Tribological behaviour of TiB whisker reinforced AZ31 magnesium composites processed by multi directional forging

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Abstract:

The objective of this research is to determine the influence of multi-directional forging (MDF) on the wear characteristics of 5% titanium boride (TiB) whiskers reinforced AZ31 magnesium alloy composites. Magnesium-based metal matrix composites were prepared via a liquid metallurgy process known as stir casting. During the wear test, a pin-on-disc wear tester was used to evaluate the wear rate. The samples were made to wear against a steel counter disc rotated at several speeds of 1.25, 1.56, and 1.87 meters per second. A sliding distance of 2000 m with various loads of 30, 40, 50 and 60 N was used for the test. The test specimen was examined using scanning electron microscopy (SEM) to study the worn surfaces. Investigations revealed that MDF composites failed less often compared to non-MDF materials. Observations indicate that wear rates for both the unreinforced alloy and the composite samples rise with an increase in the levied load and a reduction in speed. The samples made of composite materials showed wear mechanism to be abrasion at low loads, whereas at high loads, the wear loss occurred mainly due to delamination.

Keywords: *AZ31 alloy, Titanium boride, Composites, Multi directional forging*.

1. Introduction:

Studies have shown that metal alloys as well as ceramic composites can exhibit significantly enhanced properties such as strength and elongation when subjected to specific plastic deformation techniques including extrusion, rolling, and forging [1, 2]. Abundant investigations have been conducted to observe the effects of severe plastic deformation (SPD) on grain refinement in various alloys and in composites too. Research by Miura et al. [3] found that MDF had a significant impact on the microstructure of alloys, resulting in the formation of extremely fine grains, with an average of 2 µm size after three passes, and 1 µm after six passes. With the increase in the number of passes, the primary planar structure was found to moderately transform into a spheroidal structure, dispersing regularly and thereby significantly improving strength and elongation aspects.

Purcek et al. [4] examined the influence of equal channel angular pressing process (ECAP) on the tribological and mechanical characteristics of Zn-40Al-2Cu-2Si alloys. Studies revealed that the samples elongation percentage rose from 0.8% to 14.4% following ECAP process, with no effect on its strength. The samples that were modified showed enhanced resistance to wear when sliding over longer distances due to changes in their morphology and the alloy's heightened impact resistance and ductility.

The multi directional forging (MDF) process is regarded as a very capable severe plastic deformation (SPD) technique. It is used extensively to obtain ultra-fine grains in alloys. This process provides several advantages such as cost-effectiveness and ease of execution, as it does not call for complex machines as in most of the other SPD processes [5]. Furthermore, it is possible to work on large sized samples by exposing them to extreme stress with minimum variations to dimensions. In the MDF process, the specimens are compressed repeatedly across their entire surface. Such a compressive process results in decrease in grain size and improved mechanical behavior.

A frequently encountered industrial problem leading to part and assembly replacement is wear of components. Heavy consumption of power and oil coupled with replacement of components on a regular basis can lead to decreased efficacy in operational equipment, even if the damage is not usually severe [6,7]. Machines that can operate reliably in tough environments, such as increased friction, higher load requirements, and higher temperatures, are highly sought after today.

Significant wear issues occur in industrial settings involving bearings, gears, conveyor rollers and in machinery used for slurry pumps in waste tanks and elsewhere, especially in extreme temperature conditions. In various contexts, including metalworking processes and engines, sliding wear signifies considerable material loss procedure. Wear at high-temperature wear coupled with oxidation demonstrates aggressive action in controlling material loss during sliding.

Hence, it is crucial to assess and comprehend the wear characteristics of materials. This study found that the impact of temperature combined with stress had a greater effect on the microstructural development of the AZ31 alloy at 300°C. Research was carried out to study the influence of the MDF process and its relationship with wear characteristics. The findings were able to offer crucial information for streamlining and also provide foundational awareness for fine-tuning the processing parameters for the practical production of magnesium alloys. The aim of this research is to investigate the effect of the MDF process on the wear and hardness characteristics of AZ31/TiB manufactured via stir casting and subjected to MDF techniques as well as the influence of particle dispersion.

2. Methodology:

The prime aim of this research is to assess the influence of multidirectional forging and TiB whisker reinforcement on the surface characteristics, particularly, the wear resistance of the composite samples produced from the AZ31 alloy. The AZ31 alloy was selected as the base matrix due to its improved mechanical properties, high load-bearing capacity, and reduced wear rate. Several researchers who have worked on magnesium AZ31 alloy have reported their widespread usage in the casting industry due to their highly desirable properties like high mechanical properties, dimensional stability, excellent machinability, good damping characteristics, and recyclability [8-10]. The elements of the alloy used in this investigation are detailed in Table 1 and are in accordance with ASTM B90 specifications. TiB whiskers were used as reinforcement to make composite samples. Various advantages of whisker reinforcement include cost savings, the ease of accessing reinforcement, and the usage of cost effective, conventional practices for fabrication of the samples.

AZ31 alloy composite samples reinforced with TiB whiskers were fabricated via the liquid metallurgy technique of stir casting method. Five percent TiB whiskers by weight preheated to 300°C were added to the AZ31 alloy in its liquid state. This study did not use the option of multiple reinforcing materials and testing a hybrid composite, but investigated a single reinforcement for the surface properties, particularly the wear behavior of composites.

The melt was thoroughly mixed for 15 minutes at a speed of 600 rpm by a ceramic coated impeller to ensure the reinforcement was completely dispersed throughout the alloy matrix. The molten mixture was then poured into metal molds of diameter 25 mm and height of 40 mm. The castings were machined to their final dimensions after sufficient time had elapsed for them to cool down to room temperature.

The cast specimens were later heated to 300°C and exposed to multiple passes of the MDF process with split dies. In total, the test samples were subjected to 6 passes, ultimately accumulating a total strain of 1.10.

The samples were then treated by heating the furnace to the required temperature for 20 minutes. During each pass, a strain of 0.19 was applied on the samples by pressing them downwards. The formula used for arriving at equivalent strain is found elsewhere [8]. The test samples were then prepared for the subsequent passes by rotating them to the required axis and forging it with the same strain as in the preceding passes. A schematic diagram of the MDF process has been showcased in multiple publications [9–11] and all the three dimensions of the samples were elongated in order to achieve one full cycle.

The ASTM G99 Guidelines were implemented to assess the wear behavior of the samples by utilizing a pin-on-disc wear tester under dry conditions. The dimension of the samples measured 12 mm in diameter and 16 mm in length. Prior to the test, the samples and the disc were subjected to acetone treatment to eradicate presence of grease, oil, dust, or dirt. The specimen was made to rub against a counter disc made of EN 32 steel. The disc's hardness was rated at 68 HRc. The loads were chosen in intervals of 10 Newton, spanning from 30 to 60 Newton.

3. Results and Discussions:

The results of the wear tests conducted are visually represented in Figures 1 (a) through (c), which depict the wear rate under different loads and speeds used in the study. The graphs indicate that the rate of wear for the composites under non-MDF conditions was considerably much less than found in the unreinforced alloy. In comparison, the composite with MDF disclosed a wear rate substantially lower than that of samples without MDF. The relationship between the wear rate and load applied is almost linear, as indicated by the Archard type correlation [12].

Images taken by a SEM microscope are provided in fig.2 a-d which show worn-out composite surfaces under varying conditions of loads of (a) 30 N, (b) 40 N, (c) 50 N, and (d) 60 N and sliding speed of 1.56 m/s. The SEM micrographs indicate that the abrasion wear takes place at lower loads while delamination wear occurs at higher loads. The SEM images also show that cracks are present beneath the surface, which eventually spread and lead to delamination wear. High loads levied on worn surfaces cause considerable damage and severe plastic deformation, leading to delamination of the surface layers. The results showed that the unreinforced alloy samples exhibited a comparable pattern to the composite specimens. The wear-mechanism map presented by Liu et al. [13] is advantageous in this scenario. The wear pattern map suggests that a constant wear rate drop signifies lower observed wear rates when increasing sliding speed at a constant load within this speed and load range. Oxidation of the base alloy is enhanced at higher interfacial temperatures, producing a thicker oxide layer which protects the sliding surface and reduces wear rates.

Shifting of the wear mechanism from abrasion to delamination led to substantial rise in wear severity under the levied load. The extent of wear was dependent on the quantum of reinforcement used, in spite of adhesion-abrasion being a major wear mechanism for all tribo-systems. The shift from micro-cutting, ploughing, and wedge formation to delamination induced by particle fracture is likely the major cause of the increased wear rate at higher loads. At higher loads, delamination wear seems to be the predominant wear mechanism, with wear rates that are notably greater.

The composite also revealed a lower wear rate compared to the unreinforced alloy. When the composite samples slide, there is deposition of TiB on the opposite surface, leading to enhanced wear resistance. Actually, the TiB whiskers experience shearing during wear process, after which the removed layers bond to the metal surface with their major axes aligned parallel to the direction of sliding, forming a slender film in between the rubbing surfaces. The TiB film exhibits minimal elasticity and can withstand stress at low load levels without experiencing fracture or plastic deformation.

Researchers [14,15] have demonstrated categorically that by averting permanent deformation of the material at the contact interface, wear along with surface damage can be significantly reduced. The TiB film formed in the composites is highly effective in reducing wear, as it can withstand higher stress levels without experiencing plastic deformation or cracking. The implication is that TiB whiskers contribute to reduced wear rate of MMC materials depending on their capacity to stick to the sliding surface after being subjected to shearing action. Several key implications arise from the film's presence at the interface. It typically enlarges the contact area, modifies the contact pressure distribution, and reduces the contact pressure.

The contact stress field experiences a substantial change due to the difference between the elastic properties of the film and the substrate it is supported by. Under the specified loading conditions, the tensile stress in the film peaks immediately above the boundary between the film and the substrate, not at the film's surface. In situations like these, fractures can start to form beneath the surface as a direct result. The film produced on interlace exhibits a higher level of hardness, but it has lower fracture toughness. As a result, fracture and delamination are found to be the principal causes leading to failure.

It is reported [16] that a robust relation exists between the thickness of the flakes and the depth at which the subsurface cracks are observed. According to another study [17], a significant correlation existed between the thickness of the flakes and the depth at which subsurface cracks were observed. The TiB whiskers are found in the material close to the point where they come into contact.

Such an observation was previously noted in zinc alloy composites reinforced with SiC whiskers as well as Zn-A1-Si alloy with silicon acting as a hard primary phase. The principal load-bearing element in multicomponent systems is the hard silicon carbide reinforcement. In this combination, the AZ31 matrix alloy serves as a soft phase, whereas the TiB whiskers function as hard reinforcing component. Stress above a certain threshold can lead to the breakdown of reinforcing particles, which ultimately form a layer of crushed particles which function as a shielding barricade to prevent failure. Composites of AZ31 and TiB subsequently reveal boosted wear resistance compared to the AZ31 alloy.

Researchers have conducted experiments to determine the relationship between the material's wear performance and its fundamental characteristics, with the goal of pinpointing the property that has greatest impact on wear [18]. Several studies indicate that wear and friction, as measured by pin-on-disc devices, reliably relates with a variety of mechanical properties of the samples tested [19,20]. Surface hardness of the samples is a vital consideration when predicting the wear characteristics. The Archard wear equation emphasizes the importance of material hardness as a fundamental factor in wear, thereby emphasizing the close relationship between wear and hardness.

The information provided in the present study in the form of tables, graphs, and micrographs clearly demonstrates the effects of MDF. The use of MDF caused considerable enhancements in durability and resistance to wear of the composite samples.

Conclusion:

In this investigation, as-cast samples were subjected to a stipulated number of passes in the MDF process at 300°C utilising split dies. A total of six passes were carried out on the samples, resulting in a cumulative strain of 1.10. The samples were exposed to 300°C for 20 minutes to attain the necessary temperature uniformly throughout. During each pass, a strain equivalent of 0.19 was levied by pushing the sample downwards. In comparison with the unreinforced AZ31 alloy specimens, the TiB whisker composites displayed a decreased wear. The wear rate decreased as the TiB quantum was enhanced. As the applied load increases, the wear of both the unreinforced alloy and the composites increased, while the speed decreases. Low-load specimens showed abrasion wear, whereas delamination wear was the predominant wear mechanism under high loads. Examinations under heavy load of the composite specimens showed the existence of visible cracks underneath the surface, which developed as a result of strain and continued to grow during the wear process. The wear resistance of the composites increased steadily as the concentration of TiB was enhanced. The composites' wear behaviour was found to have been significantly impacted by the MDF process.

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Data availability: Data is available with the authors and will be made available if reasonable requests are made.

Declaration of conflicting interest: The authors declare that no conflict of interest exists.

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LIST OF CAPTIONS

Table 1: Composition of AZ31 alloy (Wt. %)

Aluminium	Zinc	Manganese	Magnesium
2.5 – 3.5	0.6 – 1.4	0.20	Remaining

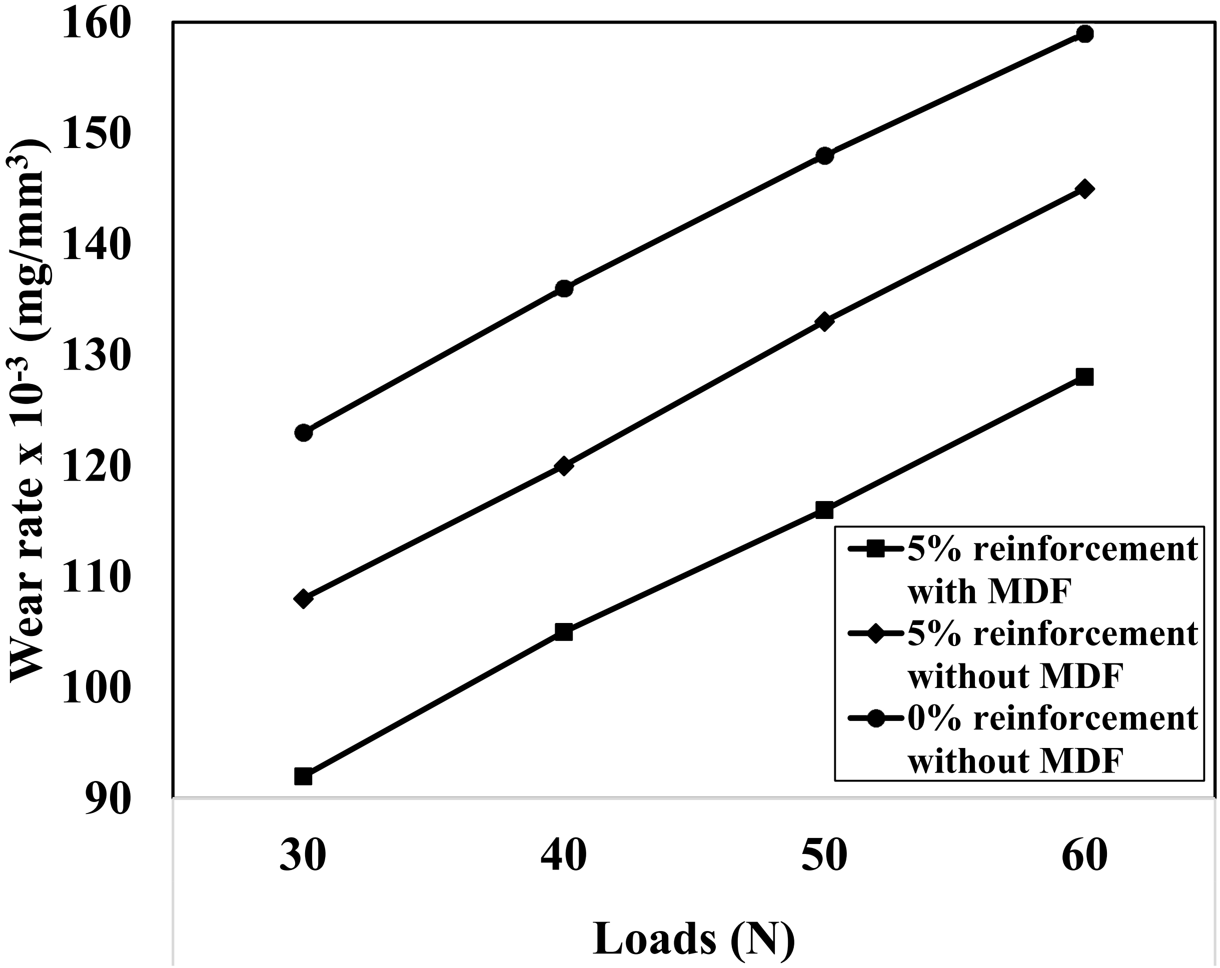

Fig 1a. Graph of wear rate v/s loads at sliding speed of 1.25 m/s

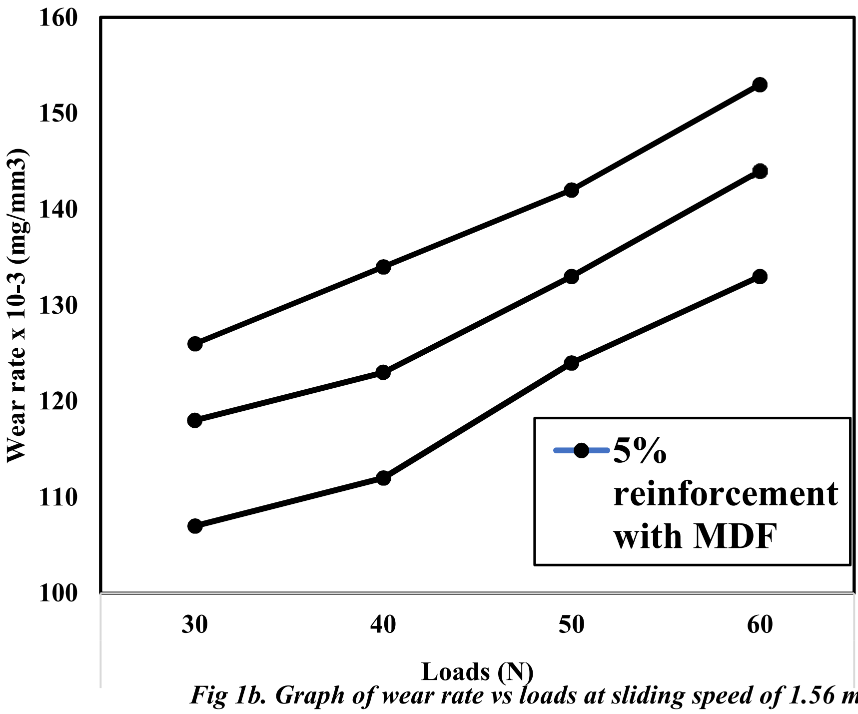

Fig 1b. Graph of wear rate vs loads at sliding speed of 1.56 m/s

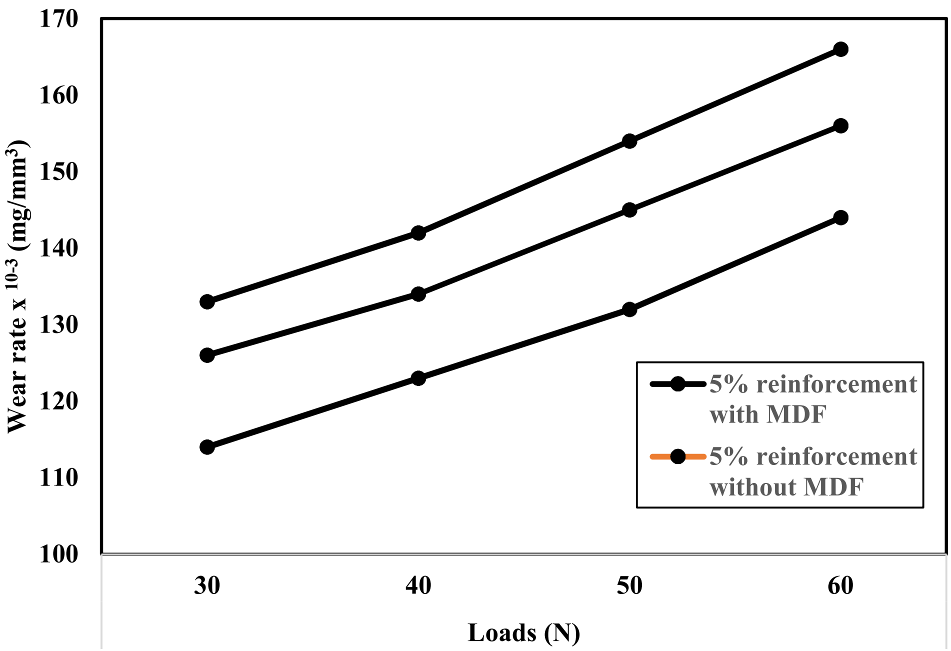

Fig 1c. Graph of wear rate v/s loads at sliding speed of 1.87 m/s

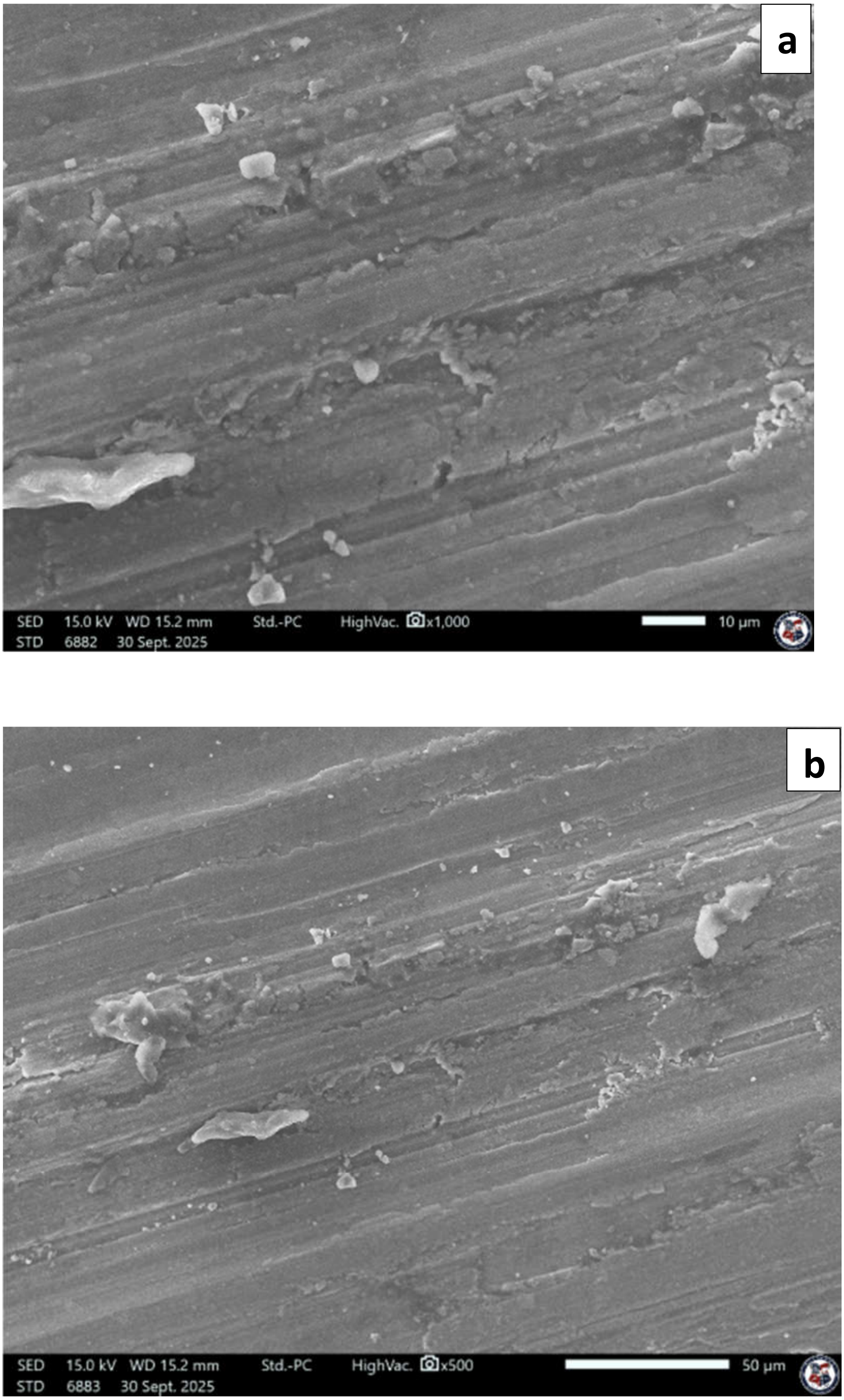

Figure 2: SEM micrographs showing worn out surfaces of composites at sliding speed of 1.56 m/s and loads of (a) 30 N (b) 40 N (c) 50 N, and (d) 60 N.

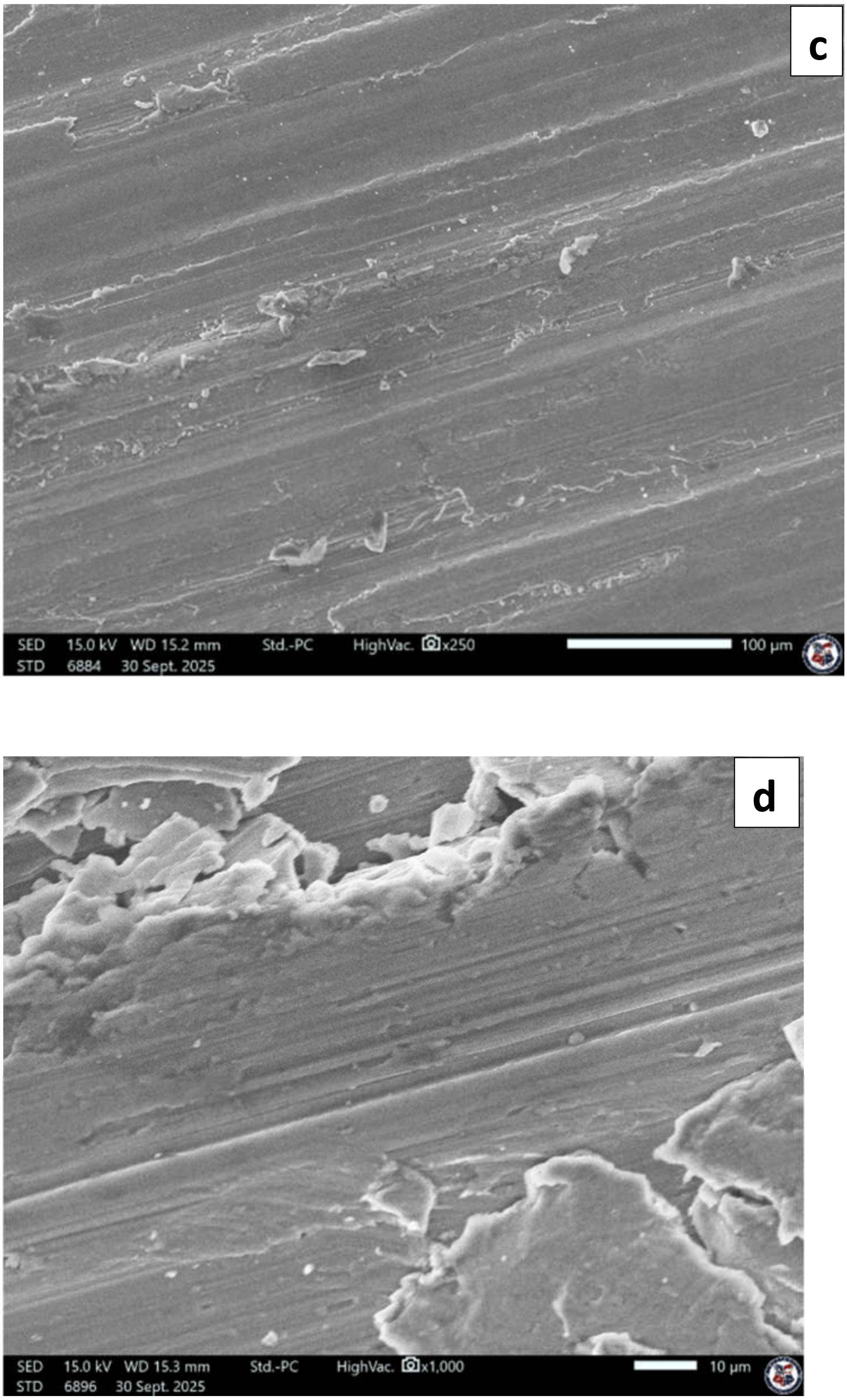

Figure 2: SEM micrographs showing worn out surfaces of composites at sliding speed of 1.56 m/s and loads of (a) 30 N (b) 40 N (c) 50 N, and (d) 60 N.