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Enhancement of Mechanical Properties and Microstructure of Aluminium alloy AA2024 By adding TiO_2 Nanoparticles

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ABSTRACT

Modern engineering applications, especially in the automotive and aerospace industries, require essential and appealing properties such as lightweight with high strength and resistance. The key objective of the present study is to investigate the effect of TiO_2 *nanoparticles on the microstructure, impact strength, hardness and wear resistance of the stir cast aluminum alloy AA2024, An aluminium alloy was reinforced with different mass fractions (0 %, 2.5 %, 5 %, 7.5 %) of titanium dioxide nanoparticles by stir casting followed by solution annealing at 500°C for 3 h, quenching in water and aging at 175°C for 3 h. Results showed that regular morphology and fine grain size of primary AA2024 particles are achieved after the addition of 2.5 wt.%* TiO_2 *compared to the sample without the addition of nanoparticles composite. In addition, it was found that adding nanoparticles increased energy absorption, and this effect is improved by increasing impact strength by adding nanoparticles, the impact strength increased from 5* j/m^2 *to 7* j/m^2 *at 5%. At the same time, the increase of nanoparticles effect decreases the mass losses (increase in wear resistance). With a weight fraction of 5 wt.%* TiO_2*, the alloy exhibits the highest value of hardness.*

Keywords: Metal matrix, nanoparticles, microstructure, Charpy impact, wear resistance.

1. INTRODUCTION

Aluminium alloys are utilised for various applications because of their unique properties such as corrosion resistance, low density, high ductility, adequate high strength, high reflectivity and low cost [1]. They are non-toxic and recyclable and have a useful combination of ductility and strength [2]. The first step in understanding the advantages of aluminum alloys is to review some of the basic qualities that make them interesting candidates for a wide range of applications, besides determining their disadvantages [3, 4]. Compared to other metals, aluminum has a lower density, making it appropriate for both military and commercial applications. Aluminum has also been used in packaging, electronic, industrial, and aerospace systems [5, 6]. Its high toughness over a wide range of temperatures makes it good for use in aerospace, and its high resistance to stress loading makes it a great choice [7]. Metal matrix Nano composites (MNCs) with lightweight alloy matrix and reinforced with nanoparticles or nano fibers are among the most promising materials [8, 9]. Zinc-based alloys are one of many alloys used for MNC, and for a variety of engineering applications; these alloys have gained

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widespread recognition as a cost-effective alternative to ferrous and non-ferrous alloys [10]. These alloys have outstanding qualities such as high strength, excellent cast ability and tribological properties, sensible machining, corrosion resistance, low melting point, excellent bearing and wear resistance capabilities, and low-cost production [11, 12]. These composite alloys can surpass typical engineering materials such as magnesium, cast iron, aluminum, steel, and any other reinforced metal or alloy in a variety of applications [13,14]. The addition of magnesium copper-zinc and manganese in aluminum resulted in the 2xxx series, which has its applications in airframe structures and highly stressed parts owing to its better properties [15]. In the 2xxx series, aluminum AA7050 is identified as $AlZn_6CuMgZr$, which is attracted more than the other high pure base metal such as AA 2024 and AA 7075 [16]. Furthermore, it was reinforced to get the metal matrix composite, which exhibits lightweight with higher strength, in order to tailor the properties of aluminum alloys as required. Stir casting has its own identity due to its simplicity, feasibility, and cost-effectiveness. Liquid metallurgy plays a major part in producing metal matrix composites. Next, when it comes to reinforcement, the most effective and attempted used one is the ceramic reinforcements in the form of particulates. The following are some of the research attempts to improve material qualities by adding titanium dioxide. To explore the mechanical behavior, a titanium dioxide reinforced aluminum composite was produced via friction stirring. The composite quality was improved with the addition of Titanium dioxide particles [17,18]. Titanium dioxide-reinforced aluminum composites were made using traditional sintering, spark plasma sintering, and microwave sintering. The mechanical properties of the composites were improved, and the microwave sintering composite was discovered to have a higher strength [19].

Y. Pazhouhanfar et al, studied the mechanical, microstructure, and fracture surfaces of a tensile sample of AA 6061 reinforced with TiB_2 nanoparticles. AA6061/ Ti with various weight percentages of nanoparticles was manufactured using the stir casting method. The optical micro-structure showed a uniform reinforcement distribution in the matrix and the SEM analysis showed the tight bonding between the matrix and reinforcements due to improved wettability. The composite's tensile strength was enhanced with an improvement in the wear rate of TiB_2 reinforcement particles without any significant decrease in elongation. SEM micrographs from broken surfaces of specimens subjected to tensile testing have shown that ductile fracture occurs in the Al 6061 alloy by nucleation and coalescence of micro-voids in all prepared composites [20]. A stir casting approach was used by Jaber et al. [21] to create AA 6063-T6 supported by TiO_2 nanoparticles at 3, 5, and 7wt.% TiO_2 nanoparticles. The results showed that in SEM pictures of 7 wt.% TiO_2 composites, the distribution of TiO_2 in the metal matrix was rather uniform. The magnetic tests showed that the Nanocomposites performed better than the base metal. There was no difference in magnetic characteristics between AA 6063-T4 / 7wt.% TiO_2 and the bulk matrix.

Recent studies have demonstrated a level of discrepancies in the mechanical properties of superficially identical composites which only contrasted in their method of preparation on the effect of different concentrations of TiO_2 nanoparticle (0 – 3wt.%) on the microstructure and strength of pure Al prepared using the Accumulative Roll Bonding (ARB) method. According to the microstructural characterization results, the achieved uniform distribution of the reinforcement material and ultrafine matrix grains was due to rolling after eight passes [22].
Using the stir casting liquid technique Patel and Mukesh [23] conducted a study to reinforce the AA5052 matrix with 5wt.% SiC particulates of 63μm particle size. The optical and SEM micrographs of the AA5052/SiC-p MMC showed a uniform distribution of SiC particles, while XRD analysis ascertained the presence of SiC in the AA5052 matrix. Moreover, the study found that with the addition of 5 wt. % of SiC particles, the density of the AA5052 rises by 0.8%. The developed compositions have a very low percentage of porosity (0.5%), with 0.37% and 0.26% for the as-cast AA5052 and AA5052/SiC MMC, respectively.

The micro-hardness and compressive strength of the AA5052 matrix are increased by 39.72% and 8.5%, respectively, when SiC particles are added to the matrix. The ZA-27 metal matrix composites were constructed by David et al. [24] and contain different weight fractions of TiC nanoparticles, which are used as a reinforcement material. An in-situ technique that considered the microstructure, hardness, and electrochemistry was used to create this alloy. The findings demonstrated that, in comparison to the base alloy, the hardness of composite materials has increased. However, as the amount of reinforcing grows, the hardness has decreased. The outcomes also showed that the corrosion resistance of the composite increased more rapidly than that of the basic alloy. ZA-27 performed better when manufactured with 5% TiC nanocomposite as opposed to 10% TiC nanocomposite. This is because of the particles forming a galvanic cell after clumping together [25]. This study aims to determine what weight percentage of TiO_2 nanoparticles added to aluminum alloys improves hardness, impact strength and wear rate to give enhanced microstructural characteristics, using traditional stir casting and solution aging.

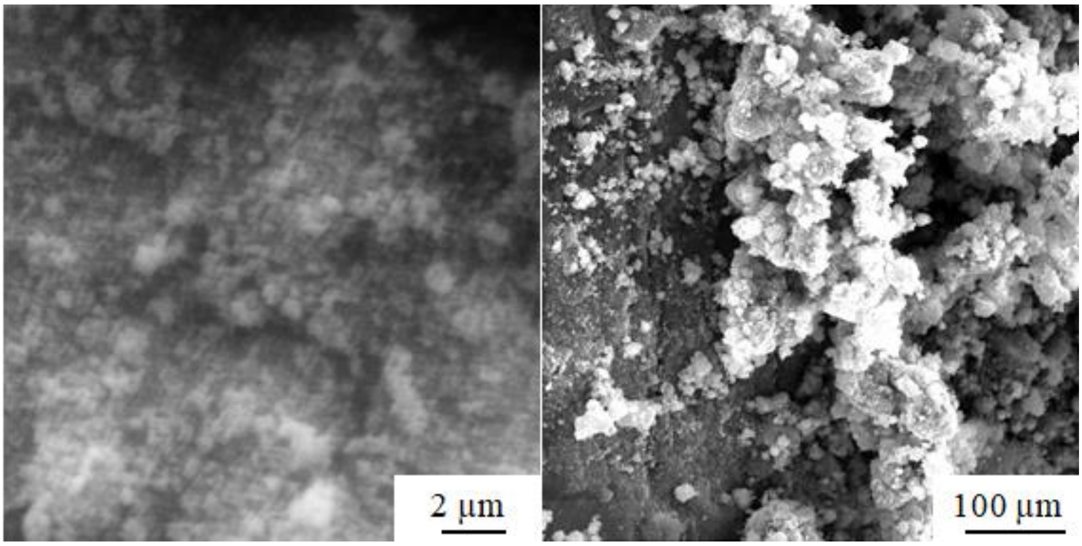
2. MATERIAL AND METHODS

The material chosen for the current research is aluminium alloy AA2024. The rationale for this selection is predicated upon the outstanding mechanical properties of aluminium alloy AA2024. Chemical composition of AA2024 alloy is shown in Table 1.

Table.1 Chemical composition of AA2024 -T3 alloy

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	1.06	0.098	4. 5	0.67	0.03	0.009	0.15	0.25	Balance

During the study, the alloy is reinforced using various weight percentages (0, 2.5, 5, and 7.5wt.% TiO_2) where the nanoparticles size of 30 ±5 nm Figure 1. 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 700°C (more than the matrix melting temperature) in a graphite crucible using an electric furnace to ensure the complete melting of all its components. The stir casting technique was utilized for 4 minutes at 200 rpm.



(a) (b)

Figure 1. SEM micrographs of TiO_2 nanoparticles.

Then the molten material was poured into molds and removed after solidification. The samples were then solution annealed by heating until 500°C for 3 h in an air circulated furnace, water quenched at room temperature and precipitation annealed (aged) at 175°C for 3 h Figure 2.

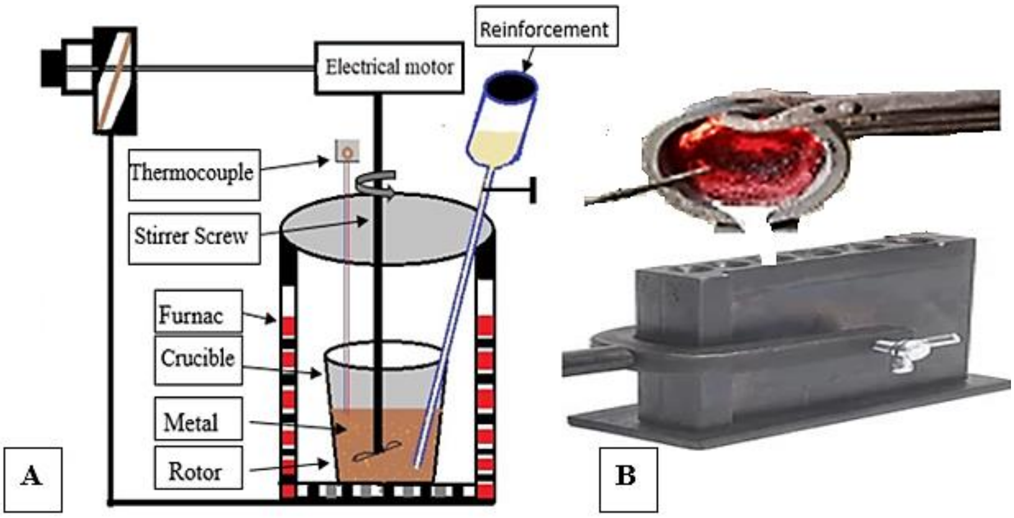
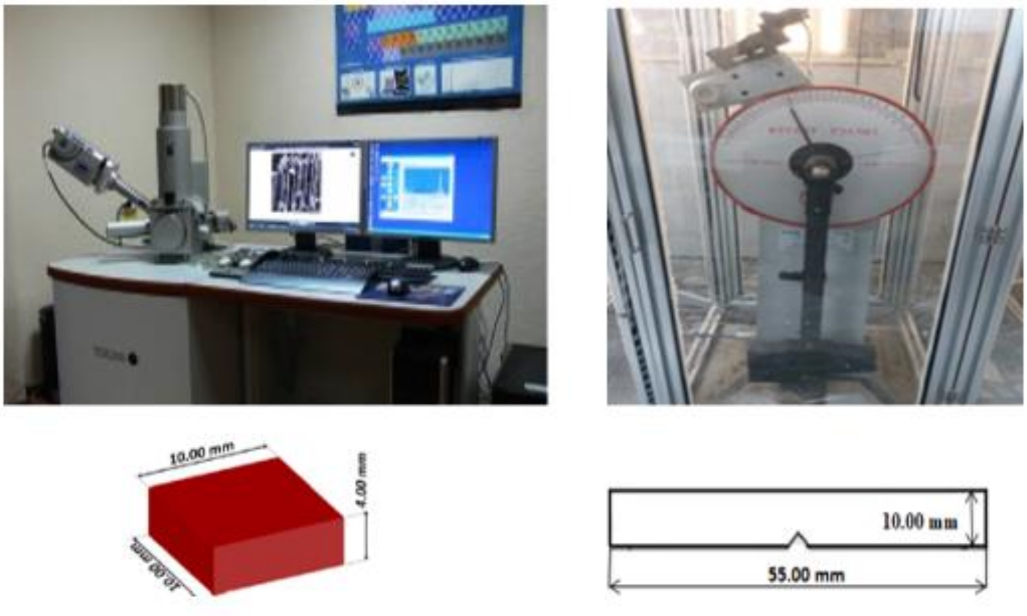


Figure. 2 A. The Stir casting furnace for melting and B. Casting mold.

The experiments were conducted per American standards (ASTM). The microstructure of the samples was assessed using a TESCAN VEGA scanning electron microscope (SEM). Kroll's reagent (H_2O: HNO_3: HF = 92: 6: 2) was used to cut samples transversally for 15 seconds following electron beam surface adjustment. In addition, the sample hardness of three samples was assessed using a digital pranail hardness analyzer category Laryee (HBRVS – 18705). A Charpy impact test was performed in accordance with ASTM-E23 to evaluate the impact strength of the developed composites. In this test, the extent to which a material is resistant to sudden shocks is evaluated. 55x10x5 mm are the dimensions of the samples used in the impact tests, as depicted in Figure 3.



(a) Microstructure tests specimen (b) Impact test specimen

Figure 3. Sample dimensions of physical and mechanical properties tests.

Per ASTM G99-95 guidelines, the wear rate of the cast AA2024 alloy reinforced with nanoparticles was examined using a pin on a disc-type wear tester. The sample was 30 x 10 mm in size. The disc potential speed was 277.4 rpm, the sliding velocity was 6 m/s, and an imposed load of 5, 10, 15 and 20 N was applied for 10 minutes; the disc hardness was 385 HV, and it was made of stainless steel. The dimensions of the samples used are displayed in Figure 4

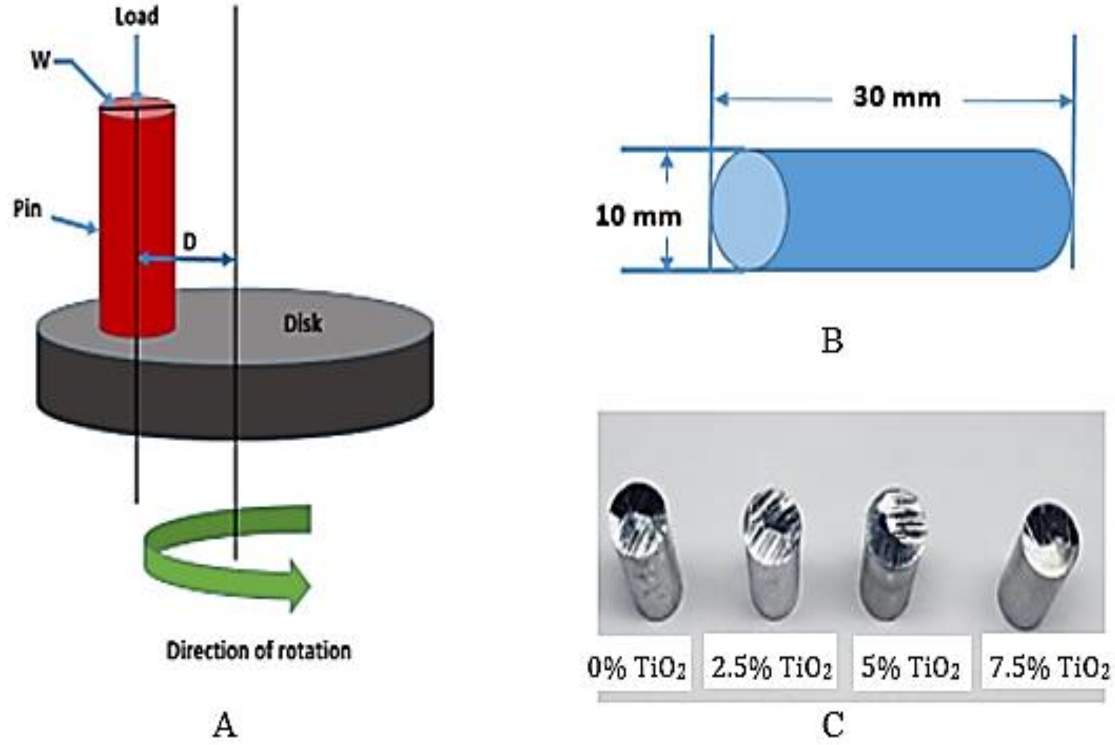


Figure 4. Diagram for pin-disk test (A -Diagram showing work, B- sample dimensions, C-samples used)

The experimental wear resistance of each specimen was measured using a sensitive weighing machine with a minimum count of 0.001 grimes. The mathematical formula accounts for weight decreases, as described in Eq. 1.

$$\Delta W = W_1 - W_2 \quad (1)$$

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

3. 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 stiffness might be improved 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 them. Additionally, the geometry of each individual reinforcement and the arrangement of those reinforcements can have an effect on the performance of the composite.

3-1 Impact strength

The impact tests of the specimens ascertained the impact strength of TiO_2 where the maximum impact strength has been obtained at 2.5wt.% TiO_2. Specifically, the reinforcing particles increase the threshold stress required for dislocation mobility and strengthen the Nanocomposite. Figure 5 shows that the aforementioned values of impact strength are reduced as a result of an increase in the number of TiO_2 particles (7.5wt.% TiO_2). Thus, this introduces the brittleness of these particles and the weakness in their ability to resist. These particles act as points for localized stress concentration regions from which the failure will begin. Furthermore, this decrease may be ascribed to these particles as they are fragile and cannot take a lot of force when they hit something, as well as the fact that these particles act as points for localised areas of stress concentration from which failure will begin. The weak ability of these particles to resist impact loading can also be the reason for the decline. These results were consistent agreements with the researchers from previous studies [18, 20].

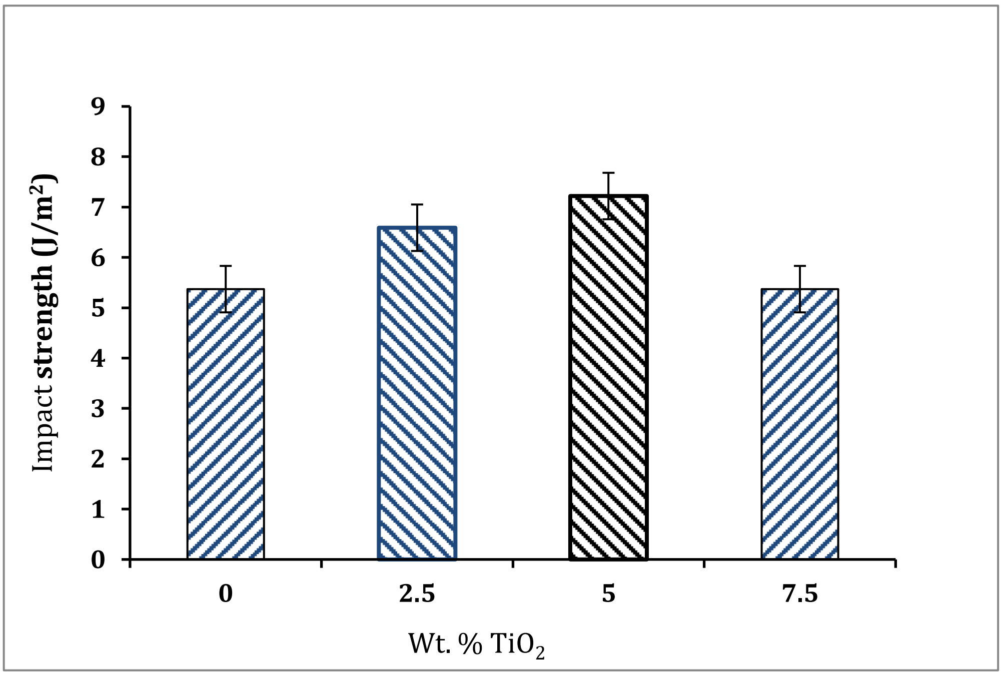


Figure 5. Relationship between Impact test and the Nanoparticles percentage (0, 2.5, 5 and 7.5 % Wt. TiO_2) of additives to AA2024.

With the formation of fine precipitates and after the heat treatment, the impact toughness values can be increased by the even precipitate and particle distribution in the microstructure. More strain fields were created by the creation of a uniform and fine precipitates and IMCs, which interact with dislocations to diminish dislocation motion ability. Accordingly, an increase in the impact strength of samples was noticed. The resistance of the sample is lower at 7.5wt.% TiO_2, can be attributed to the lower amount of Al_2CuMg precipitates in the sample without nanoparticles. As the weight percent of titanium oxide increases, the number of Al-Ti-based IMCs increases.

Figure 6 shows the fracture surfaces of the materials under study. The fracture surface of the sample of the matrix material AA2024 regularly demonstrates the ductile form of fracture,

Figure 6(b) depicts lateral narrowing which indicates significant plastic deformations. The SEM photograph of the fracture surface of the matrix alloy Figure 6(c) also shows the pitted structure of the fracture surface of the impact sample.

This is an indication of a ductile character destruction. The fractography images exhibited the dendritic arm broken failure (indicated with arrow marks). It shows a trans granular fracture, which happens along the grain boundaries and breaks away when the material breaks [21,22]. The fracture behaviour of the AA2024 composites exhibited a mixed mode of failure (i.e., ductile and brittle) with granular fracture at inter and intragranular segments.

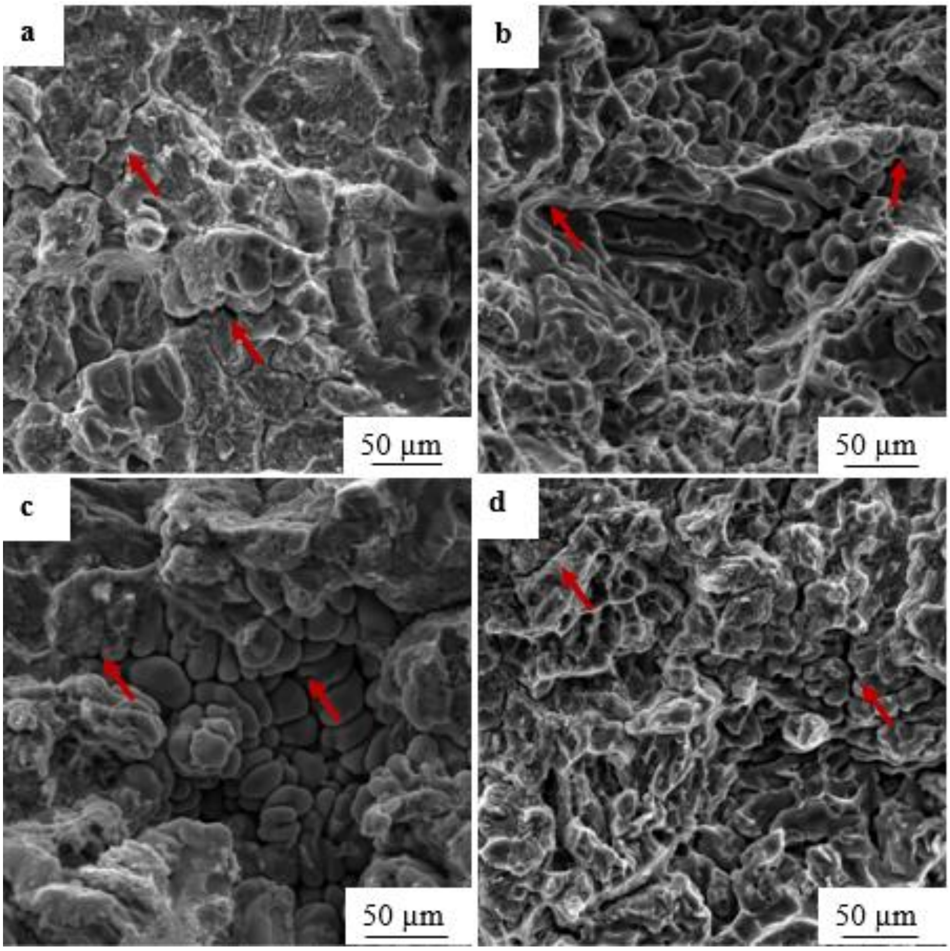


Figure 6. Fracture surface of AA2024-TiO_2 composites: (a) 0 wt.%; (b) 2.5 wt.%; (c) 5 wt.%. and (d) 7.5wt.%.

3.2 Microstructure of the materials

As a result of the metallurgical study of the obtained materials, it was found that the alloy AA 2024 in the transverse plane has a microstructure consisting of balanced fine grains and a phase of an Al-Mn-Mg-Cu composition Figure 7. Alloy AA 2024 has a large amount of copper, which contributed to the spheroidization of some inclusions. Other alloying components are also present in the silicon-rich. Copper is needed in the alloy to make it stronger. This is done by combining the solid solution and precipitation hardening to make the alloy stronger. Copper, in essence, forms a solid solution with aluminium and the rest of the copper. During the optimal quenching process at T = 500 °C, the dissolution of intermetallic phases and grain boundaries occurred during homogenization.

The alloying elements were evenly spread out in the solid solution, and the presence of Nano-reinforcements in the matrix increased the nucleation centres. This made a lot of new grains and made the strength, resistance, and microstructure much better. Due to no equilibrium crystallization, the chemical compound $CuAl_2$ is part of the eutectic and contains a mixture of crystals of the α-phase and θ-phase [25].

These phases are located along the grain boundary in the form of a limited volumetric. Compounds of copper and silicon together have high hardness and strength and form a collection of hard inclusions in the alloy. The microstructure of samples, in both 2.5%wt. and 5%wt. of oxide titanium, contains S-Al_2CuMg, Al_7Cu_2Fe, and AA (Mn, Cu, Si, Fe) precipitates. The fine black precipitates near the inter dendritic zone are S-Al_2CuMg. These precipitates grow finer and more consistently dispersed throughout the microstructure; these following the process of aging can be specified as hardening of precipitation. During the ageing process, a few alloy complexes precipitate and end up at the grain boundaries, increasing the material's strength. These grains tend to be uniformly distributed after the heat treatment, AA 2024 aluminium alloy material consists mostly of Al_2CuMg and Al_7Cu_2Fe matrix phase; the appearance of a large number of phases resulted in a substantial improvement in the qualities of the alloy. The inter-dendritic zone is also surrounded by Al_7Cu_2Fe and Al (Cu, Mn, Fe, Si). As stated by [19], these intermetallic compounds do not dissolve at high temperatures [23].

As compounds with a high titanium content absorbed much of the copper in the aluminium matrix, Al_2CuMg precipitates were unable to form once 5% wt. of TiO_2 had been added. According to (Wang et al., 2021), this stops the formation of precipitates. It is not possible to produce the Al_2CuMg precipitates; thus, precipitates are formed. When the Al-Mg-Cu system of alloys is combined with titanium, the copper’s solubility is reduced because intermetallic compounds such as Al_3TiCu and Al_7TiCu_4 are produced after titanium is added [26].

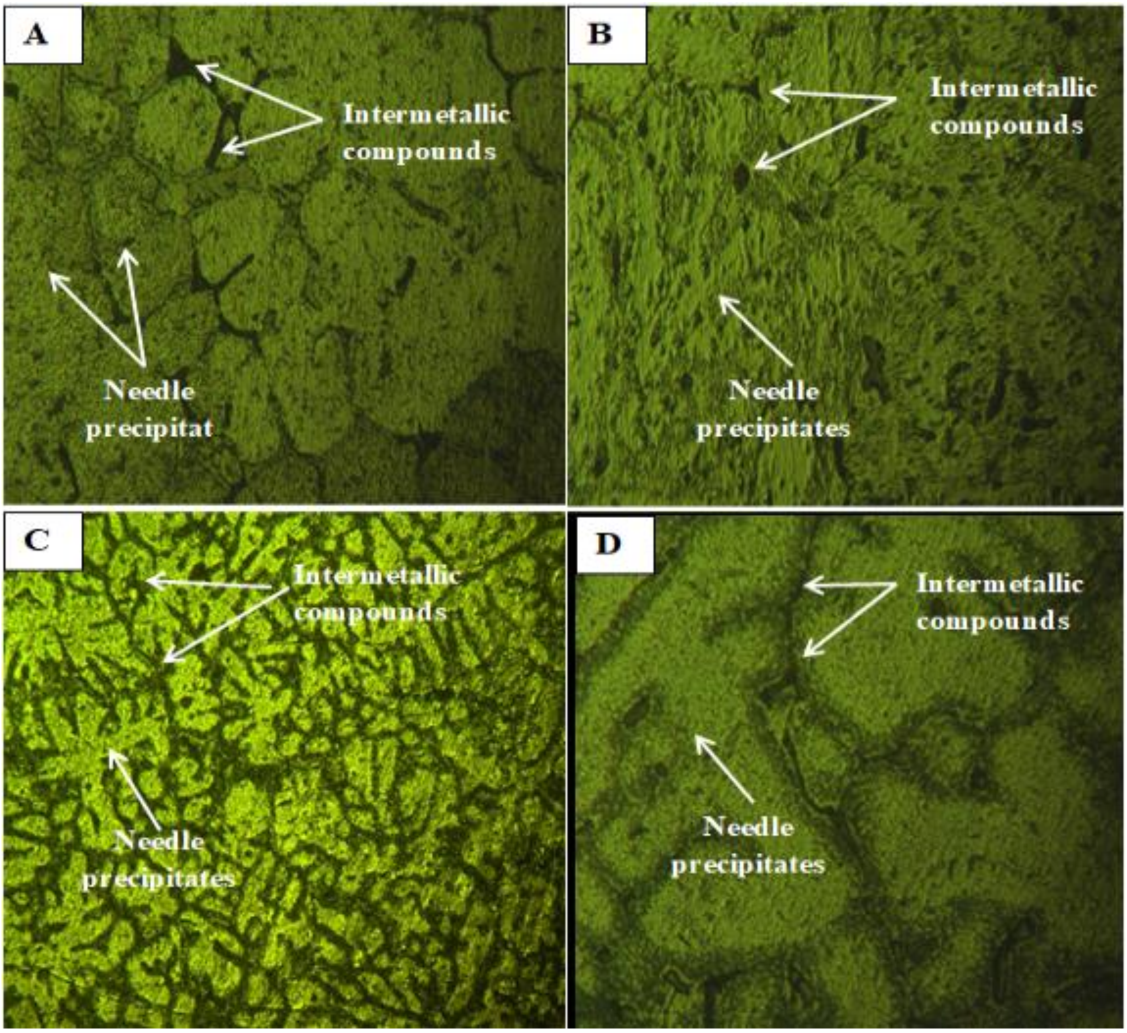


Figure 7. Optical microscopy images of; (A) Sample without adding, (B) sample 2.5%TiO_2, (C) Sample 5%TiO_2, (D) Sample 7.5 %TiO_2

3.3 wear test (Losses weight)

Figure 8 shows the average difference in specific mass for a steel (AISI 1030) disc with different surface treatments as a function of testing time (30 hours). It can be assured that increasing nanoparticles of TiO_2 would decrease the effect of in Losses weight. This specifically means an increase in wear resistance. Adding nanoparticles increases the hardness, which affects the wear resistance due to the refined grain structure. The best specimen has good wear resistance (low Losses weight) in materials as the specimen (5wt.% TiO_2). This can be summed up by saying that as the sliding speed gets faster, the temperature between the two surfaces going against each other becomes higher. Therefore, at high sliding speeds, friction has less of an effect on the surface of the specimen than at low sliding speeds, and the rate of wear becomes higher as the load gets heavier. This is because there is more plastic deformation between the two surfaces, which makes the real area of contact bigger, which explains the increase in the Losses weight.

As the temperature increases and oxidation wear becomes a main component of the wear mechanism, a reduction in the wear rate would be observed. This is due to the fact that the oxide layer is usually 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. The results were in good agreement with the findings of [21].

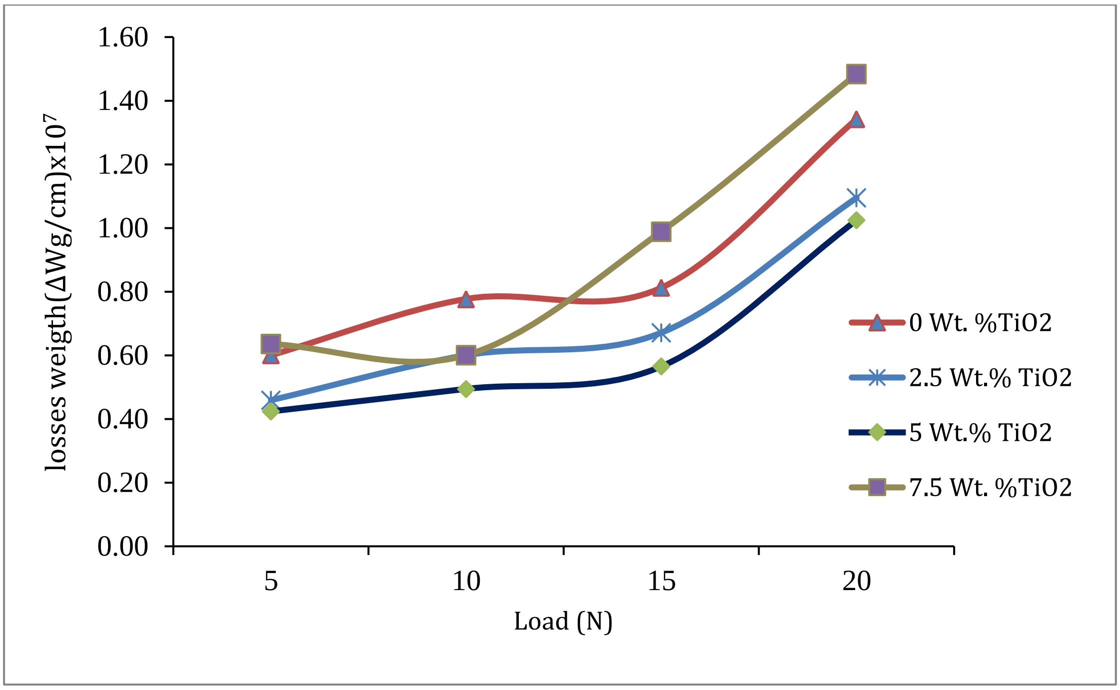


Figure 8. Variation of Losses weight of specimens as a function of weight with testing time.

The wear surface for each sample is demonstrated in Figure 9. The wear surface had highly dimpled structures and ductile failure properties. Regarding the wear of very strong aluminum alloys, the development of micro voids surrounding coarsened precipitates causes intergranular damage. 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 9(c) that were observable on the surface Figure 9(a), and abrasive wear became adhesive wear. Due to a larger number of TiO2 nanoparticles in the matrix base, its plastic deformation was countered by a mechanical mixed layer that became a barrier to the moment of dislocation and increased wear resistance (Rao et al., 2014).

The SEM micrographs of the worn surface of AA2024 matrix material and AMMCs (2.5, 5 and 7.5 wt.% of TiO_2) under sliding distance of 2 Km, sliding velocity of 2 m/s and a normal load of 20 N at room temperature were shown in figure 9(a)–(d). It can be observed that the wear tracks are layered with compacted wear debris eventually forming the transfer layer. Figure 9(a) shows the wear tracks of AA2024 matrix material. It shows heavy delamination and fracture of the transfer layer due to the abrasive action of the hardened transfer particles resulting in cutting with subsequent delamination and fracture of the compacted layer [22]. Figure 9(b) and 9(c) shows distinct grooves and ridges running parallel to one another in the sliding direction, as shown with a red mark. It can be seen from the micrographs that the grooves are wider and deeper in matrix as compared to the composites tested under similar conditions. In Figure 9(d), Ploughing can also be seen on the worn -out surface of the 7.5wt. % of TiO_2 composite , which may be due to sliding of oxide particle in the composite [27, 25].

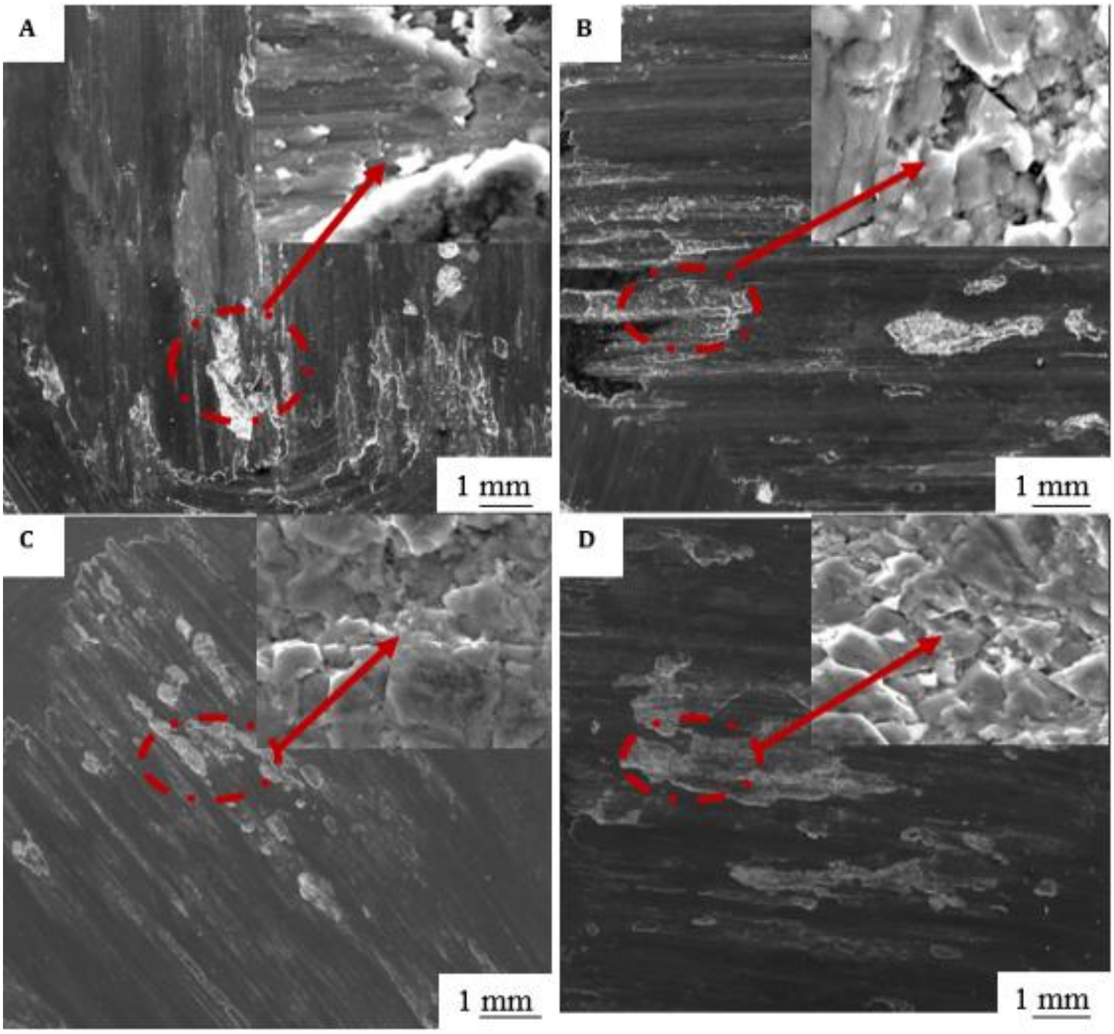


Figure.9 Morphologies of the worn surface at a load of 20N (a) AA2024 matrix material (b) AA2024\2.5%TiO_2, (c) AA2024/5%$TiO_2$and (d) AA2024/7.5%TiO_2 composite.

3.4 Hardness

The effect on hardness caused by combining TiO_2 nanoparticles of different weight percentages with aluminum alloys are described in Figure 10. The addition of 2.5%and 5% wt. of TiO_2 to aluminum alloys increased hardness by 41%, thereby lowering the intensity of distortion. The greatest levels of hardness (55 and 64 HRB) were achieved with 2.5% and 5% wt. of TiO_2, respectively.

According to Shahi et al. (2014), the well distribution of fine Al_2CuMg precipitates and the hardness of aluminum particles in the microstructure can be enhanced after adding nanoparticles. This enhanced hardness is achieved through the improved distribution of the Al3Ti compounds as the finer intermetallic compounds are better able to pin grain boundaries and improve hardness, per the Hall–Petch rule. However, increasing the weight percentage of TiO_2 to 7.5 wt. % has caused a considerable reduction of hardness. This can be attributed to an increase in the number of fine precipitates in the sample at 7.5 wt. % of TiO_2 that might distort the microstructure of aluminum composite, these results were consistent agreements with those from previous studies [27,18].

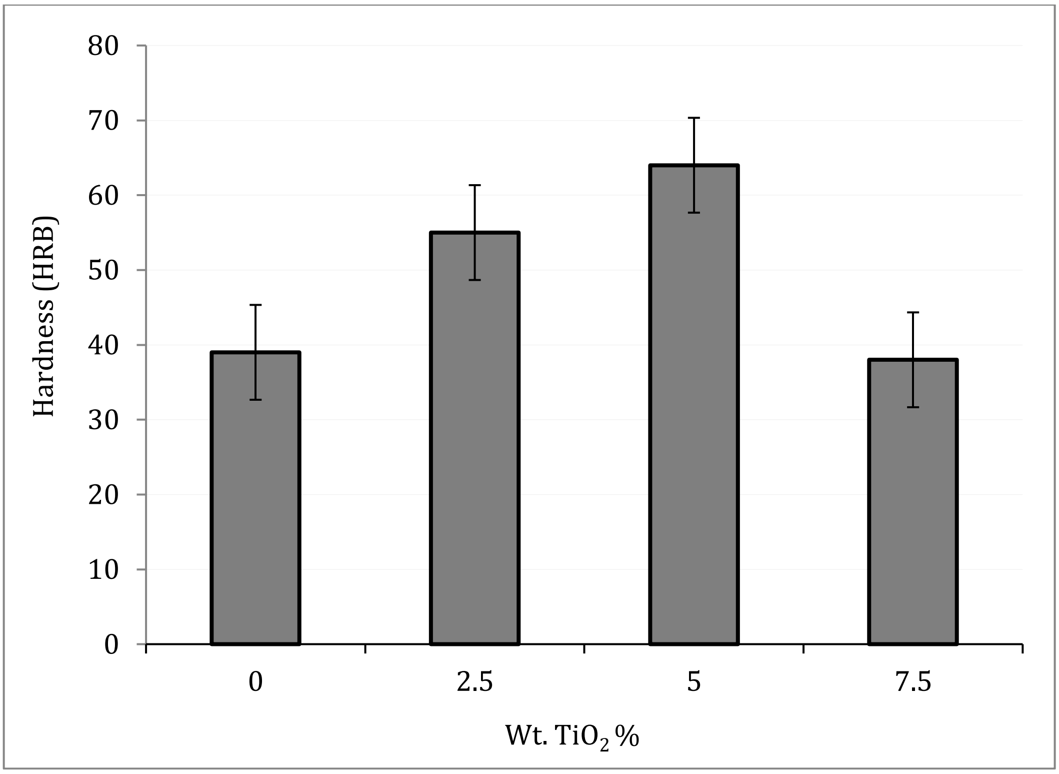


Figure 10- Effects of nanoparticles on the hardness of AA2024 composite

4. CONCLUSION

The microstructural changes, impact and wear resistance were studied using a natural ageing heat treatment. The following conclusions were obtained:

1. The titanium oxide element in the 2.5–5 wt. % composites enhanced hardness by 31–64% because of the distribution of titanium in the aluminium matrix.
2. Nanoparticles enhanced the wear characteristics of the composites by 25%, contributing to the development of a stable trilateral with self-lubricating features.
3. An increase in the added nanoparticles with 5% caused an increase in impact strength by 40 % compared to an unreinforced aluminium matrix.
4. The even dispersion of TiO_2 and the particles in the alloy were nearly homogeneous between the composites, and the dispersion of these particles enhanced the mechanical characteristics of the AMMCS more than the as-cast matrix.

Thus, we confirm that combining nanoparticles with AA 2024 alloys greatly enhances their physical characteristics. This, in turn, enhances the potential of aluminium alloys for various industry applications.

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