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# Investigations on the tribological behavior of wire arc additively manufactured AA7075-nano-TiC metal matrix composite

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KEYWORDS

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Coefficient of friction
Worn surface analysis

ABSTRACT

Aluminium alloy 7075 matrix composite, reinforced with nano-TiC, is effectively manufactured by using wire arc additive manufacturing technique with an objective to investigate tribological behavior. In-depth metallurgical analysis of the produced AA7075-nano-TiC metal matrix composite confirmed the presence and homogeneous distribution of nano-TiC reinforcement particles throughout the matrix. Investigations using standard pin-on-disc wear tests emphasized that the incorporation of nano-TiC improved the wear resistance by exhibiting the lowest wear rate at lower loads and higher sliding speeds – while at higher loads and higher sliding speeds, the wear resistance declined with an increased wear rate, up to 3.33 times. Further, the coefficient of friction was also observed to be the highest at lower load and higher sliding speeds – while at higher loads and higher sliding speeds the same was found to be decreased by 1.34 times. The worn surface analysis corresponding to maximum and minimum wear scenario, designated the manifestation of different wear mechanisms like abrasive, oxidational, delamination, and thermal softening during maximum wear scenario, and adhesive wear prevailing at minimum wear scenario. Overall, the tribological performance was found to be significantly influenced by load and sliding velocity, demonstrating that Nano-TiC reinforcement effectively enhances wear resistance and friction behavior across diverse conditions.

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## 1.0 INTRODUCTION

Additive manufacturing (AM) has appeared as a critical technology within the industrial domain for the fabrication of components utilized in automotive and aerospace structural applications (Egon et al., 2024) This advanced technology facilitates the creation of complex internal architectures, resulting in considerable weight reduction while maintaining the structural integrity. Wire Arc Additive Manufacturing constitutes a technological innovation in the production of single-wall structures and fabricate components of substantial scale (Kumar et al., 2024). The WAAM technique (Gao et al., 2024) emphasizes a thorough scrutiny of arc morphology to optimize cladding layer formation and establish parameters for stabilized arc output and consistent metal coating also highlighting its advantages in deposition efficiency and cost reduction. Further investigations into enhancing the mechanical properties and structural integrity of AA7075 due to its farfetched strength-to-weight ratio (Rahma et al., 2018; Yipeng et al., 2024). Optimizing single-bead geometry is critical in various manufacturing processes to ensure high-quality defect-free products (Hanif et al., 2023). Parvaresh et al., 2021 supervised investigation on directional mechanical and wear characteristics of specimens developed through WAAM, highlighting the analysis of both as-deposited and intermediate-layer cold-worked samples. (Bharat Kumar and Anandakrishnan, 2020) has done the analysis of weld bead width's effect relative to input parameters has been successfully implemented for both thick and thin wall construction geometries.

Aluminum alloy 7075 is used in various industrial claims for its outstanding wear analysis mechanical characteristics, which encompass a superior strength-to-weight ratio.(Ali et al., 2021) However, the wear resistance of AA7075 is relatively less and limiting its application in thermodynamic systems, MMCs, are particularly those formulated from aluminum, are increasingly preferred because of their exceptional mechanical properties and wear resistance. Investigations on tribological behavior are essential in various industries, aiding in material optimization, reducing maintenance costs, and extending component lifespan (Manjunath et al., 2020). Wear studies are crucial and important in elucidating the deterioration of materials and surfaces as a consequence of mechanical, thermal, or chemical interactions. Investigations on rate of wear and the coefficient of friction were carried out employing a pin-on-disk testing apparatus (Akilan and Mahendiran, 2021). Additionally, the importance of the integration of reinforcing materials, on wear characteristics have been studied by many researchers (Sakthi Balan et al., 2020; Patel et al., 2022; Samuel. S et al., 2020; Chigilipalli and Veeramani, 2022). Some authors (Zuo et al., 2019; Bai et al., 2021) investigated ceramic nanoparticle-reinforced MMCs for improved AA7075 tribological performance. Titanium carbide improves tribological properties by reducing wear and friction in advanced applications. The wear performance of AA7075-TiC metal matrix composites has been extensively studied to recognize the influence of various factors on wear resistance. The benefits associated with AA7075-TiC composites and WAAM are evident, obstacles persist in refining the manufacturing process to attain considerable material characteristics and reduce defects, porosity and residual stress (Scaria et al., 2022).

The present study searches for the fabrication of AA7075 alloy reinforced with TiC particles using wire arc additive manufacturing, a technique known for its high deposition efficiency. The behavior of the MMCs was experimentally assessed through pin-on-disc testing under varying loads and sliding velocities along with sliding distance. Optimal wear-resistant parameters were determined, and the corresponding key wear mechanisms were identified through surface morphology consideration.

## 2.0 EXPERIMENTAL DETAILS

### 2.1 Experimental Setup and Material Selection

Wire Arc Additive Manufacturing process to execute single-pass multilayer deposition with a continuous supply of nano-treated (NT) AA7075-TiC filler wire of 1.2 mm diameter, containing 1 wt. % of Titanium Carbide, procured from M/S Metal Li, 1601 Ruhland Avenue Manhattan Beach, 90266, USA was selected for deposition and annealed AA7075 plate with 20mm thickness was selected as substrate. The findings of scanning electron microscope with energy-dispersive spectroscopy assessment of NT AA7075-TiC filler wire are shown in Figure 1, that depict the homogeneous presence of the essential elements and TiC particles. Chemical composition of the wire is also verified using SEM and the same is indicated in Table 1.

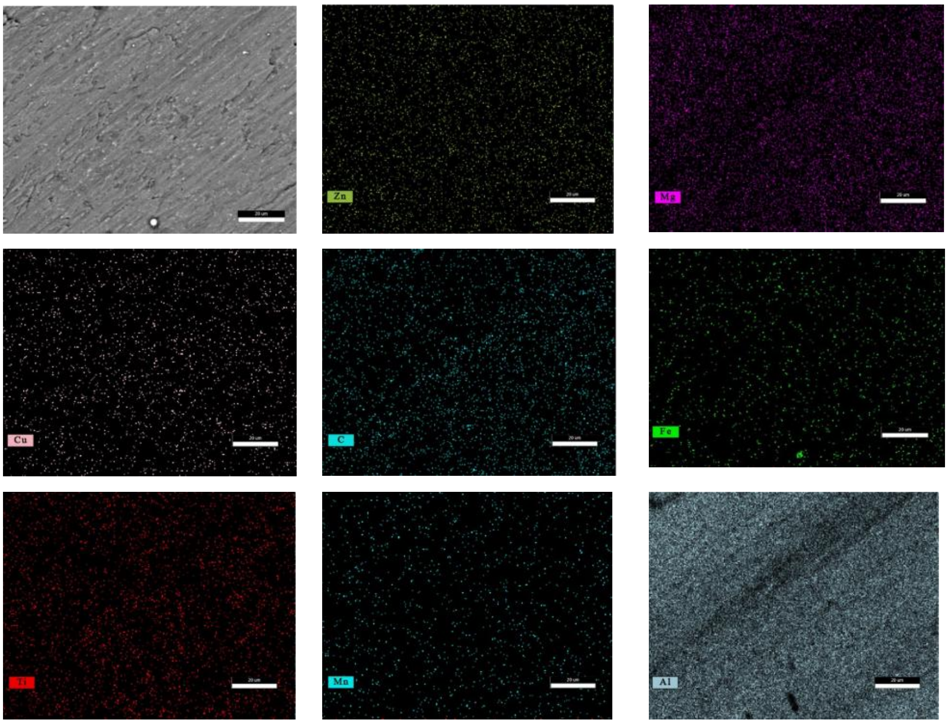


Figure 1: Scanning electron microscopic images and elemental analysis of NT AA7075-TiC filler wire.

Table 1: Chemical composition of NT AA 7075-TiC filler material.

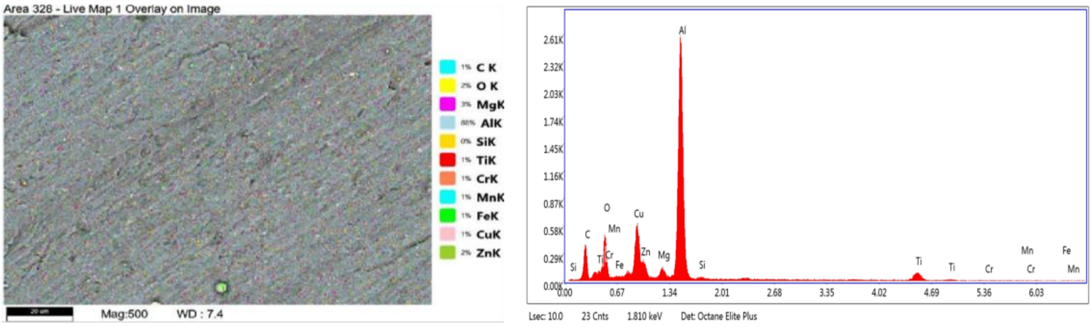
| Materials | Zn | Mg | Cr | Cu | Si | Fe | Mn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| NT 7075-TiC | 5.3 | 2-6 | 0.22 | 1.7 | 0.4 | 0.5 | 0.03 | 0.2 | Bal. |

### 2.2 Fabrication Details

To mitigate the emergence of oxide layers on the annealed AA7075 substrate, it underwent a process of grinding, cleaning, and polishing prior to the WAAM procedure. During assessment of deposition factors through experimental trials, the criteria for achieving a smooth and continuous surface finish devoid of spatter and porosity in the deposited beads were considered. In this study, wire feeding rate of 8 m/min, welding speed of 150 mm/min, Arc length correction –5 % setting along with argon as the shielding gas were used, based on the trials. AA7075 substrate with dimensions length of 300 mm, width of 120 mm and thickness of 20 mm is used throughout the deposition process. The substrate, characterized by a thickness of 20 mm, was deemed appropriate, as there was an absence of distortion observed during the experimental procedure. The resultant deposited wall had a final thickness of 12 mm, length of 160 mm, and a deposition height of 35 mm. Eighteen layers were deposited with an average height of 1.94 mm attributed to each individual bead. A post-weld radiography examination was performed to ensure that it was free from defects.

### 2.3 Characterization of WAAMed AA7075-Nano-TiC Metal Matrix Composite

Wire electric discharge machining approach was utilized to get the test sample from deposited wall for metallurgic investigation. The cross-section area of the deposited wall was analyzed by sectioning the test samples parallel to the deposition orientation. To accomplish an enhanced surface texture, the samples underwent a polishing process involving abrasive paper, with grit size range from 320 to 2500 grit size followed by an alumina polishing and colloidal silica polishing to attain mirror-like finish. Subsequently, the test samples were etched for 10–20 seconds using Keller's etchant. SEM with EDS and elemental diagramming, as depicted in Figure 2, was performed to verify the presence, size, distribution, and morphology of TiC particles. The corresponding spectrum in Figure 2 confirms the retention of all the essential elements of the metal matrix composite.



(a) (b)

Figure 2: (a) Scanning electron microscopic image with elemental mapping & (b) energy dispersive spectroscopy, of the WAAMed AA7075-Nano-TiC metal matrix composite.

### 2.4 Wear Testing

Specimens for testing were extracted from AA7075–nano–TiC metal matrix composite fabricated via Wire Arc Additive Manufacturing in alignment with ASTM G99 – Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus, utilizing a wire electric discharge machining process. The diagram of the cylindrical test samples, which are 25 mm length and 4 mm in diameter, obtained from the deposited wall structure is depicted in Figure 3. This study examined the wear behavior of the vertically deposited material. Prior to the wear tests, the tested samples undergone surface polishing to achieve mirror–like surface finish with roughness below 0.8 micrometer, followed by cleaning with acetone. A pin-on-disk tribometer was utilized to accomplish tribological tests, where load, sliding velocity and distance were measured to determine wear lost and friction coefficient. The experimental procedure systematically explored three loads and three velocities, while maintaining a constant 1,500 m sliding distance. The control parameters are provided in Table 2. The samples were prepared to ensure full pin-to-disc surface contact.

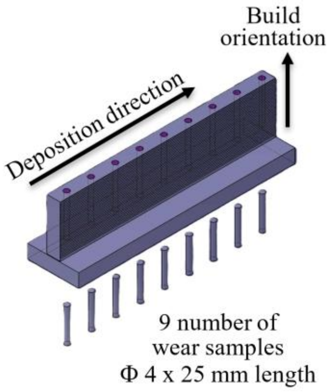


Figure 3: Schematic representation of the extraction of wear specimen.

Table 2: Experimental Control elements and their levels.

| Control elements | Units | Levels | | |
|---|---|---|---|---|
| | | **1** | **2** | **3** |
| Load | N | 2 | 4 | 6 |
| Sliding Velocity | m/s | 1 | 2 | 3 |
| Sliding Distance | m | 1,500 | 1,500 | 1,500 |

A comprehensive data-acquisition system was utilized to precisely measure and record the frictional force experienced throughout the duration of the wear tests performed under a diverse range of experimental conditions. The coefficient of friction was then estimated established on the calculated relationship between the measured frictional force and the normal load. An EN8 steel disc, exhibiting a hardness of 61 HRC and measuring 100 mm in diameter, served as the counter material for wear experiments. The experimental protocol involved positioning the test sample's surface against the counterpart material, ensuring the application of a compressive load in vertical direction. The worn-out surface was analyzed by scanning electron microscopy and elemental mapping by using energy-dispersive X-ray spectroscopy. Consequently, a comparative analysis was conducted between the surfaces exhibiting the least and most wear in relation to WAAM-processed alloys. A high-precision digital analytical balance with a readability of 0.0001 g was employed to measure the test samples' weights beforehand and after the experiment, enabling the quantification of the abrasive wear loss. Estimated wear rate, $k$ in (mm$^3$/m), was determined using Equation (1).

$$Wear\ rate\ (k) = \left(\frac{m_1 - m_2}{\rho\ \times S}\right)\ mm^3/m \tag{1}$$

where the masses (g) of the pin specimens before and after the experiment were denoted as $m_1$ and $m_2$ respectively. $\rho$ denotes the density (g/mm$^3$) of the AA7075-nano-TiC metal matrix composite specimens. The frictional force (N) was directly determined using a frictional force monitor and the coefficient of friction (COF) was calculated using Equation (2).

$$Coefficient\ of\ friction = \frac{Frictional\ Force}{Load} \tag{2}$$

## 3.0 RESULTS AND DISCUSSION

### 3.1 Wear Assessment

The pin-on-disc wear test findings for WAAMed AA7075-nano-TiC composite, underneath varied load, sliding velocity and gliding distance conditions, are summarized in Table 3.

**Table 3:** Experimental outcome of Pin-on-disk wear tests conducted on WAAMed AA7075-Nano-TiC MMC.

| Sl. No. | Load (N) | Sliding Velocity (m/s) | Wear rate (mm³/m) | Coefficient of friction |
|---|---|---|---|---|
| 1 | 2 | 1 | 0.000561 | 0.163 |
| 2 | 2 | 2 | 0.001435 | 0.192 |
| 3 | 2 | 3 | 0.005122 | 0.382 |
| 4 | 4 | 1 | 0.002503 | 0.283 |
| 5 | 4 | 2 | 0.002131 | 0.296 |
| 6 | 4 | 3 | 0.013869 | 0.342 |
| 7 | 6 | 1 | 0.002226 | 0.165 |
| 8 | 6 | 2 | 0.006884 | 0.174 |
| 9 | 6 | 3 | 0.017074 | 0.285 |

Among the various wear parameters, the lowest wear of 0.000561 mm$^3$/m with a specific wear rate of 0.000561 mm$^3$/m and the lowest coefficient friction of 0.163 was obtained for the amalgamation of 2 N of load and 1 m/s of sliding velocity and the extreme wear of 0.017074 mm$^3$/m with a specific wear rate of 0.017074 mm$^3$/m and the highest coefficient of friction of 0.285 was obtained for the combination of 6 N of load and 3 m/s of sliding velocity.

### 3.2 Influence of Wear Parameters on Wear rate

Figures 4(a) to 4(c) illustrate the impression of various experimental wear parameters of WAAMed AA7075-nano-TiC metal matrix composite with different load of 2, 4 and 6 N, sliding velocities of 1, 2, and 3 meter per second, for a sliding distance of 1,500 m. The wear behavior of WAAMed AA7075-nano-TiC composite is significantly affected by factors such as load, sliding velocity, and gliding distance. Research has indicated that TiC enhances the tribological properties of AA7075, leading to reduced wear rates and improved friction coefficients under various operating conditions. The greater influence of Increased applied load results in higher wear rates owing to the greater contact pressure, which exacerbates material removal. This is in line with studies showing that wear loss is directly proportionate to the applied load, with significant increases observed at higher loads, which is similar to the findings of (Lingaraju et al., 2022). In addition, the Effect of higher sliding velocities generally leads to increased wear rates; however, the presence of TiC slightly mitigates this effect. The optimal sliding velocity for minimal wear was approximately 2 m/s, balancing frictional heat and material removal (Lingaraju et al., 2022). The impact of the extended sliding distances contributed to the cumulative wear as the wear rate increased as the distance increased. This is also in agreement with research indicating that wear behavior stabilizes after a certain distance, suggesting a wear-in period (Gobikannn et al., 2022). Conversely, although TiC reinforcement improves wear resistance, excessive loading or sliding conditions can still lead to significant wear, highlighting the need for careful optimization of the operational parameters to maximize the benefits of these composites.

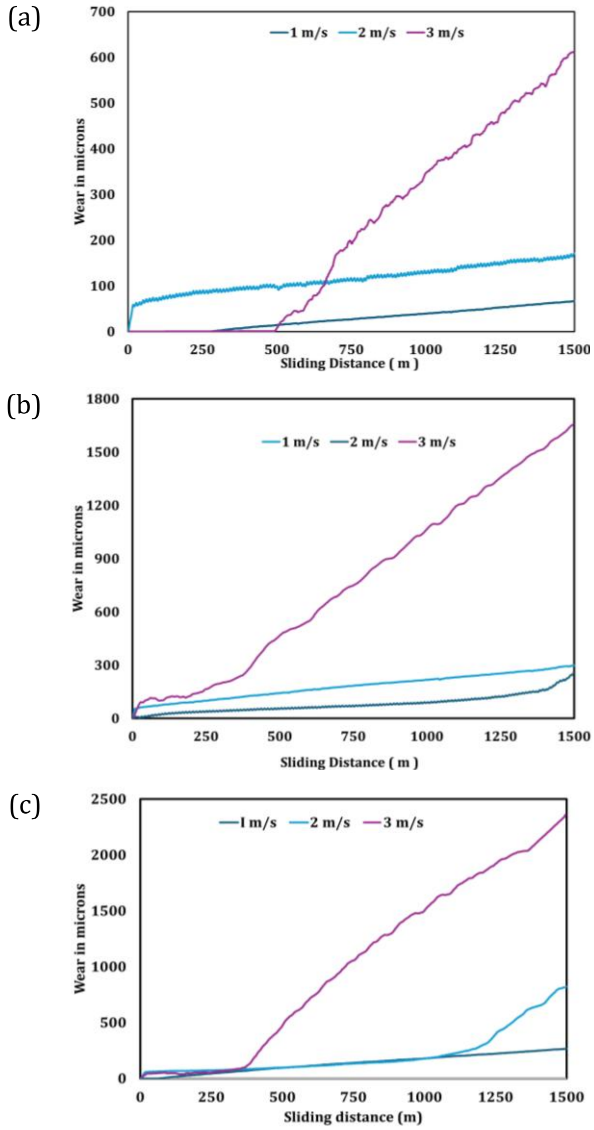


Figure 4: Variation of wear with respect to sliding distance for different sliding velocities, corresponding to (a) 2 N (b) 4 N and (c) 6 N load.

### 3.3 Effect of Wear Parameters on Coefficient of Friction

Figures 5(a), 5(b) and 5(c) depict the effects on experimental parameters on the friction coefficient of AA7075-nano-TiC composite under altering loads, velocities and distances. The friction coefficient behavior in AA7075-nano-TiC MMC reinforced with TiC is notably affected by load, sliding velocity, and distance. Research indicates that these parameters interact to affect wear rates and friction coefficients, which are critical for significance in aerospace and automotive industries. An increased applied load (2, 4 and 6 N) correlated with higher wear rates and lower coefficients of friction. This trend is consistent across various studies, indicating that higher loads exacerbate wear due to the augmented contact pressure (Ramakoteswara et al., 2016). The sliding velocity also plays a crucial role: higher velocities (up to 3 m/s) can lead to increased wear rates. However, the specific impact varies depending on composition and structure. The wear behavior is further influenced by the sliding distance, with longer distances (up to 1,500 m) typically resulting in increased wear. The wear rate tended to stabilize after a certain distance, indicating a wear-in period for the composite. Although these studies highlighted the detrimental effects of increased load and sliding distance on wear, it may be essential to consider that optimizing these parameters can lead to improved performance in specific applications. Balancing the load, velocity, and distance is crucial for maximizing the lifespan and efficiency of the AA7075-nano-TiC composite. TiC reinforcement improves wear resistance, and excessive loading or sliding conditions can still lead to significant wear, highlighting the need for careful optimization of the operational parameters to maximize the benefits of these composites.

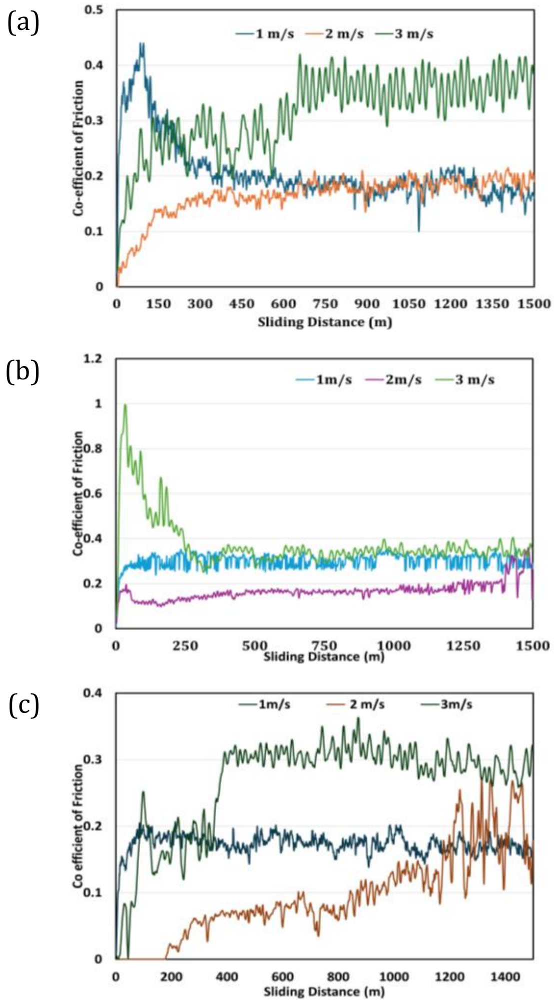
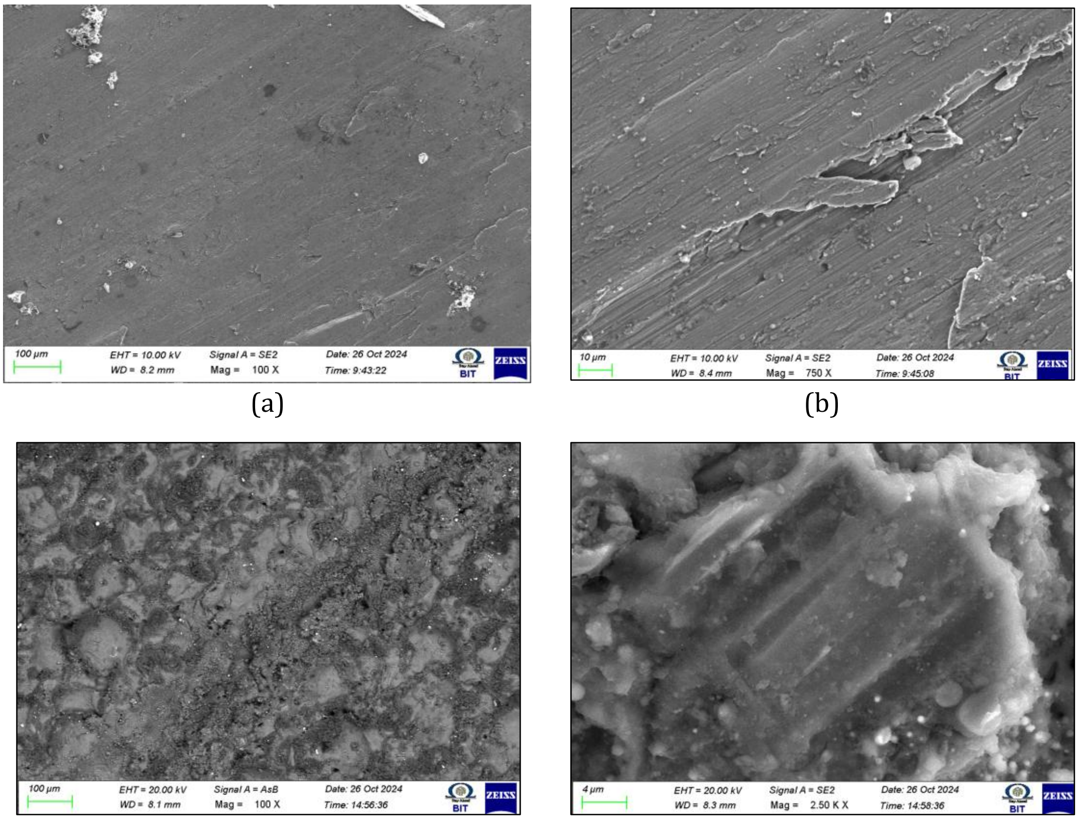


Figure 5: Variation of Coefficient of friction with respect to sliding distance for different sliding velocities, corresponding to (a) 2 N (b) 4 N and (c) 6 N load.

### 3.4 Worn Surface Analysis

After the culmination of the wear evaluation, the termini of the pins were transversely bisected and examined by using SEM to explore the wear mechanisms involved in WAAMed AA7075-nano-TiC MMC. The deteriorated surfaces of the pins were linked to the conditions leading to peak wear. (6 N of load and 3 m/s of sliding velocity) and minimum wear (2 N of load and 3 m/s of sliding velocity) are shown in Figures 6(a) and 6(b), and Figures 6(c) and 6(d) respectively.

Figure 6(a) indicates that the worned surface of pin with maximum wear scenario shows evidence of multiple scratches along with sliding direction, plough and crack and further fractured particles, which clearly evident that the mechanism of delamination and oxidation in line with observed morphologies on wear mechanism by (Ramakoteswara et al., 2016). Appropriate magnification has been chosen based on identification wear mechanisms on test samples. Figure 6(b) displays the buildup material at the pin contact surface area due to the extra of smeared material on the wear surface. A layer of an accumulation of peeled material is mainly attributed to easing of material followed by scooping action indicates that the evidence of thermal softening of MMCs. Figure 6(c) indicates that the worned surface of wear pin for minimum wear scenario with the micro crack with the multiple orientation, craters, debris and plastic deformed particles for the process of adhesion. Figure 6(d) displays the adhesion mechanism with stickiness and transfer of the composite material.



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

Figure 6: Worn surface of WAAMed AA7075-nano-TiC metal matrix composite corresponding to (a) maximum wear scenario (b) magnified view for maximum wear (c) minimum wear scenario (d) magnified view for minimum wear.

## 4.0 CONCLUSION

The present study demonstrates the successful fabrication of AA7075-nano-TiC composite utilizing the wire arc additive manufacturing process. Microstructural characterization and tribological analysis revealed that the WAAM-produced AA7075-nano-TiC composite exhibited homogeneous distributed of the reinforcement particles and elements. The integration of nanoscale titanium carbide particulates has improved tribological performance. The wear rate was the lowest at lower load and higher sliding speed, whereas it was 3.33 times more severe at higher load and higher sliding speed. The Coefficient of friction was the highest at lower load and higher sliding speed, whereas it was 1.34 times less at higher load and higher sliding speed. Under high wear conditions, the dominant wear mechanisms included abrasion, oxidation, delamination, and thermal softening, whereas adhesive wear mechanisms were prevalent under conditions of lowest wear rates. The tribological performance of WAAMed AA7075-nano-TiC composite is strongly affected by operational parameters such as load and sliding velocity. Empirical evidence indicates that the addition of TiC reinforcement substantially improves wear resistance and friction behavior across a range of operational conditions.

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