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Research Article

Mechanical and wear characterization of nitrided Al-5%Ti-B metal matrix composite reinforced with Al_2O_3 particles

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Abstract

The mechanical behavior and wear characteristics of nitrided Al-5%Ti-B alloy reinforced with Al_2O_3 have been investigated in this paper. The integration of Al_2O_3reinforcement into the Al-5%Ti-B alloy matrix offers promising opportunities for enhancing the mechanical and wear resistance properties of the composite material. Through a comprehensive experimental approach, various mechanical properties like tensile strength and hardness are evaluated alongside wear behavior under different conditions. The study also investigated how the nitriding treatment influenced both characteristics of microstructures and mechanical properties of the composite material. The results indicate significant improvements in mechanical properties and wear resistance following the incorporation of Al_2O_3 reinforcement and nitriding treatment. Microstructural analysis using techniques such as scanning electron microscopy and X-ray diffraction provided insights into the structural changes induced by the reinforcement and nitriding processes. The findings of this study contribute to the understanding of the synergistic effects between reinforcement, alloy composition, and surface treatments in enhancing the mechanical and wear properties of metal matrix composites, thereby offering potential applications in various engineering fields.

1. Introduction

Metal matrix composites (i.e. MMCs) have emerged as promising materials for a wide variety range of engineering applications due to their superior mechanical properties and tailored functionalities [1, 2]. Among MMCs, aluminum-based alloys have attracted extensive interest due to their lightweight nature, corrosion resistance, and high strength-to-weight ratio [3, 4]. In recent years, there has been a focus on improving the tribological and mechanical characteristics of Al-based MMCs by integrating reinforcement materials and implementing surface treatments. Aluminum matrix composites have emerged as a focal point of research and development, owing to their remarkable attributes which outshine those of traditional monolithic aluminum alloys. [5, 6].

In this context, the combination of Al-5%Ti-B alloy with Al_2O_3 reinforcement presents an intriguing avenue for improving the mechanical and tribological characteristics of aluminum-based composites. Incorporating Al_2O_3, a ceramic material known for its exceptional hardness, thermal stability, and resistance to wear, into the matrix of the Al-5%Ti-B alloy presents an

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opportunity to elevate the overall performance of the composite material [7, 8]. Additionally, the introduction of nitriding treatment further augments the surface properties and microstructural characteristics of the composite, potentially leading to enhanced mechanical strength and wear resistance.

The rationale behind investigating nitrided Al-5%Ti-B alloy reinforced with Al_2O_3 lies in the quest for materials advancement with enhanced properties to meet the demanding requirements of modern engineering applications. By comprehensively studying the wear and mechanical characteristics of this composite system, valuable insights can be gained into its performance under several loading conditions, providing crucial information for potential applications in sectors such as aerospace, automotive, and manufacturing.

2. Material Synthesis

2.1 Raw Materials

Aluminum-based MMCs are commonly used due to its lightweight, good thermal conductivity, and high strength-to-weight ratio. Adding elements like titanium and boron to aluminum can further improve its mechanical properties. Al-5%Ti-B alloy, often referred to as a master alloy, is a specialized material commonly used in the aluminum alloy industry. This alloy holds significant importance in the manufacturing of aluminum alloys tailored to possess distinct properties and characteristics. Kori et al. [9] conducted detailed experiments aimed at elucidating the mechanism involved in the reaction between molten aluminum and salts during the production of Al-Ti-B master alloys.

Al-5%Ti-B is primarily known for its grain refinement capabilities. The addition of Al-5%Ti-B allows for better control over the microstructure of the aluminum. In the casting process, Al-5%Ti-B can help reduce the formation of defects like shrinkage cavities and porosity. This is particularly important in industries where high-quality cast aluminum components are required, such as the automotive and aerospace sectors. With Al-5%Ti-B it can lead to increased tensile strength, elongation, and overall mechanical performance in aluminum alloys. This makes it valuable for manufacturing components where high-strength aluminum is necessary.

2.2 Reinforcement

Reinforcement particles can interact physically or electrochemically with the matrix, which is important for enhancing oxidization. Additionally, the relationship of the reinforcement and matrix can also accelerate oxidization. The oxidization at the particle and matrix interface can lead to high diffusion along the enormous interfacial regions in Metal Matrix Composites (MMCs), resulting in enhanced corrosion resistance. The particles such as Al2O3, SiC, B4C, etc., when reinforced in aluminum can improve the mechanical and tribological properties while reducing ductility. Nevertheless, there has been a moderate degree of sparse reporting on the optimization of weight percentages of reinforcements (Al_2O_3 and SiC) and heat treatment aimed at enhancing the mechanical and tribological properties of MMCs. Over the past few decades, numerous research reports have emphasized the tribological and mechanical attributes of MMCs. Arun et al. [10] studied the influence of Al_2O_3 and Gr on the tribological and mechanical behavior of Al-MMC. They used various weight percentages of Al_2O_3 (5, 10 and 15%) and a constant weight percentage of graphite (5%) to produce composites by a stir casting process. From the results, they concluded that the composites' hardness increased with the increase in weight percentage of Al_2O_3 particles.

Vedrtnam and Kumar [11] have investigated the behavior of wear on aluminum reinforced with silicon carbide and copper. From the work, it shows that the most influential parameter on wear rate of the composite was weight percentage of the reinforcements. Load and sliding speed were second and third, respectively in the order of dominance while sliding distance had the least effect.

2.3 Material Processing

Stir casting is a widely used technique for the fabrication of MMCs such as Al-Ti-B alloy reinforced with Al_2O_3 particles. This technique entails integrating reinforcing materials, such as ceramic particles, into a molten metal matrix via mechanical agitation during solidification. The process typically begins with the melting of the base metal alloy, followed by the addition of the reinforcement particles into the molten metal [12, 13]. Mechanical stirring is then applied at a speed of 250 rpm to disperse the reinforcement particles uniformly throughout the matrix as shown in figure 1. The major benefits of this process are applicability to mass production. The stir casting process costs very low (up to 1/10th) for mass production of MMCs when compared to powder metallurgical process. To achieve proper filler distribution within the matrix during the stir casting process, it is essential that the temperature of the melt exceeds that of the Aluminum because of these factors, stir casting emerges as the predominant and viable technique for manufacturing MMCs [14, 15].

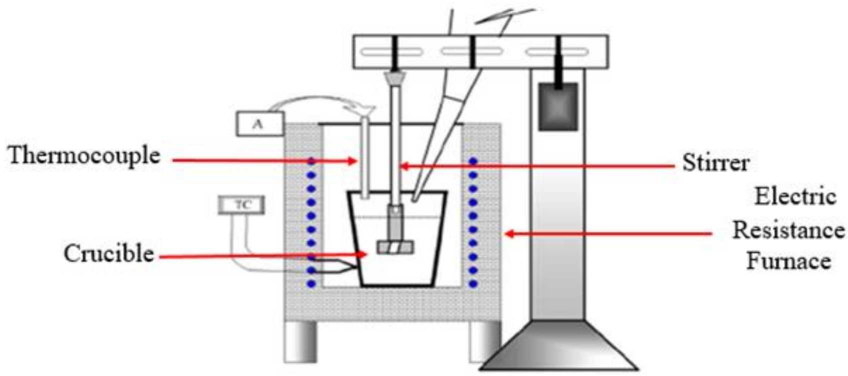


Fig. 1. The schematic diagram of the furnace used for composite ingot preparation

2.4 Gas Nitriding

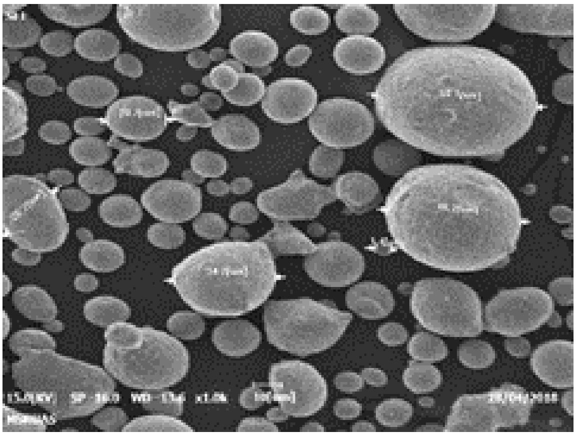
Gas nitriding is a thermo-chemical process aimed at enhancing the surface properties of materials, typically steel, through nitrogen enrichment. Gas nitriding process was carried out at Vescon Engineering, Bengaluru. In this particular instance, theAl-5%Ti-B alloy with Al_2O_3 material in varying percentages has undergone gas nitriding treatment for 72 hours at 520°C.The treatment was conducted to bolster the material's hardness and wear resistance. After the 72-hour treatment period, the chamber was allowed to cool to room temperature, and samples were later removed for analysis. While the primary focus of gas nitriding is on diffusing nitrogen into the surface layers of steel, it's worth noting that if aluminum is present in the system, it could potentially react with ammonia gas under specific conditions to form aluminum nitride (AlN). However, the primary goal of the gas nitriding process remains the enrichment of the alloy surface with nitrogen to optimize its mechanical properties [16, 17].

$$3NH_3 + 2Al \rightarrow AlN + 3H_2 \quad (1)$$

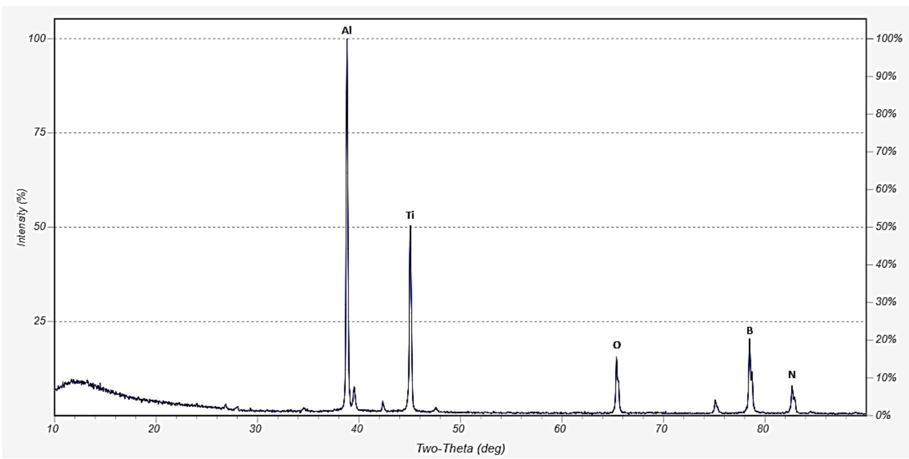
This reaction represents the formation of aluminum nitride (AlN) from ammonia and aluminum, which is consistent with the presence of aluminum and ammonia gas. The alloying elements (Al, Ti, B) may form solid solutions or intermetallic compounds with nitrogen. The formation of aluminum nitride (AlN) on aluminum and aluminum alloys can indeed be enhanced by microstructure refining and micro-alloying. This enhancement is attributed to several factors, and grain boundary diffusion of nitrogen in AlN is one of them [18,19,20].

3. Experimental Details

Figure 2 (a) is SEM micrograph of alumina particles and energy-dispersive X-ray spectroscopy (EDXS) serves as a tool for identifying the elemental composition of materials in a nitrided (Al-5%Ti-B) alloy specimen reinforced with Al2O3 as shown in figure 2 (b). The distinct nitrogen peak in the spectrum confirms the presence of nitrogen among other elements.



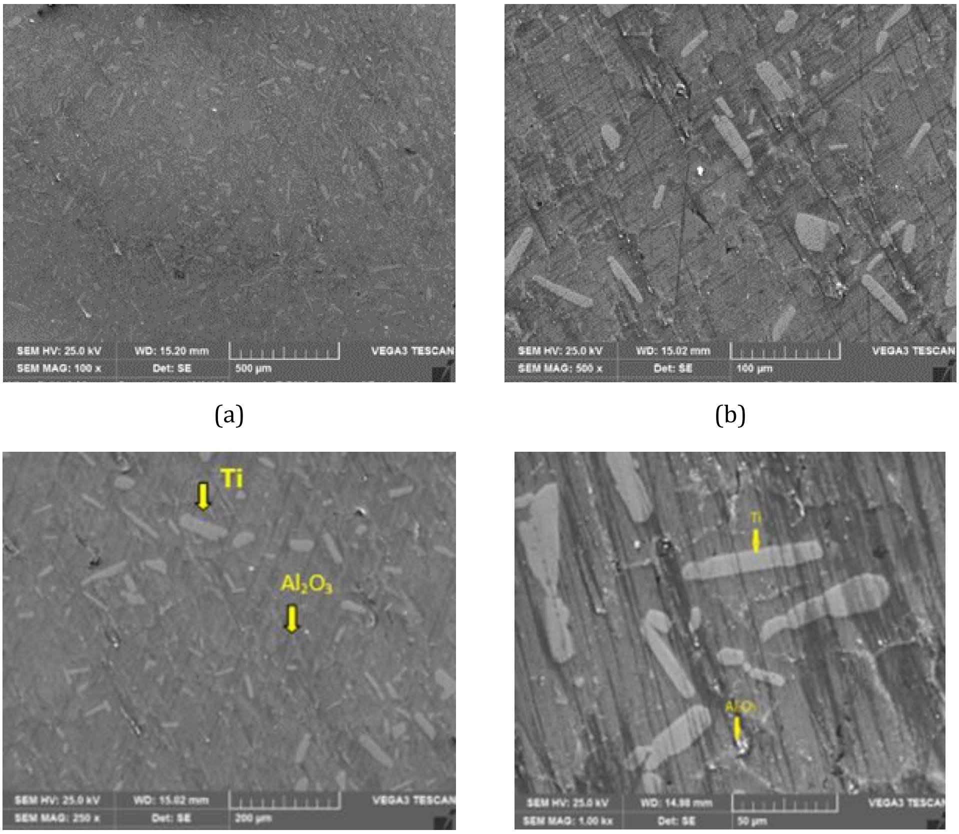
(a)



(b)

Fig. 2. (a) SEM micrograph of Al_2O_3 particles (b) XRD result of nitrided Al-Ti-B composition reinforced with Al_2O_3

The scanning electron microscope (SEM) as shown in figure 3 facilitates microanalysis and the examination of the dispersion of reinforcement particles within the matrix material. At a magnification of 100x,250x and 500x SEM enables the observation of distribution characteristics, surface texture, and particle orientation within the material's reinforcement distribution. Meanwhile, grain size is scrutinized at 500x magnification, providing insights into the alloy's microstructure and mechanical properties.



(a) (b) (c) (d)

Fig. 3. SEM result of (a-b) Al-5%Ti-B composition (c-d) Al-5%Ti-B composition reinforced with Al_2O_3

4. Results and Discussions

4.1 Tensile Test

The process begins with the preparation of composite ingots, which are subsequently chopped into smaller pieces to facilitate re-melting. Re-melting occurs within an atmospheric controlled electrical resistant furnace, using graphite crucible to hold the chopped ingots. Al–5Ti–1B rods were cut and weighed accurately and added to the molten material at 75^{o}C, until they reach a molten state. Once molten, the reinforcement material Al_2O_3 is added and is gently stirred by stirrer for approximately 5-10 minute to achieve uniformity. The Tensile specimen is prepared as per the ASTM standards as shown in figure 4(a). One set the tensile specimen underwent gas nitriding treatment for 72 hours at 520°C as shown in figure 4 (b). The composite samples underwent tensile testing utilizing a computerized PC2000 tensometer from Kudale Instruments (P) Ltd. Initial specimen preparation was conducted following the guidelines outlined in the ASTM E8M standard.

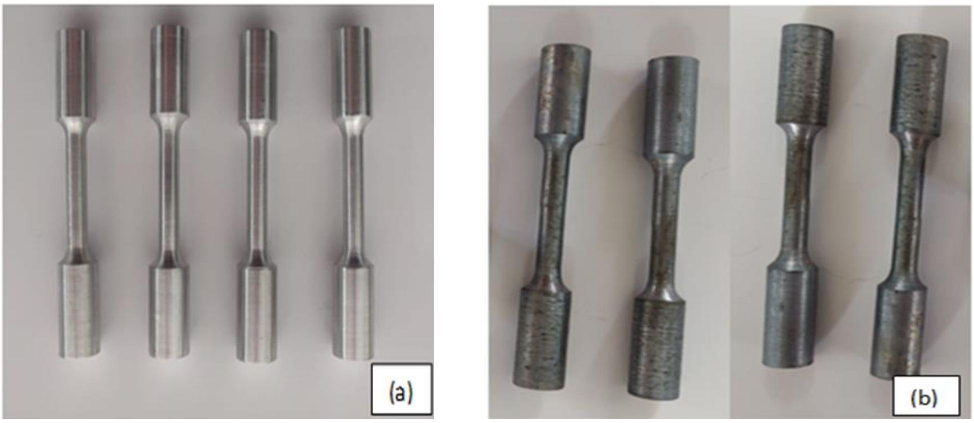


Fig. 4. (a) Non-Nitrated Tensile specimen and (b) Nitrated Tensile specimen as per ASTM standard with 0%, 2%, 4% and 6% of reinforced Al_2O_3

The tensile test results in the figures 5 indicate a noticeable increase in the ultimate true stress of the composites incorporating Al_2O_3 particles. Specifically, as shown in figure 5, it clearly indicates that the 6% Al_2O_3 sample exhibited the highest tensile strength, whereas the 0% Al_2O_3 sample displayed the lowest. This improvement in tensile strength for the sample can be attributed to the enhanced bonding between the matrix and the hybrid reinforcements. The same composition is nitrided and tested for tensile strength it is observed that there is improvement in its tensile property as well. Nitriding introduces nitrogen into the surface of the material, creating a hard, wear-resistant layer of nitrides. This layer increases the surface hardness and resistance to deformation, contributing to overall tensile strength.

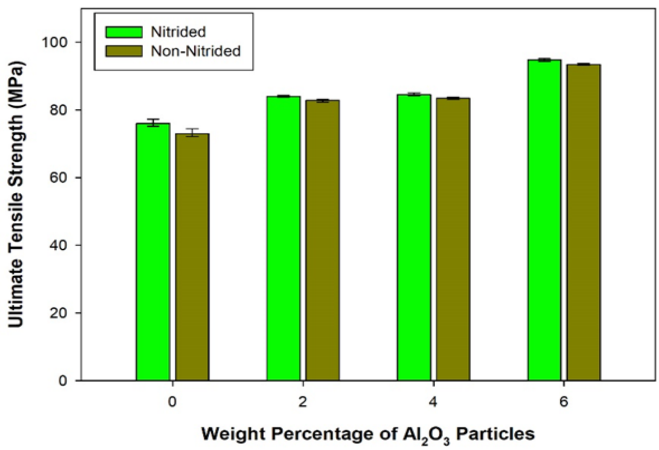


Fig. 5. Nitrated and Non- Nitrated Tensile strength of (Al-5%Ti-B) materials with 0%, 2%, 4% and 6% of reinforced Al_2O_3

4.2 Hardness test

Microhardness examination was conducted on the Micro-Vickers hardness testing machine by Mitutoyo in accordance with ASTM requirements to determine the hardness values in the (Al-5%Ti-B) with Al_2O_3 composite. The indentation made by applying the test force to a specimen using a quadrangular shaped pyramid diamond indenter whose face to face angle is 136°. The intention of this experiment was to evaluate the impacts of nitriding and the rise in weight percentage (wt.%)of aluminum oxide on the lightweight aluminum alloy matrix, as hardness serves as an indicator of a product's resistance to plastic deformation.

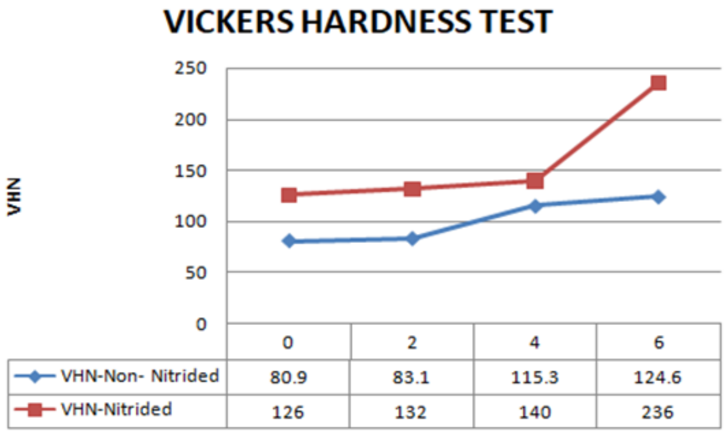
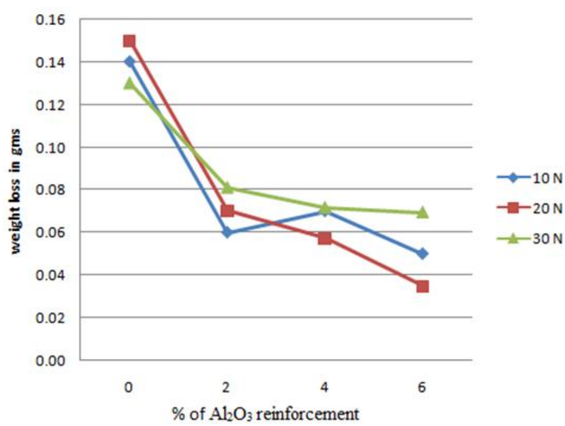


Fig. 6. Nitrided and Non- Nitrided Vicker's hardness of (Al-5%Ti-B) materials with 0%, 2%, 4% and 6% of reinforced Al_2O_3

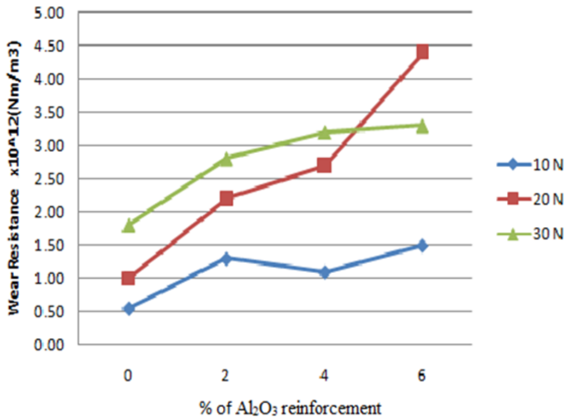
The examination aimed to observe the influence of addition of aluminum oxide and nitriding on the hardness values to Al-5%Ti-B alloy. Figure 6 display the variation in hardness values with the wt.% of 0,2,4 and 6 aluminum oxide. It was noted that the hardness values increased with the increase in aluminum oxide content. This observation can be endorsed to the ceramic nature of aluminum oxide particulates, which are inherently harder compared to the aluminum matrix alloy. Now since the same composition is nitrated and tested for hardness, it results in an increase in the resistance to deformation and, consequently, an increase in hardness.

4.3 Wear Test

Al-5%Ti-B samples as per ASTM G99 with varying weight percentage of Al_2O_3 are made ready for dry sliding type of wear test. The test is performed on 10mm diameter and 30mm length cylindrical specimens with the help of pin on disc wear testing equipment. The test was conducted at 10N, 20N and 30N with the sliding speed of 500rpm for duration of 15min.



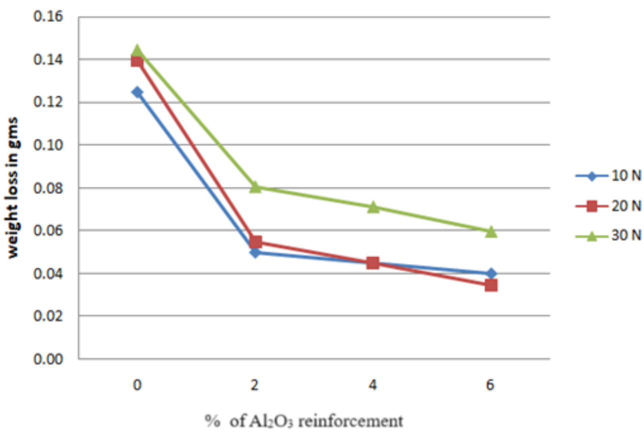
(a)



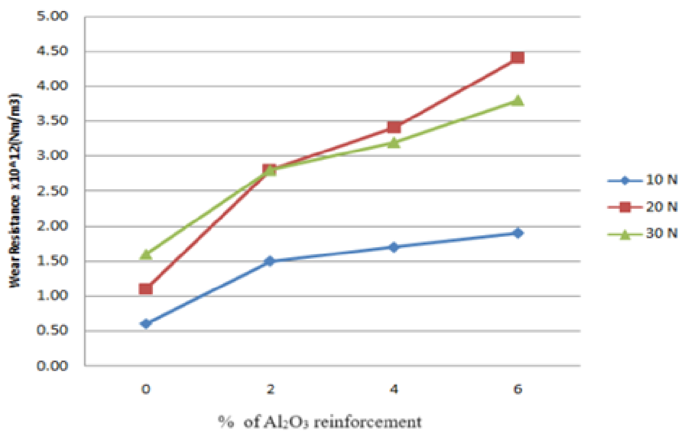
(b)

Fig. 7.(a) Wear loss and 7and (b) Wear Resistance of non Nitrided (Al-5%Ti-B) materials with 0%, 2%, 4% and 6% of reinforced Al_2O_3

Figure 7(a) and 8(a) shows wear loss of non-nitrided and nitridedAl-5%Ti-B material is of about 0.15gms and 0.13gm without inclusion of Al_2O_3 reinforcement. But with increasing in percentage of Al2O3 the composites have shown a greater wear resistance as compared to (Al-5%Ti-B). Effect of varying load on wear resistance of non-nitrided and nitrided (Al-5%Ti-B) alloy and its composites is presented in figure 7(b)and 8(b) respectively. The graph shown in the figures consists of three curves representing the behavior of material for varying loads of 10N, 20N and 30N for a track radius of 60mm with time of 15min and speed 500rpm.For the case of alloy without reinforcements the wear resistance of non-nitrided and nitrided is found to be 0.55and 0.61x10^12 Nm/m^3 respectively for 10N and 1.8 and 1.61x10^12 Nm/m^3 respectively for 30N. The wear resistance tends to increase with the increase in load from 10 N to 30 N. The increase in wear resistance is quite minimal with the increase in load.



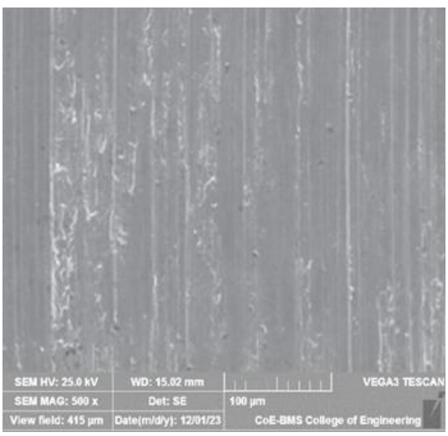
(a)



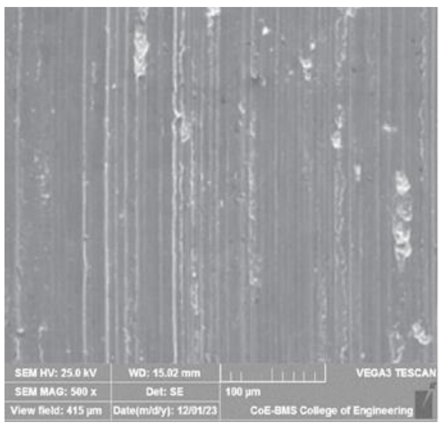
(b)

Fig. 8. (a)Wear loss and 7(b) Wear Resistance of nitride (Al-5%Ti-B) materials with 0%, 2%, 4% and 6% of reinforced Al_2O_3

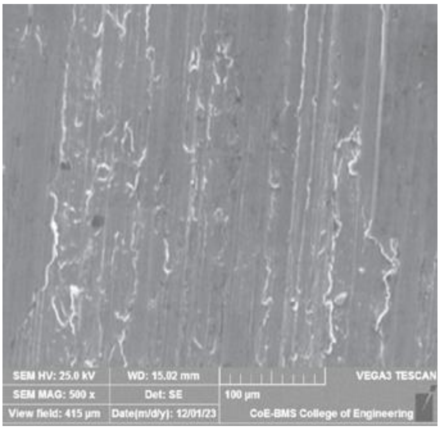
For the case of (Al-5%Ti-B)with 2% Al_2O_3 reinforcement wear resistance of non-nitrided and nitrided is found to be 1.3 and 1.5x10^12Nm/m3 respectively for 10N and 2.8 and 2.81x10^12 Nm/m3 respectively for 30N. For the case of Al-5%Ti-Bwith 4% Al_2O_3 reinforcement wear resistance of non-nitrided and nitrided is found to be 1.10and 1.70x10^12Nm/m^3 respectively for 10N and 3.2 and 3.33 x10^12 Nm/m^3 respectively for 30N and for the case of Al-5%Ti-Bwith 6% Al_2O_3 reinforcement wear resistance of non-nitrided and nitrided is found to be 1.5 and 1.9x10^12Nm/m3 respectively for 10N and 3.30 and 3.80x10^12 Nm/m^3 respectively for 30N. The wear resistance tends to increase with the increase in load from 10 N to 30 N. The wear resistance typically experiences a gradual increase with higher loads for all materials, whether alloys or composites. The SEM micrographs illustrate distinct wear characteristics between the nitrided and non-nitride samples of varying % Al2O3 reinforced composite materials under dry sliding conditions. Figure 9(a), the non-nitrided sample displays noticeable rough patches on the wear surface, indicating significant material removal or deformation. Conversely, Figure 9(b) depicts the nitrided composite sample with a smoother surface and fewer instances of delamination [21-24].



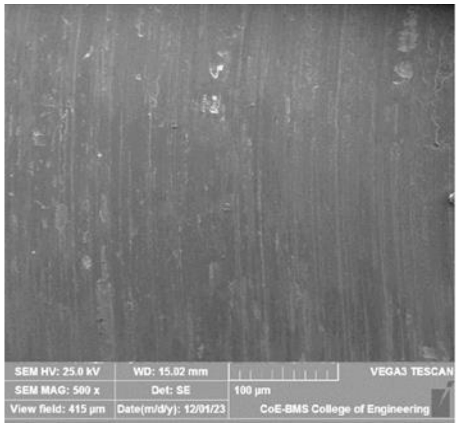
(a-1)



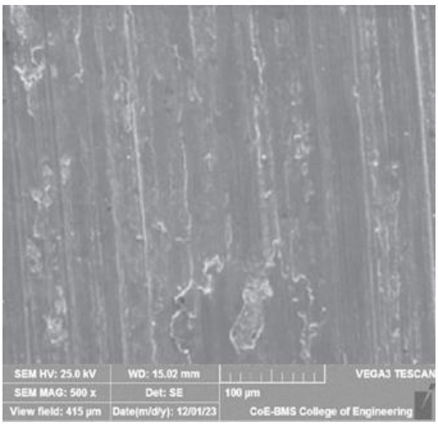
(a-2)



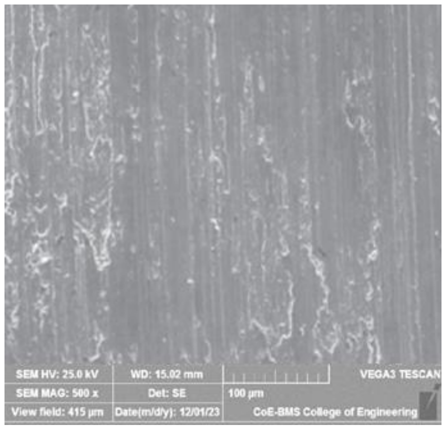
(a-3)



(a-4)



(b-1)



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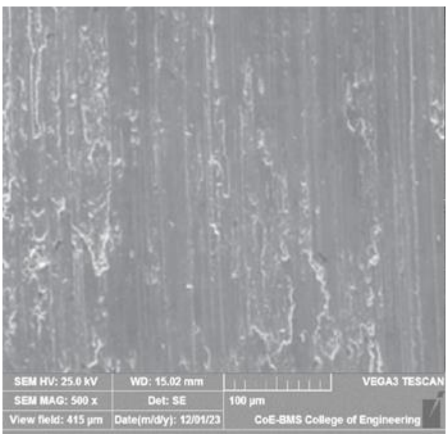
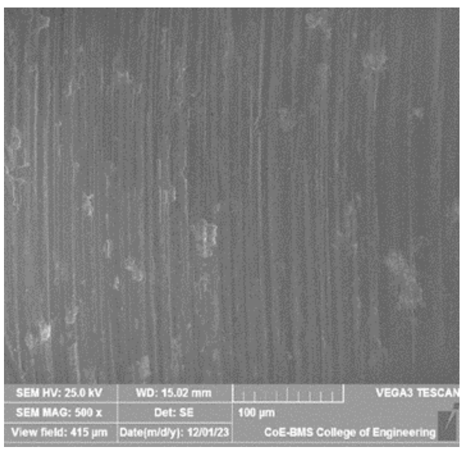


(b-3)



(b-4)

Fig. 9. (a) Non Nitrided (b) Nitrided SEM showing wear surface of Al-5%Ti-B composition reinforced with varying percentage (0,2,4and6%) of Al_2O_3

This smoother surface suggests reduced wear severity compared to the non-nitrided sample, highlighting the beneficial role of the nitrided layer in enhancing wear resistance. Additionally, the presence of reinforcement particles in the nitrided composite further contributes to its improved wear resistance.

5. Conclusion

The study on the mechanical and wear characterization of nitrided Al-5%Ti-B metal matrix composite reinforced with Al2O3 has provided valuable insights into the behavior and performance of this composite material. These Al-5%Ti-B with Al2O3 composites were synthesized by the liquid metallurgy technique i.e., stir casting method. Al-5%Ti-B with 2, 4 and 6 varying weight percentages of alumina particles were successfully synthesized by the stir casting method. The comprehensive analysis of mechanical properties and wear behavior, several key findings have been elucidated. The incorporation of Al2O3 reinforcement particles into the Al-5%Ti-B matrix has led to improved mechanical properties such as increased strength and hardness. It was noted that the hardness values increased with the increase in aluminum oxide content. This improvement can be credited to the reinforcing influence of the ceramic phase embedded within the metal matrix. The Al-5%Ti-B - alumina composites with nitriding exhibited more hardness and ultimate tensile strength as compared to the normal alumina particles reinforced composites.

Nitriding treatment has demonstrated a significant impact on the wear behavior of the composite material. The combination of nitriding treatment and Al2O3 reinforcement has shown synergistic effects in enhancing the wear resistance of the composite material. The nitrided layer, in conjunction with the reinforcing particles, has contributed to mitigating wear mechanisms such as abrasion, adhesion, and delamination, thereby improving the overall durability of the composite material. The results of this research carry practical significance for utilizing Al-5%Ti-B metal matrix composites reinforced with Al2O3 in industries where wear resistance holds paramount importance, including automotive, aerospace, and machinery sectors. The augmented mechanical attributes and wear resistance exhibited by the composite material render it a highly promising choice for components exposed to rigorous operational environments. The combined effect of nitriding process on the surface of the wear specimens and addition of the alumina particles resulted in the higher wear resistance as compared to the normal composites.

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