research is to gain a deeper knowledge of the effects of TiO2 nanoparticles and heat treatment on the hardness, wear resistance, and microstructure features of TiO_2-AA2024 nanocomposites.

Material and Methods

The chemical composition of the AA2024 matrix is shown in Table 1. TiO_2 (Titanium oxide) particulates of particle size of 30 nm are utilised as reinforcement in the present investigation. Table 2 presents the properties of

AA2024 matrix material and reinforcing material nanoparticles (TiO_2), respectively.

Table 1: Chemical composition of AA2024 -T_3 alloy [23]

Element	Mg	Si	Cu	Mn	Ti	Cr	Zn	Fe	Al
Standard	1.2-1.8	Max 0.5	3.8-4.9	0.3-0.9	Max 0.15	Max 0.1	Max 0.25	Max 0.5	90.7-94.7
Measured	1.04	0.098	5. 5	0.62	0.03	0.008	0.11	0.25	Balance

Table 2: Physical-chemical properties of nanoparticles (TiO_2) [24]

Properties	TiO_2
Density (g/cc)	4.23
chemical composition	Titanium 59.93 and oxygen 40.07
Crystal's structure	Tetragonal
Melting temperature (°C)	1843
Size range (nm)	30-50
Boiling point (°C)	2,972

The reinforcement material nanoparticles of TiO_2 were used in this study with a purity of 99.8% and a size of 30±5 nm (spherical-shaped nanoparticles) made in China (Changsha Santech Co.). Before adding TiO_2 nanopowder with the different weight percent of 2.5 wt.%, 5 wt.%, and 7.5 wt.%, AA2024 Aluminium alloy was preheated to 750 °C in a graphite crucible using an electric furnace (Nabertherm NAB-8101) to ensure the complete melting of all its components. The stir casting technique was utilized for 4 minutes at 200 rpm. The SEM picture of the TiO_2 nanopowder is shown in Figure 1. Figure 2 depicts the pouring of the melt into a steel mould. Figure 3 depicts the heat treatment techniques used, including quenching and aging. First, the AA2024 Aluminium alloy solution was heated in an electric furnace for 3 hours to a temperature of 500 °C to 510 °C. The sample was then quenched in water to bring it down to room temperature. Second, the sample was placed in an electric furnace (Gallen Hamp hot stop BR-17M / XD-17M) for 3 hours to achieve the aging (precipitation heat treatment) stage between 180 °C to 190 °C, followed by cooling in air. Figure 3 demonstrates a schematic diagram of the sequenced heat treatment processes [25].

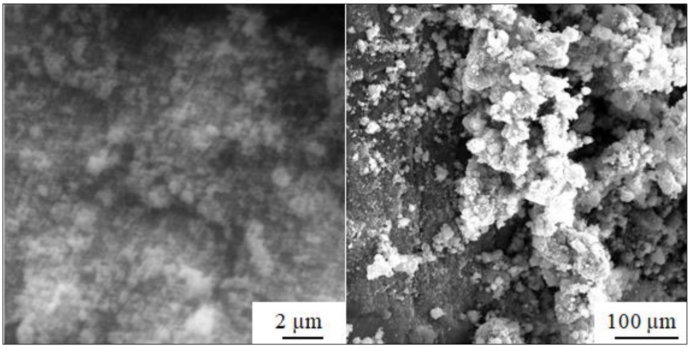
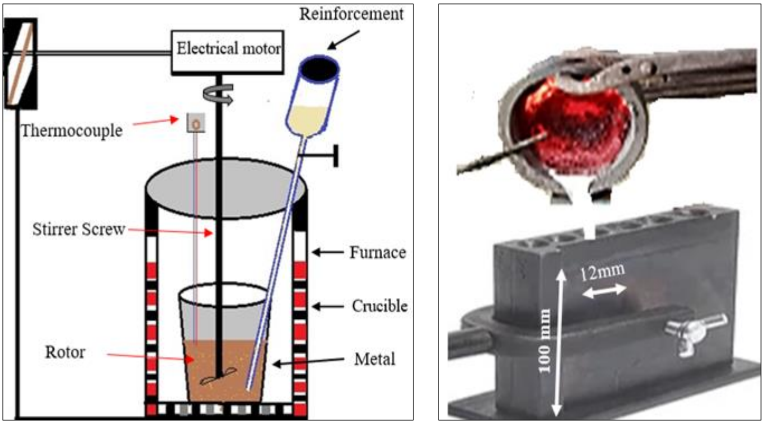


Figure 1: SEM images of spherical-shaped nanoparticles



(a) (b)

Figure 2: (a) The stir casting furnace for melting, and (b) the casting mould

The microstructural characterization of the samples was conducted by the standard metallographic procedure and etched for 15 seconds using Kroll's reagent (H_2O: HNO_3: HF=92:6:2). Scanning electron microscopy (SEM) (by TESCAN VEGA) and energy disperse spectroscopy (EDS) (by INCA Energy) analyses were carried out to investigate the microstructure and elemental composition distribution of materials.

The digital Vickers hardness analyser category Laryea (HBRVS-18705) was also used to determine the sample's hardness. Three samples were tested for hardness, with average readings taken for each sample. The flow chart of the experimental method and a simplified representation of the process are depicted in Figure 4.

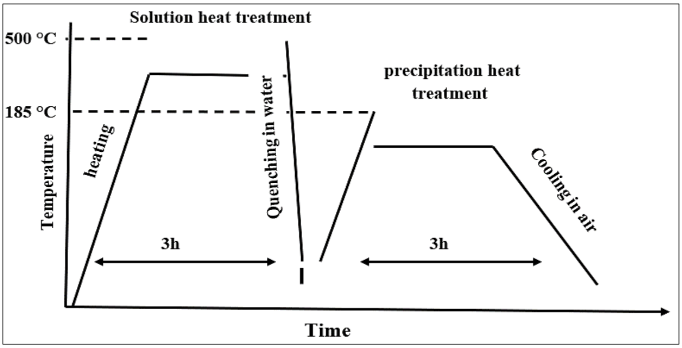


Figure 3: Heat treatment processes

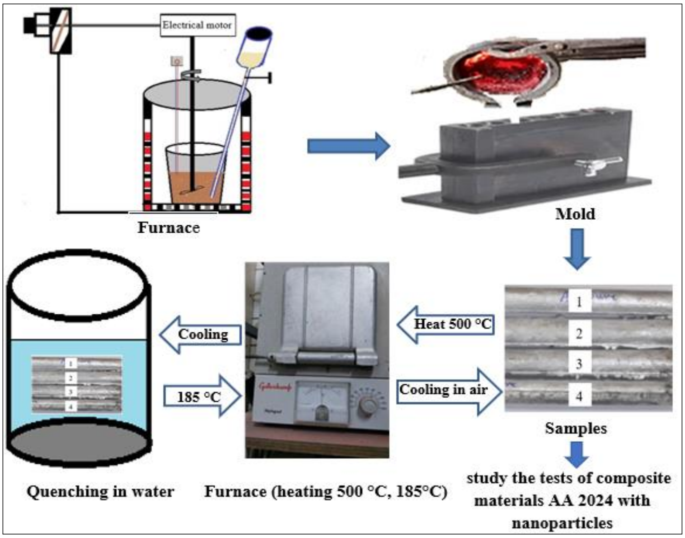


Figure 4: Diagram of the experimental method and the stir casting

A wear test was performed on the Aluminium alloy AA2024 before and after adding TiO_2 nanoparticles, per ASTM G99-95 guidelines [26]. The wear rate of the cast AA2024 alloy reinforced with nanoparticles was examined using a pin on a disc-type wear tester. The cylinder shape sample was 30 mm in length and 10 mm in diameter (note: wear specimen dimensions, according to ASTM G99-95). The disc potential speed was 277.4 rpm, while the sliding velocity was 6 cm/s and imposed loads of 5, 10, 15, and 20 N were applied for 10 minutes. The pin was made by SKD 61 (Vickers hardness=560 HV) [24] as shown in Figure 5.

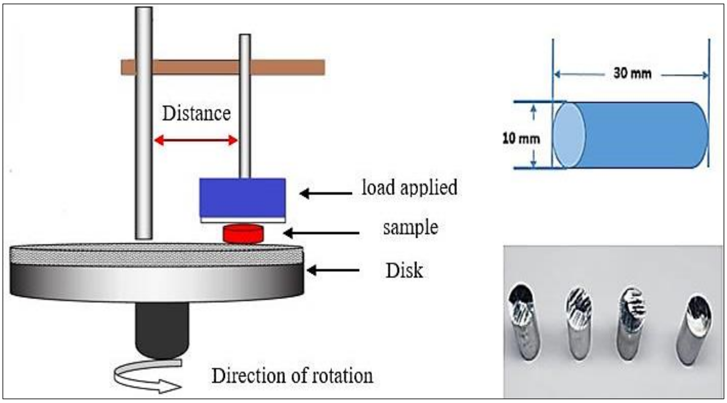


Figure 5: Diagram of pin-on-disk test (ASTM G-99)

The wear rate was determined using the weighing method by calculating the lost weight of the samples, weighing the sample before and after each test, using a sensitive digital sensor scale of 0.0001 g. Specifically, the effect of different applied loads of 5, 10, 15, and 20 N is evaluated on the wear rate while considering a fixed sliding time of 10 minutes and sliding speed of 6 m/s throughout the experiments.

The experimental procedure of determining the wear rate includes a number of steps; i) setting up the wear testing apparatus, ii) positioning the sample to be tested perpendicular to the sliding disc, iii) the cylindrical sample carrier installed by a rectangular section arm, where the radius from the centre of the sample to the centre of the disc is 5 cm, and iv) running the apparatus for a predetermined period. Equation (1) is used to calculate the wear rate.

$$\Delta W = W1 - W2 \tag{1}$$

ΔW: variation in mass losses (gm), W_1: weight of the specimen before the test (gm), and W_2: weight of specimen 2 after the test (gm).

$$W.R = \Delta w/\pi\ D\ N\ t \tag{2}$$

W.R: wear rate (gm/cm s)
$\Delta\ w$: $W_0 - W_1$
W_0: sample weight before the test (gm)
W_1: sample weight after the test (gm)
D: sliding distance (14 cm)
t: time (s)
N: velocity (rpm)

Results and Discussion

The mechanical properties of composite materials are directly related to the properties of the reinforcement, as well as its concentration and geometry. To a certain extent, however, both the composite's strength and its stiffness might be enhanced by increasing the volume fraction of the reinforcing material. When there is a further rise in the volume percent of the material that is being reinforced, there will not be enough matrix to contain the material that is being reinforced. Additionally, the geometry of each reinforcement and the arrangement of those reinforcements can affect the performance of the composite.

Hardness

Figure 6 shows the effects of adding TiO_2 nanoparticles at different weight percentages to Aluminium alloy on the hardness property. When compared to an initial Aluminium alloy of AA2024, the inclusions of 5 wt.% of TiO_2 without heat treatment has resulted in the maximum improvement of hardness property by 26%. Statistically, this improvement has entailed having 38 HRB compared to 30 HRB for an Aluminium alloy of AA2024.

Referring to Shahi et al. [27] and based on Hall–Petch rule, the finer intermetallic compounds can have a more effective role in the pinning of grain boundaries and enhance the hardness. However, increasing the weight percentage of TiO_2 to 7.5 wt.% causes a considerable reduction in hardness. This can be attributed to an increase in the number of fine precipitates in the sample of 7.5 wt.% of TiO_2 that might distort the microstructure of Aluminium composite. The recent results are consistent with those from a previous study by Al-Alkawi et al. [28].

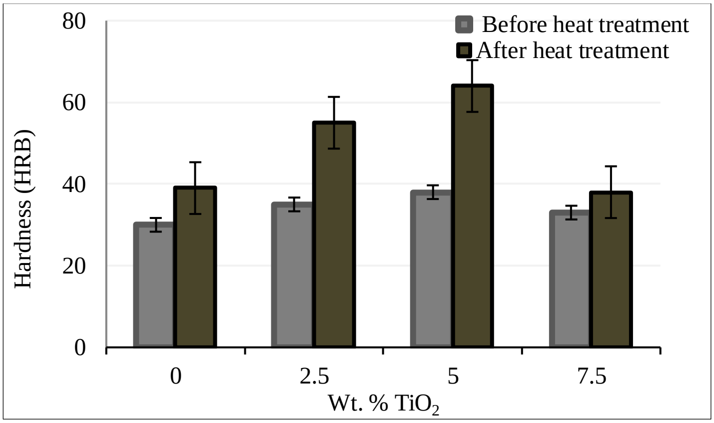


Figure 6: Effects of nanoparticles on the hardness of AA2024 composite

More importantly, the hardness values of TiO_2-AA2024 nanocomposites have significantly increased after the heat treatment as depicted in Figure 6. Statistically, the hardness property increases by 68% after the heat treatment of 5 wt.% TiO_2-AA2024 nanocomposite. Furthermore, this is an improvement of the hardness of 113% if the obtained result is compared against the hardness of AA2024 before heat treatment. This is specifically attained as a result of a uniform distribution of precipitates and particles in the microstructure, as tiny precipitates occur after heat treatment. Figure 7 introduces the optical microscopy images of different weight percentages of TiO_2.

More strain fields are created by the development of uniform and fine precipitates and IMCs, which interact with dislocations to reduce dislocation motion ability and, therefore, the hardness of samples has increased. The hardness of Al-Ti-based IMCs also grows as the weight percent of titanium oxide increases. Because of their high hardness, it is anticipated that the manufacturing of these IMCs will be the primary consideration in enhancing the hardness of alloys by adding titanium oxide. Additionally, the addition of nanoparticles up to 5 wt.% resulted in a rise of fine needle-shaped precipitates in the interdendritic regions. However, the addition of further titanium lowered their amount in this zone. As seen in Figure 7, the proportion of these intermetallic compounds rose with titanium concentration [29].

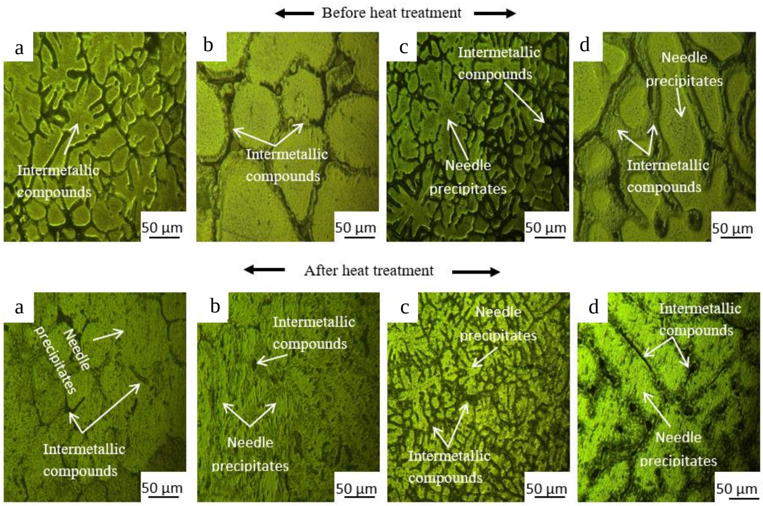


Figure 7: Optical microscopy images of; (a) sample 0 wt.% TiO_2, (b) sample 2.5 wt.% TiO_2, (c) sample 5 wt.% TiO_2, and (d) sample 7.5 wt.% TiO_2

The addition of nanoparticles resulted in the formation of a more homogeneous microstructure, leading to improved mechanical properties of the alloy. The SEM images showed that the nanoparticles were distributed uniformly throughout the matrix and played a crucial role in refining the grain size of the alloy. These findings indicate that the addition of nanoparticles is a promising approach for enhancing the properties of Aluminium alloys. To assess the microstructure and intermetallic compounds accurately, SEM images of different sample structures are presented in Figure 8. As shown in Figure 8(a), the microstructure of the titanium-free sample contained precipitates and intermetallic compounds of Al_2CuMg, Al_7Cu_2Fe, and Al (Cu, Mn, Fe, Si). Upon adding titanium and conducting heat treatment, Al_3TiCu intermetallic compound was observed to form in the microstructure, as shown in Figure 8(b). This compound can act as nucleation sites for the formation of small and uniform precipitates in the Aluminium matrix. The addition of nanoparticles can facilitate the formation of fine precipitates. Due to the high dissolving temperature of these intermetallic compounds, the inter-dendritic zone was also surrounded by Al_7Cu_2Fe and Al (Cu, Mn). By adding titanium to the sample, Al_3TiCu and Al_9TiFe intermetallic compounds were formed in the microstructure. Previous studies [25], [27] have also investigated the formation of these intermetallic compounds, copper becomes part of the titanium aluminide structure's crystal structure when present.

The content samples of 5 wt.% TiO_2 showed a more uniform distribution of the reinforcing particles within the Aluminium matrix, promoting better bonding between the matrix and reinforcement. This can be attributed to the fact that the increased concentration of TiO_2 particles promotes nucleation, leading to the formation of finer grains in the Aluminium matrix. Moreover, the high surface energy of the TiO_2 particles allows them to act as heterogeneous nucleation sites for the Aluminium during solidification, further contributing to grain refinement. Notably, increasing titanium from 2.5 to 5 wt.% of TiO_2 reduced the size of Al_2CuMg precipitates and increased the composite Al_3TiCu, as depicted in Figure 8(c). In this context, Wang et al. [30] found that when Al-Mg-Cu alloys are coupled with titanium at a weight percentage of 5 wt.%, the solubility of copper drops, and metallic compounds such as Al_3TiCu and Al_7TiCu_4 are generated following titanium addition. Figure 8 introduces the SEM images and illustrates this phenomenon. The SEM images showed that the addition of TiO_2 nanoparticles to the Aluminium alloy resulted in a refined microstructure characterised by a decrease in grain size and an increase in the density of grain boundaries. The refined microstructure led to an increase in the mechanical properties of the Aluminium alloy.

When adding 7.5 wt.% nanoparticles, the nanoparticles can agglomerate, which reduces their effectiveness as a strengthening agent. However, agglomeration and unwanted reactions between the nanoparticles and the Aluminium matrix can further reduce the effectiveness of the nanoparticles, ultimately leading to a reduction in the mechanical properties of the material. The addition of nanoparticles changes the size and distribution of the grains in the alloy, which in turn affects its mechanical properties. The presence of nanoparticles reduces the grain size, improving the hardness and wear resistance of the alloy. Moreover, the addition of nanoparticles can also increase the thermal stability of the alloy. The nanoparticles act as barriers to the movement of dislocations in the alloy, preventing them from reaching the underlying metal. This effect helps to prevent deformation at high temperatures, leading to a reduction in the corrosion rate and an increase in the lifespan of the alloy. Specifically, the use of TiO_2 nanoparticles as a strengthening agent has been shown to upgrade the wear properties of Aluminium Matrix Composites (AMCs) [18]. However, it should be noted that the optimal weight content of TiO_2 is 5 wt.%, as it has been found to provide the best balance between hardness, wear resistance, and weight loss. The improved wear resistance is due to the formation of new phases such as $AlTi_3$, which act as hard particles that prevent wear. Additionally, the nanoparticles form a barrier layer on the surface of the Aluminium matrix, preventing the penetration of corrosive agents and reducing the rate of wear.

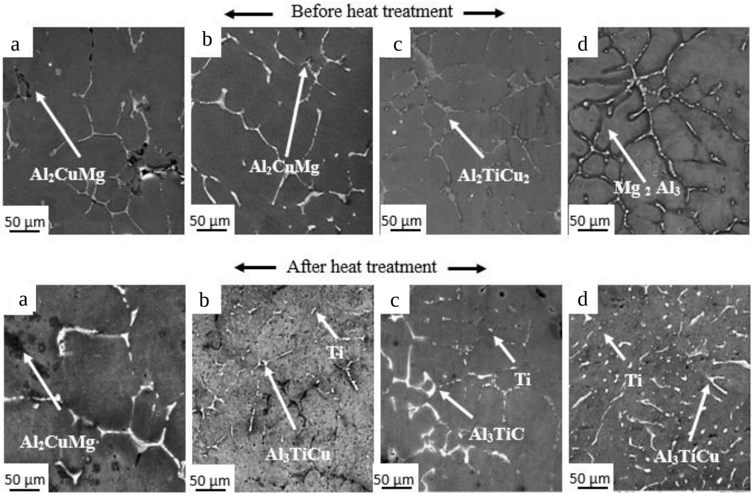


Figure 8: SEM image of AA-2024 alloy; (a) AA 2024-2.5 wt.% TiO_2, (b) AA 2024 5 wt.% TiO_2 (c) 5 wt.% TiO_2 sample, and (d) 7.5 wt.% TiO_2

Wear resistance

Figure 9 presents the relationships between the wear resistance and applied load for a set of different nanocomposites of different weight content of TiO_2 combined with AA2024. Figure 9 depicts that utilising the optimum 5 wt.% of TiO_2 nanoparticles with Aluminium alloys would lower the wear resistance for the whole applied loads. This is in a comparison against the other weight contents of TiO_2 and the base case of Aluminium alloy of 0 wt.% of TiO_2. Statistically, the wear resistance of AA2024 alloy has been improved by 220% after the inclusion of 5 wt.% of TiO_2. The highest increase of the hardness property for 5 wt.% TiO_2-AA2024 (Figure 6) can attribute the reason behind this. In this situation, adding 5 wt.% of TiO_2 nanoparticles allows the formation of a protective oxide layer that expands the contact area and increases the friction and wear resistance (Figures 7 and 10). It is important to mention that enhancing wear resistance is advantageous for developing a stable trilateral composite. However, the wear resistance of the reformed composite components slightly decreased when the volume fraction of TiO_2 nanoparticles was improved to 7.5% compared to those with 5% TiO_2 nanoparticles. This is due to the greater agglomeration of TiO_2 nanoparticles, making it difficult to uniformly disperse them, resulting in a decrease in their effective dispersion within the 2024 matrix. This ultimately reduces the wear resistance, as presented in Figures 9 and 10. Therefore, the deformation rate of Aluminium alloys increases as the amount of TiO_2 increases [31].

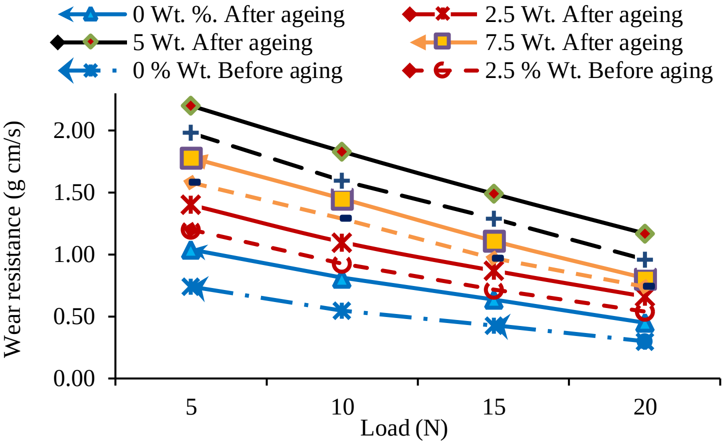


Figure 9: Wear resistance of AA2024 alloy against supplied loads before and after heat treatment

The wear resistance of the nanocomposites increased after the heat treatment for the whole applied loads (Figure 9). Statistically, the wear resistance of 5 wt.%TiO_2-AA2024 has been improved by around 22% after the heat treatment. Indeed, the utilisation of heat treatment has improved the wear resistance due to having a uniform distribution of precipitates and particles in the microstructure, as tiny precipitates occur after heat treatment. Furthermore, the reinforcing distribution has a significant impact on the composite's ductility and fracture toughness. As a consequence, for reinforcement load-carrying capability, homogeneous reinforcement distribution is crucial [32].

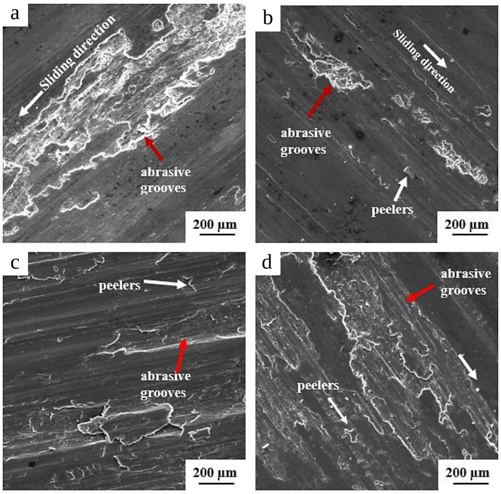


Figure 10: SEM micrographs of circular wear marks on AA2024/ TiO_2 sample after the friction test (severe deformation and plastic flow). Arrows indicate the sliding direction

Weight loss (wear rate)

Figure 11 shows that the average weight loss has significantly increased with the applied load besides considering a sliding time of 10 minutes and sliding speed of 6 m/s. Figure 11 ascertains that the load has a significant effect on weight loss, which is an indication of wear rate. At the lowest load of 5 N, the weight loss will be formed as fine particles, and it will form a protective oxide layer that would decrease the contact area between the samples and disc, one of the reasons for enhancement wear resistance of studied alloys is their ability to form protective oxide layer during wear. Therefore, the wear rate will be at its lowest value, Figure 12. At the highest applied loads, the area of the surface that makes contact between the sample and disk would be larger, increasing the friction between the two sliding surfaces and thus increasing the wear rate [30], [33].

Thus, the wear rate will have the highest value at the highest applied load. Undoubtedly, the load has a direct relationship with plastic deformation that occurs near the surface. Thus, there will be more movement of the dislocations as the load goes up and this leads to more plastic deformation.

Figure 11 also shows that the inclusion of TiO_2 into the AA2024 alloy would decrease the weight loss where the maximum reduction occurs using the 5 wt.% of TiO_2. This is specifically denoted by the maximum improvement of hardness and wear resistance as illustrated in Figure 10. Seemingly, the oxide layer formed with 5 wt.% TiO_2-AA2024 has a harder surface than the disc substrate. Therefore, it would act as a protective third body, reducing the effect of sliding wear on the surface below. However, it should be noted that utilising TiO_2 with more than 5 wt.% would elevate the weight loss. The results are in good agreement with the findings of [30], [33].

Comparing the results of Figure 11 would introduce the advantage of heat treatment in reducing the weight loss for the whole nanocomposites compared to the ones before the heat treatment. This indicates that the sample after heat treatment was more resistant to wear than the sample before heat treatment. The wear resistance of the samples has therefore increased after annealing [18], [30] as represented in Figures 6 and 9.

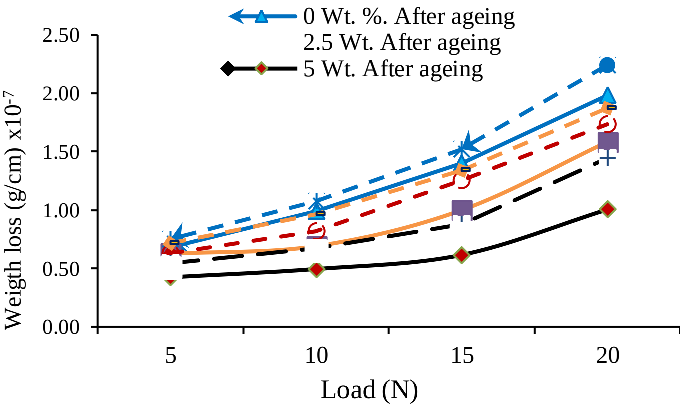


Figure 11: Variation of mass loss of specimens as a function of applied load before and after heat treatment

Optical micrograph of the contact surface

The wear surface for each sample is demonstrated in Figure 13. The wear surface had highly dimpled structures and ductile failure properties for the samples without nanoparticles. Regarding the wear of very strong Aluminium alloys, the development of microvoids surrounding coarsened precipitates causes intergranular damage. The surface displayed clear grooves that ran lengthwise, caused by the ploughing effect of harder steel particles. When more TiO_2 nanoparticles were added to the composite, the depth of these scratches reduced, indicating an improvement in wear resistance. This was because the hardness of the composite increased with an increase in the volume of TiO_2 nanoparticles. Improving the hardness of the material helped enhance its wear resistance. Furthermore, SEM images indicated irregular characteristics among wear surfaces, revealing that the wear rate was derived from various failure mechanisms. Large, clear grooves were diminished to fine scratches along the sliding direction (Figure 13(c)) that were observed on the surface (Figure 13(a)), and abrasive wear became adhesive wear. Due to a larger number of TiO_2 nanoparticles in the matrix base, its plastic deformation was countered by a mechanically mixed layer that became a barrier to the moment of dislocation and increased wear resistance [34]-[35].

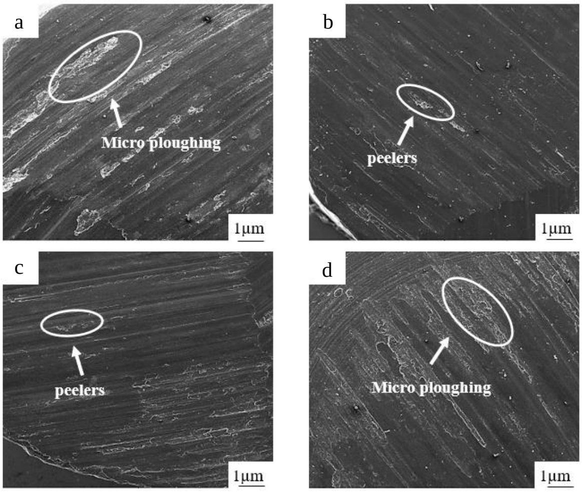


Figure 12: Worn surface morphology of AA2024 under the load 5 N; (a) AA2024 matrix material (b) AA2024-2.5 wt.% TiO_2, (c) AA2024- 5 wt.% TiO_2, and (d) AA2024-7.5 wt.% TiO_2

The weight loss and wear tracks of the AA2024 matrix material following heat treatment are depicted in Figure 14. It demonstrates low delamination and fracture of the transfer layer as a result of the abrasive effect of the hardened transfer particles, which results in cutting with subsequent delamination and fracture of the compacted layer [30]. Figures 14(b) and 14(c) illustrate different grooves and ridges that run parallel to one another in the sliding direction, as indicated by the red mark. Because the surface of the fixed specimens in the current experiment is in constant contact, one reason for the examined alloys' greater wear resistance is their capacity to produce a protective oxide layer during wear. Due to their high reactivity, Ti-based alloys exposed to an oxidative environment rapidly generate an oxide layer on the surface. Therefore, the investigated alloys have an improved wear resistance due to their ability to create a protective oxide layer while in constant contact rapidly.

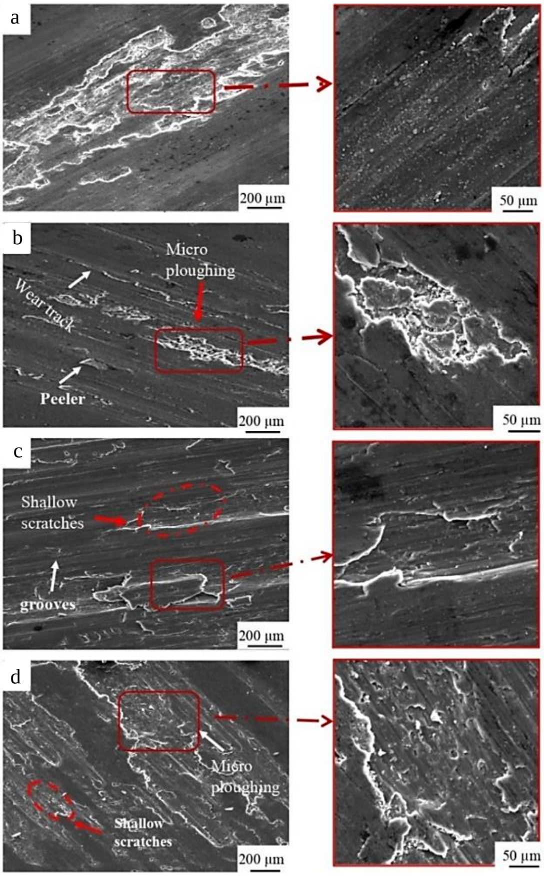


Figure 13: Morphologies of the worn surface at a load of 20 N; (a) AA2024 matrix material, (b) AA2024-2.5 wt. % TiO_2, (c)AA2024-5 wt.% TiO_2, and (d) AA2024-7.5 wt. % TiO_2 composite before heat treatment

The process of abrasion is linked with the creation and expansion of cracks. Any element that restricts the growth of these cracks can minimize the amount of wear. When there is a strong bond between the reinforcement and the substrate, the reinforcement particles can act as a factor to prevent the growth of cracks. Furthermore, it should be noted that when the composite surface is harder, it generates more heat during the wear process, forming oxide layers that require even higher temperatures. This ultimately enhances the wear resistance. Additionally, Figure 7 shows that the grooves are lower and wider in the matrix as compared to the composites tested under similar conditions. Figure 14(d) demonstrates the ploughing on the worn-out surface of the 7.5

wt.% of TiO_2 composite, which may be due to the sliding of oxide particles in the composite [34].

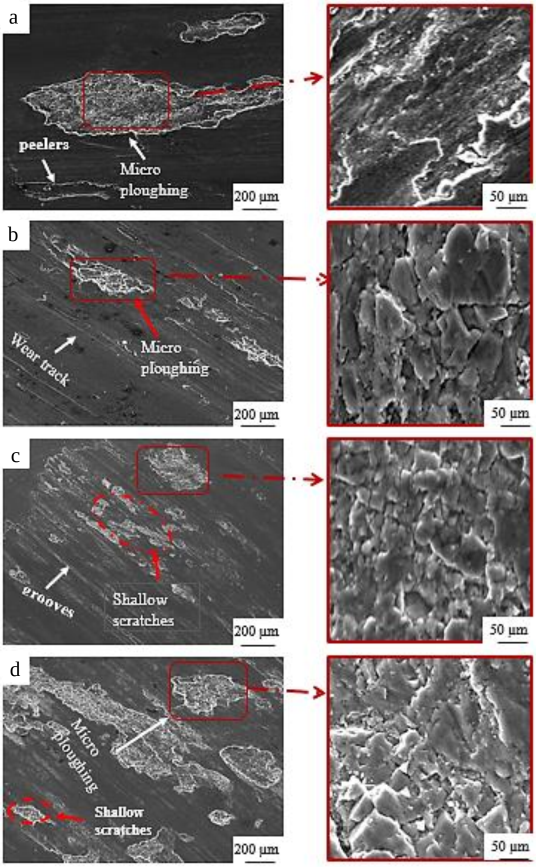


Figure 14: Morphologies of the worn surface at a load of 20 N; (a) AA2024 matrix material, (b) AA2024-2.5 wt. % TiO_2, (c) AA2024-5 wt. % TiO_2, and (d) AA2024-7.5 wt. % TiO_2 composite after heat treatment

The wear rate of the rheoformed composite components reduced insignificantly when the volume fraction of TiO_2 nanoparticles reached 7.5% compared to those with 5% TiO_2 nanoparticles. However, the increased agglomeration of TiO_2 nanoparticles made it challenging to disperse them evenly, resulting in a reduction of their effective dispersion within the 2024 matrix and ultimately decreasing the wear resistance. Both SEM tests show indications of nano-sized particle integration and entrapment inside the interdimeric interface that forms during the solidification of the dispersed alloys. Furthermore, it is hypothesized that the homogeneous dispersion of nanoparticles provides locations for heterogeneous nucleation throughout the solidification process, leading to a more refined microstructure. The nanoparticle reinforcement in composites can be explained by the fact that particles cannot move around in the melt as it solidifies since the melt and matrix become more viscous [30].

Conclusions

TiO_2/AA2024 nanocomposites of 2.5 wt.%, 5 wt.% and 7.5 wt.% TiO_2 nanoparticles were prepared with the stir casting method, followed by heat treatment. Precipitation wear rate and hardness properties were investigated. The following conclusions can be made:

i. Mechanical tests showed that the hardness and wear resistance have increased as the percentage of nanoparticles increases, while the wear rate has decreased as the percentage of reinforcing materials increases.
ii. Aluminium alloy containing 5 wt.% TiO_2 nanocomposites have got the highest wear resistance and the hardest surface than the other tested nanocomposites. Thus, it can be stated that the 5 wt.% is the optimum weight content of TiO_2.
iii. Nanoparticles have specifically enhanced the wear characteristics of the composites contributing to the development of a stable trilateral with self-lubricating features.
iv. A bimodal microstructure has been formed in the samples as they were extruded, and it was still there after heat treatment. This is likely because the dispersed TiO_2 nanoparticles pinned the grain boundaries together.

Thus, the combination of 5 wt.% TiO_2 nanoparticles with AA2024 alloys have greatly enhanced the physical properties. In turn, this would enhance the potential of Aluminium alloys for various industrial applications.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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References

[1] S. K. Moheimani, A. Keshtgar, S. Khademzadeh, M. Tayebi, A. Rajaee, and A. Saboori “Tribological behaviour of AZ31 magnesium alloy reinforced by bimodal size B4C after precipitation hardening”, *Journal of Magnesium and Alloys*, vol. 10, pp. 3267-3280, 2021. https://doi.org/ 10.1016 /j.jma.2021.05.016

[2] D. Brough, H. Jouhara, “The aluminum industry: a review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery”, *International Journal of Thermofluids,* vol.1–2, no. 100007, pp. 1-39, 2020. https://doi.org/10.1016/j.ijft.2019.100007.

[3] P. Garg, A. Jamwal, D. Kumar, K.K. Sadasivuni, C.M. Hussain, P. Gupta, “Advance research progresses in aluminum matrix composites: manufacturing & applications”, *Journal of Materials Research and Technology*, vol. 8, no. 5, pp. 4924-4939, 2019. doi.org/10.1016/j.jmrt.2019.06.028.

[4] R. David, V. Shrivastava, R. Dasgupta, B.K. Prasad, and I.B. Singh, “Corrosion investigation of zinc–aluminum alloy (ZA-27) matrix reinforced with in situ synthesized titanium carbide particle composite”, *Journal of Materials Engineering and Performance*, vol. 28, no. 4, pp. 2356-2364, 2019. https://doi.org/10.1007/s11665-019-03992-6.

[5] H. Mahan, D. Mahjoob, K. Mahmood, "Mechanical properties of alumina nano-particles and glass fiber, kevlar fiber reinforced composites”, *Journal of Engineering and Applied Sciences*, vol. 13, no. 21, pp. 9096-9100, 2018. https://doi.org/10.3923/jeasci.2018.9096.9100.

[6] A. Karakaş, T.O. Fenercioğlu, T. Yalçinkaya, “The influence of flow forming on the precipitation characteristics of Al2024 alloys”, *Materials Letters,* vol. 299, pp. 218-227, 2021. doi.org/10.1016/j.matlet.2021.130066.

[7] F. Kiarasi, M. Babaei, M. Omidi Bidgoli, K. Reza Kashyzadeh, K. Asemi, K., “Mechanical characterization and creep strengthening of AZ91 magnesium alloy by addition of yttrium oxide

nanoparticles. Proceedings of the Institution of Mechanical Engineers", *Journal of Materials: Design and Applications*, vol. 236, no. 8, pp. 1489-1500, 2022. https://doi.org/10.1177/14644207211073.

[8] X. Yu, H. Bakhtiari, J. Zhou, M.O. BidgoliK. Asemi, "Investigating the effect of reinforcing particles size and content on tensile and fatigue properties of heat-treated al7075-sic composites fabricated by the stir casting method", *The Journal of The Minerals, Metals & Materials Society*, vol. 74, no. 5, pp. 1859-1869, 2022. https://doi.org/10. 1007/ s11837-022-05248-6.

[9] D. Rahmatabadi, R. Hashemi, B. Mohammadi, T. Shojaee, "Experimental evaluation of the plane stress fracture toughness for ultrafine grained aluminum specimens prepared by accumulative roll bonding process", *Materials Science and Engineering*, vol. 708, pp. 301-310, 2017. https:// doi.org/10. 1016/j. msea.2017.09.085.

[10] S. Borji, M.K. Zanganeh, M. Ahangarkani, Z. Valefi, '"The feasibility of W-Cu composite production by submicron particles addition and infiltration", *Iranian Journal of Materials Science and Engineering*, vol. 14, no. 1, pp. 1-11, 2017. https://doi.org/10.22068/ijmse.14.1.6.

[11] S. S. Ahn, S. Pathan, J. M. Koo, C. H. Baeg, C. U. Jeong, H. T. Son, S. J. Hong, "Enhancement of the mechanical properties in Al–Si–Cu–Fe–Mg alloys with various processing parameters", *Materials*, vol. 11, no. 11, pp. 1-12, 2018. https://doi.org/10.3390/ma11112150.

[12] M. Araghchi, H. Mansouri, R. Vafaei, and Y. Guo, "Novel cryogenic treatment for reduction of residual stressesin 6061 aluminum alloy", *Materials Science and Engineering,* vol. 689, pp. 48-52, 2017. https://doi.org/10.1016/j.msea.2017.01.095

[13] J. Xia, J. J. Lewandowski, M. A. Willard, "Tension and fatigue behavior of Al-2124A/SiC-particulate metal matrix composites", *Materials Science and Engineering*: A, vol. 770, p. 138518, 2020. https://doi.org/10.1016 /j.msea.2019.138518.

[14] M. S Patel, and K.S. Mukesh, "Fabrication and Investigation of mechanical properties of sic particulate reinforced AA5052 metal matrix composite", *Journal of Modern Material*, vol. 7, no. 1, pp. 26-36, 2020. https://doi.org/10.1016/j.matpr.2021.10.331.

[15] T. İsmail. "Investigation of wear behavior of particle reinforced AL/B4C composites under different sintering conditions", *Tehnički Glasnik*, vol. 14, no. 1, pp. 7-14, 2020. https://doi.org/10.31803/tg-20200103131032.

[16] J. Jiang, G. Xiao, C. Che, Y. Wang, "Microstructure, mechanical properties and wear behavior of the rheoformed 2024 aluminum matrix composite component reinforced by Al_2O_3 nanoparticles", *Metals*, vol. 8, no. 6, p. 460, 2018. https://doi.org/10.3390/met8060460.

[17] M. Vaghari, R. Gholam, and S. A. Jenabali Jahromi. "Studying on the fatigue behaviour of Al- Al_2O_3 metal matrix Nanocomposites processed through powder metallurgy", *Journal of Ultrafine Grained and*

Nanostructured Materials, vol. 52, no. 2, pp. 210-217, 2019. https://doi.org/10.22059/ JUFGNSM.2019.02.10.

[18] E. Simonetto, R. Bertolini, A. Ghiotti, S. Bruschi, S., “Mechanical and microstructural behaviour of AA7075 aluminium alloy for sub-zero temperature sheet stamping process”, *International Journal of Mechanical Sciences,* vol. 187, p. 105919, 2020. doi.org/10.1016/j.ijmecsci.2020.105919.

[19] Y. X. Lai, W. Fan, M. J. Yin, C. L. Wu, J. H. Chen, “Structures and formation mechanisms of dislocation-induced precipitates in relation to the age-hardening responses of Al-Mg-Si alloys”, *Journal of Materials Science & Technology,* vol. 41, pp. 127-138, 2020. https://doi.org/10.1016 /j.jmst.2019.11.001.

[20] V. Verma, A.H.M. Sayyed, C. Sharma, D.K. Shukla “Tensile and fracture properties of epoxy alumina composite: Role of particle size and morphology”, *Journal of Polymer Research*, vol. 27, pp. 1-14, 2020. https://doi.org/10.1007/s10965-020-02359-z.

[21] S. Alagarsamy, M.Ravichandran, M. Meignanamoorthy, “Multi-objective optimisation of dry sliding wear control parameters for stir casted AA7075-TiO_2 composites using Taguchi-Grey relational approach”, *Australian Journal of Mechanical Engineering,* vol. 20, no. 5, pp. 1453-1462, 2022. https://doi.org/10.1080/14484846.2020.1815997.

[22] M. Singh, B. K. Prasad, D. P. Mondal, & A. K. Jha, “Dry sliding wear behaviour of an aluminium alloy–granite particle composite”, *Tribology International* vol. 34, no. 8, pp. 557-567, 2001. https://doi.org/10.1016/S0301679X (01)00046-9.

[23] R. Farajollahi, H. J. Aval, R. Jamaati, “Effects of Ni on the microstructure, mechanical and tribological properties of AA2024-Al3NiCu composite fabricated by stir casting process”, *Journal of Alloys and Compounds,* vol. 887, p. 161433, 2021. https://doi.org/10.1016/j.jallcom. 2021.161433.

[24] S. Z. A. Sakinah, W. H. Azmi, J. Alias, “Characterization of TiO_2 nanopaint for automotive application”, *IOP Conference Series: Materials Science and Engineering*, vol. 863, no. 1, p. 012053, 2021. https://doi.org/10.1088/1757-899X/863/1/012053.

[25] Q. Li, X. Zhang, L.Wang, and J. Qiao, “The effect of extrusion and heat treatment on the microstructure and tensile properties of 2024 aluminum alloy”, *Materials*, vol. 15, no. 21, p. 7566, 2022. https://doi.org/10. 3390/ma15217566.

[26] J. Salguero, J. M. Vazquez-Martinez, I. D. Sol, M. Batista, “Application of pin-on-disc techniques for the study of tribological interferences in the dry machining of A92024-T3 (Al–Cu) alloys”, *Materials*, vol. 11, no. 7, p. 1236, 2018. https://doi.org/10.3390/ma11071236.

[27] A. Shahi, M.H. Sohi, D. Ahmadkhaniha, and M. Ghambari, "In situ formation of Al–Al_3Ni composites on commercially pure aluminium by

friction stir processing", *The International Journal of Advanced Manufacturing Technology*, vol. 75, no. 9, pp. 1331-1337, 2014. doi.org/10.1007 /s00170-014-6162-3.

[28] H. J. M. Al-Alkawi, A.A. Al- Rasiaq, and M.A.A. Al- Jaafari. "Mechanical properties of 7075 aluminum alloy matrix /Al_2O_3 particles reinforced composites", *Engineering and Technology Journal,* vol. 35, no. 3, Part A, pp. 239-245, 2017. doi.org/10.1016/j.matpr2020.12.747.

[29] H. M. Mahan, S. Konovalov, I. Panchenko, "Effect of heat treatment on the mechanical properties of the aluminium alloys AA2024 with nanoparticles", *International Journal of Applied Science and Engineering,* vol. 20, no. 2, pp. 1-6, 2023. https://doi.org/10.6703/IJASE.202306_20(2).011.

[30] Y. Wang, Y. Lu, S. Zhang, H. Zhang, H. Wang, and Z. Chen "Characterization and strengthening effects of different precipitates in Al–7Si–Mg alloy", *Journal of Alloys and Compounds,* vol. 885, p. 161028, 2021. https://doi.org/10.1016/j.jallcom.2021.161028.

[31] Z. Fangyuan, D. Chunzheng, S. Wei, J. Kang, "Influence of white layer and residual stress induced by hard cutting on wear resistance during sliding friction", *Journal of Materials Engineering and Performance*, vol. 28, pp. 7649-7662, 2019. https://doi.org/10.1007/s11665-019-04479-0.

[32] C. Melik "Abrasive wear behaviour of cast Al–Si–Mn alloys", *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering,* vol. 233, no. 4, pp. 908-918, 2019. https://doi.org/10.1177/0954408918818735.

[33] H. M. Mahan, S. Konovalov, Omran A. Shabeeb, "Enhancement of mechanical properties and microstructure of aluminium alloy AA2024 by adding TiO_2 nanoparticles", *International Journal of Nanoelectronics and Materials,* vol. 16, no. 3, pp. 441-453, 2023.

[34] D. Srinivasan, M. Meignanamoorthy, A. Gacem, M. Vinayagam, T. Sathish, M. Ravichandran and H.L. Allasi, "Tribological behavior of Al/ Nanomagnesium/ Aluminum nitride composite synthesized through liquid metallurgy technique", *Journal of Nanomaterials,* vol. 2022, no. 2, pp. 1-12, 2022. https://doi.org/10.1155/2022/7840939.

[35] S. Gangwar, V. Payak, V.K. Pathak, A. Jamwal and P. Gupta, "Characterization of mechanical and tribological properties of graphite and alumina reinforced zinc alloy (ZA-27) hybrid metal matrix composites", *Journal of Composite Materials,* vol. 54. no. 30, pp. 4889-4901, 2020. https://doi.org/10.1177/0021998320938442.