

Effect of MXene Reinforcement on The Strength, Microstructure, and Wear Performance of Copper Alloys

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Abstract

This study investigates the influence of MXene (Mx) addition into copper (Cu) matrix on their microstructural characteristics, mechanical properties, and wear resistance. Samples with varying Mx contents (0%, 0.5%, 1%, 1.5%, and 2% by weight) were synthesized and systematically analyzed using several advanced characterization techniques. SEM images reveal that MXene addition leads to a progressive refinement in the microstructure, showing denser and more uniform grain distributions with increased MXene content. Optical microscopy supports these findings, illustrating a clear transition from coarse, irregular grains in pure Cu to finer, well-defined grains in the MXene-doped composites. 3D profilometry data further corroborates these observations, showcasing smoother surface topographies as MXene content increases, indicative of enhanced surface homogeneity. Mechanical testing results indicate a substantial improvement in both density and hardness of the composites with MXene incorporation. Specifically, hardness values significantly increase from 24.17 VHN in pure Cu to 51.27 VHN in the 2% MXene composite, while density measurements also show a consistent upward trend. Additionally, wear test results demonstrate improved wear resistance with higher MXene content, suggesting that MXene effectively enhances the durability of copper composites under abrasive conditions.

Keywords: Metal alloys; Cu; MXene; tribology.

1. Introduction

Copper metals are useful in many industrial settings because they are strong, can carry electricity, and keep heat in. To meet the needs of current engineering applications, their tribological performance often needs to be improved, especially when they are used in tough conditions[1,2]. A lot of people are very interested in new materials like MXenes to deal with this. The name for two-dimensional transition metal carbides and nitrides that have great mechanical, electrical, and tribological qualities is MXenes[3]. Because of this, they are a good choice for making things stronger. Many researchers are interested in adding MXenes to copper structures because it might improve the microstructural properties, mechanical performance, and wear resistance of copper-based alloys. MXenes are two-dimensional transition metal carbides and nitrides with special qualities like being very resistant to wear, being flexible, and having high conductivity. Because of how they are made, they are good choices for strengthening metal matrices[4].

The problem with making MXene-reinforced copper composites is getting the MXene particles to mix well with the copper matrix and let the copper get wet easily. According to early research, the functional groups on the surface of pure MXene crystals stop them from mixing properly with copper. MXenes (Ni-MXene), on the other hand, have better mechanical properties because they can wet and bond with the copper matrix better[5]. The better wettability makes it easier for the MXene particles to spread out. This makes the mix stronger and more flexible[6].

Researchers are interested in the mechanical and tribological qualities of copper composites that are reinforced with MXene. Ti3C2 nanosheets and other MXenes have shown a lot of promise as lubricant nanofillers. When mixed with copper frameworks, these nanosheets greatly lower the rates of friction and wear compared to their MXene-free counterparts. They are good at improving the tribological properties of metal matrix composites[7,8]. During wear studies, a useful tribolayer forms, which makes MXene-reinforced composites more resistant to wear and very durable when they're moving. How the MXene particles are arranged and spread out in the copper matrix also has a big effect on how resistant the metal is to wear. According to the results of the study, even a small amount of MXene can change wear resistance in different ways. How the MXene particles are arranged in the direction of moving affects how they wear[9,10]. This uneven wear resistance shows how important it is to control the microstructural direction of MXene particles during production. This work shows how MXene-doped copper alloys change their surface and how well they wear under different situations. The wear efficiency, mechanical properties, and changes in the microstructure are all looked at. The present results will help researchers to make new materials in this field of investigation that work better in applications like electronics, cars, and planes.

2. Experimental Section

2.1. Materials

Copper powder with 99.7% purity was procured from LOBA Cheme Pvt. Ltd., Colaba, Mumbai, Maharashtra. MAX Phase Multilayer Nanoflake (Ti_3C_2) was sourced from The Nanoshel, Derabassi, Punjab. These materials were chosen for their high purity and compatibility with the preparation requirements of the composite.

2.2. Preparation of Cu-MXene Composite

The preparation of the Cu-MXene composite involved a basic methodology of powder metallurgy route [11]. First, the composition of the samples was determined through an extensive review of relevant literature to establish a foundation based on prior empirical findings. Materials were then procured according to predetermined mass calculations essential for achieving the intended stoichiometry of the composite. Each powder was quantified with high precision using a calibrated analytical balance to ensure accuracy and reproducibility.

The powders were homogenized through a systematic blending process carried out under rigorously controlled conditions to prevent contamination. This process ensured uniform particle distribution, facilitated intermetallic mixing, and enhanced powder flow characteristics by integrating specific ratios of lubricants and MAX phase materials. The ratios varied between 0% and 2.0% for MAX phase and 0% and 20% for MoS_2 by weight, mitigating inter-particle friction and extending die life. Metallic and non-metallic powders were co-blended to form a composite ready for further processing.

Before milling, the powders were pre-mixed in a mortar and pestle for 15 minutes to reduce agglomeration. Ball milling was performed at a rotational speed of 250 rpm for 210 minutes, with citric acid used as a process control agent to prevent excessive cold welding and agglomeration. The ball-to-powder weight ratio was maintained at 10:1 throughout the process.

Powder compaction was carried out using a die-punch assembly with a diameter of 25 mm. A gradual pressure of 320 KN was applied using a bespoke die designed with Ansys software and machined on a lathe, ensuring the integrity of the compacted green pellets. Sintering was conducted in a multi-chamber muffle furnace under an argon atmosphere to prevent oxidation.

The furnace temperature was elevated to 900 °C and held for 120 minutes under a pressure setting of 20 psi. The sintering process included a burn-off chamber to remove residual lubricants, a high-temperature chamber to facilitate particle bonding, and a cooling chamber to gradually reduce the temperature, preventing thermal stresses.

2.3. Characterization

The initial surface finishing of the sintered specimens was performed manually using a progressive series of emery papers with grit sizes ranging from P220 to P2000. This step incrementally refined the surface finish, effectively removing irregularities and preparing the substrates for high-resolution analyses. Subsequent polishing with a cloth polishing machine ensured a mirror finish, eliminating microscopic scratches and achieving a uniformly smooth surface critical for accurate material characterization.

Mechanical property evaluation was performed using micro indentation techniques. Tests were conducted under a range of applied forces from 1 to 1000 grams-force (gf) to accommodate different material hardness scales. Indentation measurements were carried out with a light microscope equipped with a filar eyepiece, allowing for precise dimensional analysis of the indentations. The hardness testing apparatus was meticulously designed and calibrated in compliance with ASTM E92 standards, featuring a system capable of precisely controlling the indenter's descent into the material at preselected forces. The force application system ensured smooth application and maintenance of force for a duration of 10 to 15 seconds, which was critical for obtaining valid measurements. Vibration control mechanisms minimized environmental vibrations during testing, ensuring the integrity of the measurements. The optical system of the apparatus included a high-quality microscope to measure the diagonals of the indentations accurately, a crucial factor in calculating precise hardness values.

3. Results & Discussion

3.1. Microstructure analysis prepared powder mix

The optical microscopy images reveal the microstructural differences among copper (Cu) and its composites with varying MXene (Mx) concentrations. Fig.1 (a) shows pure Cu, the structure appears highly heterogeneous with numerous voids and irregular grain boundaries, indicative of the natural grain structure of copper without any additives. As MXene is introduced, the microstructures begin to change notably. With the addition of 0.5% MXene, the grains still display some irregularities, but the structure starts to appear slightly more uniform compared to pure

Cu as shown in Fig.1(b). The MXene seems to begin filling the gaps and influencing grain refinement, albeit subtly at this low concentration. Increasing the MXene content to 1% enhances this effect, with more defined grain boundaries and a noticeable reduction in voids[12,13]. The microstructure becomes denser, and the distribution of MXene appears more evenly spread throughout the copper matrix, suggesting better integration and interaction between the copper grains and MXene as shown in Fig.1(c). At 1.5% MXene, the grains further refine and the microstructure shows a greater level of uniformity and compactness as shown in Fig.1(d). The MXene content seems to act effectively in modifying the copper's internal structure, possibly enhancing its mechanical properties due to the reduction in structural defects and voids[14]. The highest concentration of MXene at 2% results in the most homogeneous and dense structure among the samples. The copper grains are tightly packed, and the presence of MXene is evident as it significantly alters the copper matrix, leading to an almost complete transformation of the grain structure with minimal voids and enhanced uniformity as shown in Fig.1(e).

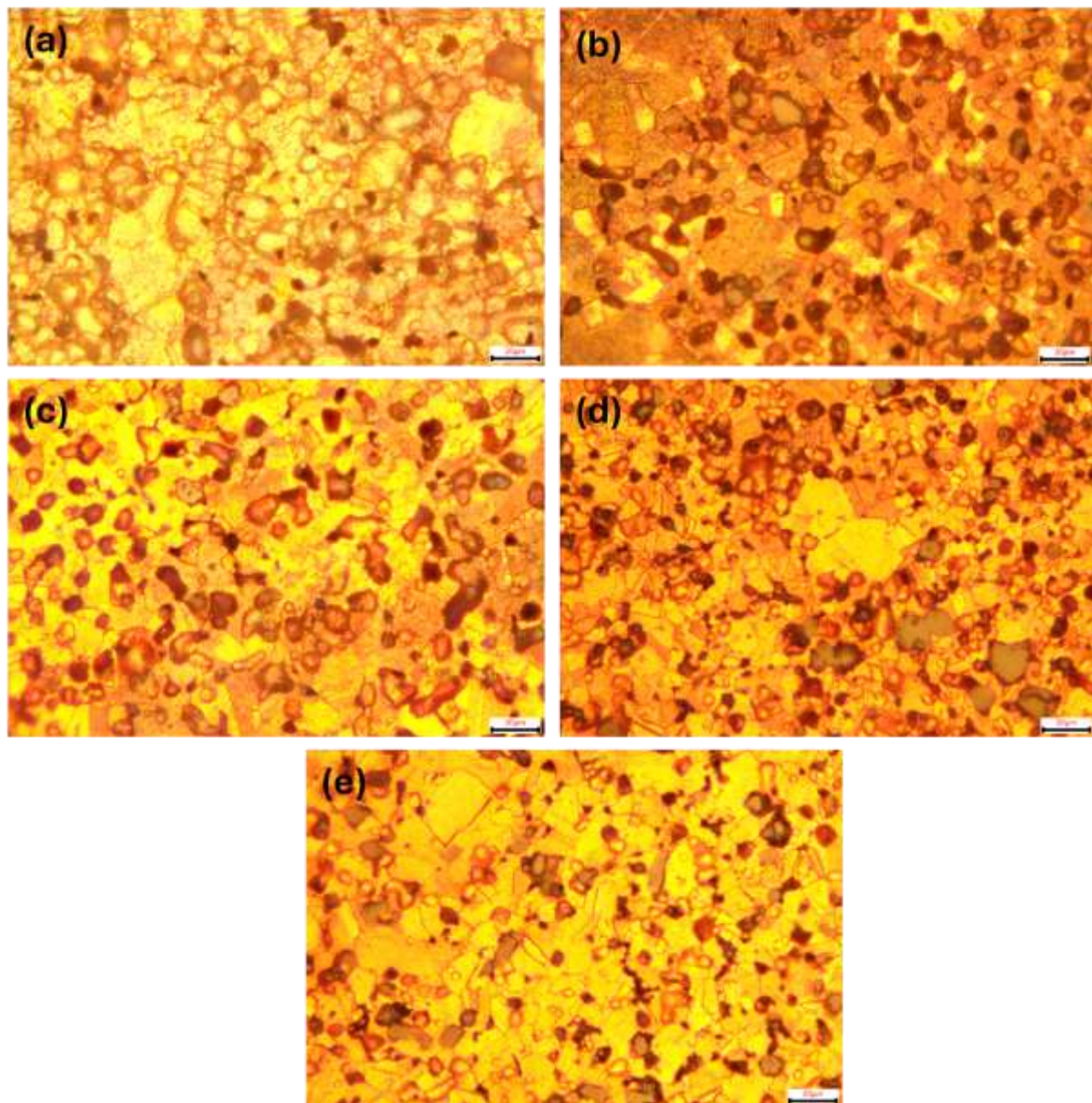


Figure 1. Optical images: (a) Cu, (b) 99.5% Cu-0.5% Mx, (c) 99%Cu-1%Mx, (d) 98.5%Cu-1.5%Mx, and (e) 98%Cu-2.0% Mx

3.2. Microstructure analysis prepared composite

Scanning Electron Microscopy (SEM) morphologies depict the microstructural evolution of copper (Cu) surfaces with increasing concentrations of MXene (Mx) from 0% to 2%. The highest MXene concentration results in the most

uniform and aligned microstructure among the series. The surface is characterized by long, continuous channels, with very few breaks or defects. This indicates a substantial integration of MXene into the copper matrix, which likely results in the most pronounced changes in properties such as thermal and electrical conductivity, as well as mechanical strength.

Figure 2 shows a series of backscattered SEM micrographs illustrating how increasing additions of Mx affect the microstructure of a Cu-based system. Each micrograph is taken at the same nominal magnification ($\times 500$) and a $100\text{ }\mu\text{m}$ scale bar. The pure copper sample exhibits a characteristic lamellar or layered fracture surface (Figure 2a). Large, relatively smooth facets and step-like features are visible, suggesting ductile tearing with some cleavage-like planes. The brightness is uniform because no second-phase particles are present (in backscattered mode, brighter contrast often indicates heavier elements or a second phase). With a small amount of Mx added (99.5 wt% Cu–0.5 wt% Mx) shown in Figure 2b, the microstructure shows numerous, roughly spherical or rounded particles (bright spots) dispersed throughout the darker Cu matrix. The overall size of these inclusions appears uniform, and they are well-distributed. The background Cu matrix retains a mostly homogeneous appearance[15,16]. As the Mx content increases to 1 wt% (99 wt% Cu–1 wt% Mx) shown in Figure 2c, the particles remain discrete and rounded but become more numerous, covering a larger fraction of the surface. Some slight clustering is evident, though individual particles still appear isolated and do not form continuous networks. The bright Mx regions (98.5 wt% Cu–1.5 wt% Mx) shown in Figure 2d become increasingly interconnected or slightly elongated in some areas. Compared to (b) and (c), there is an apparent increase in both the number and areal coverage of Mx particles. The fractured Cu matrix (darker regions) shows more complex surface features, possibly due to the influence of Mx on the deformation or fracture path. At the highest Mx content shown (98 wt% Cu–2 wt% Mx) shown in Figure 2e, the backscattered image reveals even denser coverage of the bright secondary phase. The matrix appears more fragmented, with numerous interfaces between Cu and the dispersed Mx particles. Ridges and striations in the Cu matrix are visible, possibly reflecting localized plastic flow around the increasingly abundant Mx inclusions.

From a purely microstructural standpoint, the 1.0 wt.% MXene addition (Figure 2c) appears to achieve the most uniform dispersion in the copper matrix, striking a balance between good interfacial bonding and minimal agglomeration/void formation. In contrast, higher MXene contents (1.5 wt.% and 2.0 wt.%) show increasingly pronounced clusters or lamellar regions (Figures 1d and 1e) that may degrade mechanical or tribological performance by acting as crack initiation sites. Consequently, based on these SEM observations alone, the 1.0 wt.% MXene sample shows the most promising microstructure for surface engineering and tribological enhancement of copper alloys.

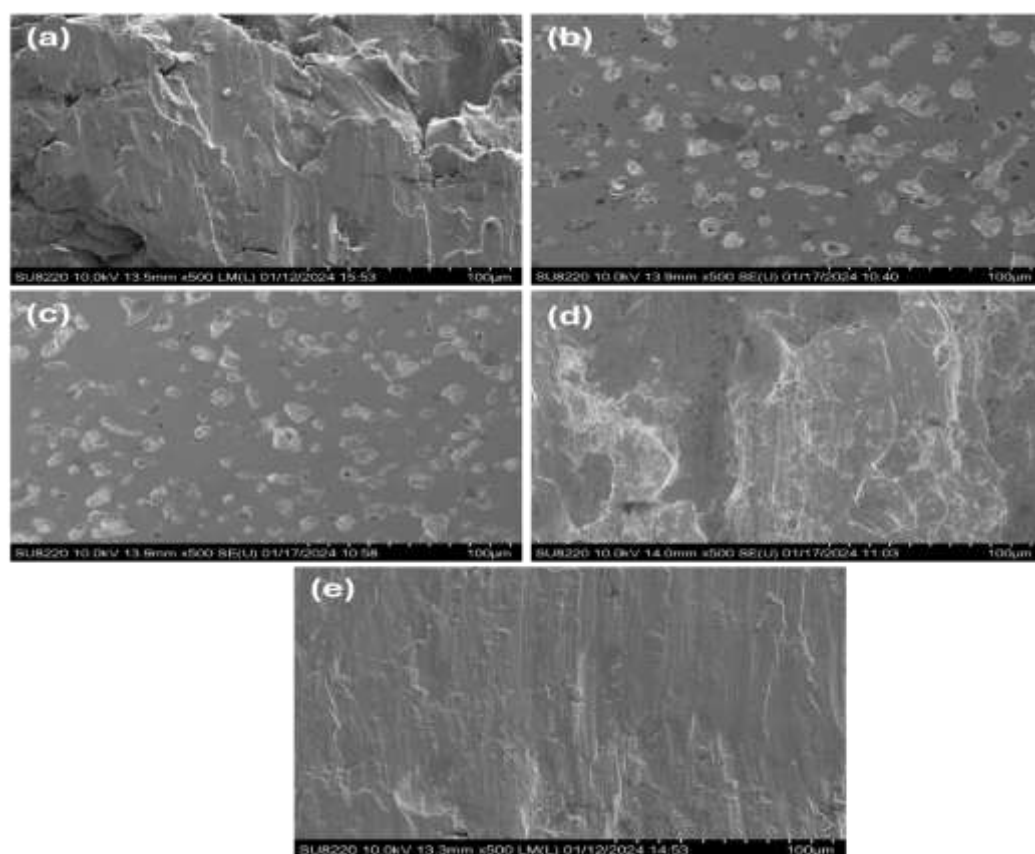


Figure 2. Backscattered SEM micrographs: (a) Cu, (b) 99.5% Cu-0.5% Mx, (c) 99%Cu-1%Mx, (d) 98.5%C-1.5%Mx, and (e) 98%Cu-2.0% Mx

3.3. Vicker's Hardness and Density

Table 1 shows the experimental results for density and hardness of Cu and its MXene composites, revealing a clear trend of increasing density and hardness with the addition of MXene. Figure 3 shows the variation in density and hardness of the prepared composite. The pure Cu sample (C) has the lowest density at 6.72 g/cm³ and a Vickers Hardness Number (VHN) average of 24.17, indicative of the inherent properties of untreated copper, which is relatively soft and less dense. As MXene is introduced and incrementally increased from 0.5% to 2.0%, both the density and hardness of the composites rise. The Cu-0.5Mx composite shows a modest increase in density to 7.41 g/cm³ and an average hardness of 27.13 VHN, suggesting initial enhancement due to MXene's integration. This trend is more pronounced in the Cu-1Mx sample, where the density further increases to 7.84 g/cm³ and hardness to 28.83 VHN, indicating that MXene contributes significantly to the matrix's compactness and mechanical resistance[17]. The enhancements are even more substantial when MXene content reaches 1.5% and 2.0%. For Cu-1.5Mx, the density slightly rises to 7.87 g/cm³, but the hardness sees a major jump to 43.97 VHN, illustrating a critical threshold where MXene's reinforcing effect becomes markedly influential in hardening the composite. The Cu-2Mx composite demonstrates the highest values with a density of 7.91 g/cm³ and an exceptional average hardness of 51.27 VHN, underscoring the significant impact of MXene in maximally enhancing the structural and mechanical properties of copper[17]. Overall, the progressive increase in MXene content not only results in denser but also much harder composites, suggesting that MXene's incorporation strategically modifies copper's characteristics to suit applications requiring harder and denser materials.

Table 1 Densities and Vicker's Hardness of the prepared samples

Sample	Composition	Measured Density (g/cm ³)	Vicker's Hardness (VHN)			
			Value-1	Value-2	Value-3	Average
Cu	Pure Copper	6.72	22.1	26.1	24.3	24.17
Cu-0.5Mx	99.5% Cu-0.5% Mx	7.41	26.3	27.8	27.3	27.13
Cu-1Mx	99%Cu-1%Mx	7.84	28.8	28.5	29.2	28.83
Cu-1.5Mx	98.5%C-1.5%Mx	7.87	42.8	41.8	47.3	43.97
Cu-2Mx	98%Cu-2.0% Mx	7.91	48.6	52.6	52.6	51.27

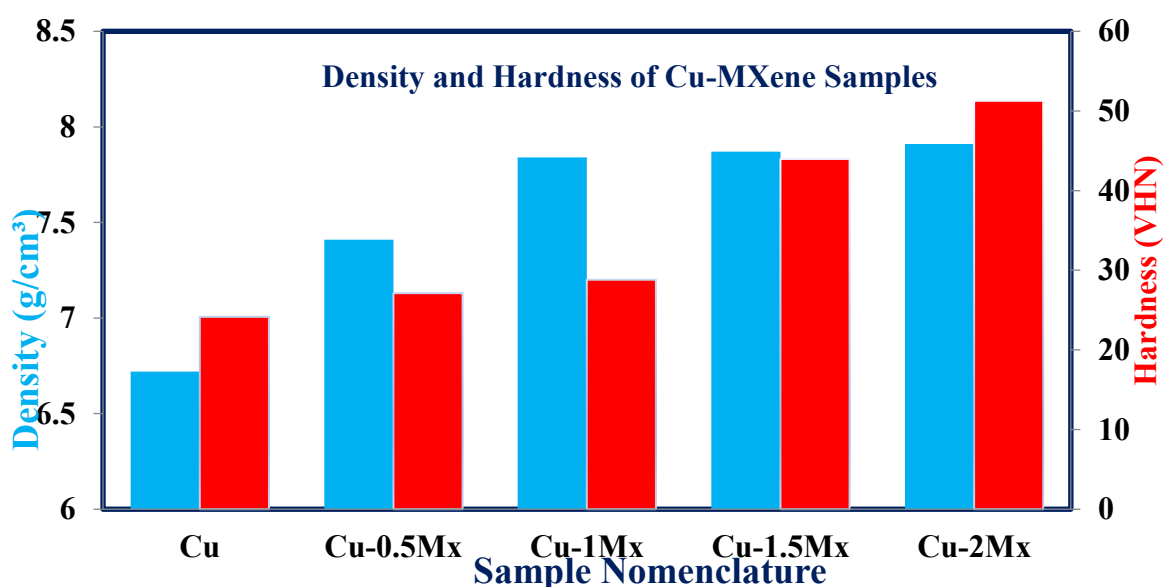


Figure 3: Variation in hardness and density of the prepared composite

3.4. Wear Behaviour of prepared composite

Table 2 illustrates the wear resistance of a series of copper (Cu) and Cu-Mx phase composites subjected to wear tests, showing variations in sample weight before and after testing. Starting with pure copper (Cu), designated as C, the sample loses weight from 16.57966 g to 16.54468 g, suggesting notable wear due to the absence of any reinforcing phase. As the MAX phase is incrementally added to copper, starting from 0.5% in sample C-0.5Mx to 2% in sample C-2Mx, there is a clear trend of enhanced wear resistance. Cu-0.5Mx sample shows a slight decrease in weight from 17.04124 gm to 17.00956 gm, indicating improved durability over pure Cu. This enhancement in wear resistance becomes more pronounced with increasing MAX phase content; for instance, the Cu-1Mx sample displays a minor reduction from 17.39705 gm to 17.36091 gm, and the Cu-1.5Mx sample from 17.57733 gm to 17.55588 gm, suggesting progressively better material integrity under wear conditions [13]. The most substantial improvement is observed in the Cu-2Mx sample, which begins at 17.63522 gm and drops only to 17.59313 gm, showing the highest wear resistance among the tested composites. Therefore, it clearly demonstrates that increasing the Mx concentration within the copper matrix significantly enhances the composite's ability to withstand mechanical degradation, thus suggesting potential applications where enhanced durability is critical [18,19].

Table 2 Wear behavior of the prepared samples

Sample	Cu (wt%)	Mx phase (wt%)	Sample weight before wear test (gm)	Sample weight after wear test (gm)
Cu	100	0	16.57966	16.54468
Cu-0.5Mx	99.5	0.5	17.04124	17.00956
Cu-1Mx	99	1	17.39705	17.36091
Cu-1.5Mx	98.5	1.5	17.57733	17.55588
Cu-2Mx	98	2	17.63522	17.59313

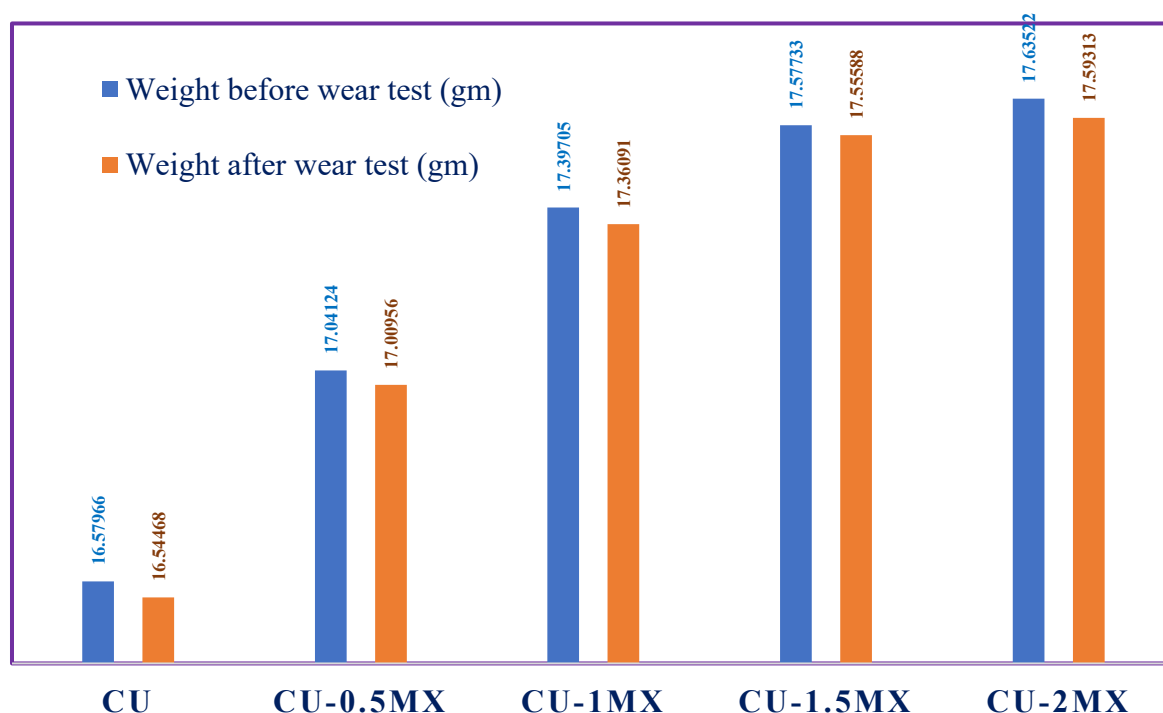


Figure 4: Comparison in weight loss of material of different composite samples

Fig.5 illustrates the three-dimensional surface topographies of copper (Cu) and its composites with varying concentrations of MXene (Mx), captured through scanning probe microscopy (SPM). Panel (a) shows pure copper with a relatively uniform surface exhibiting moderate roughness ($S_a = 5.450 \mu\text{m}$, $S_q = 5.476 \mu\text{m}$). As MXene content increases from 0.5% in (b) ($S_a = 4.326 \mu\text{m}$, $S_q = 4.509 \mu\text{m}$) to 2.0% in (e) ($S_a = 3.903 \mu\text{m}$, $S_q = 4.219 \mu\text{m}$), the images reveal a trend of increasing surface roughness and complexity. The color variation across the panels from red to diverse colors indicates significant changes in surface height and morphology[20,21]. The introduction of MXene not only increases the roughness but also introduces more pronounced textural variations, suggesting enhanced material characteristics for applications where surface interactions are crucial, such as in tribological or bonding contexts. This comparative visualization effectively highlights the impact of MXene incorporation on altering the copper matrix's surface properties.

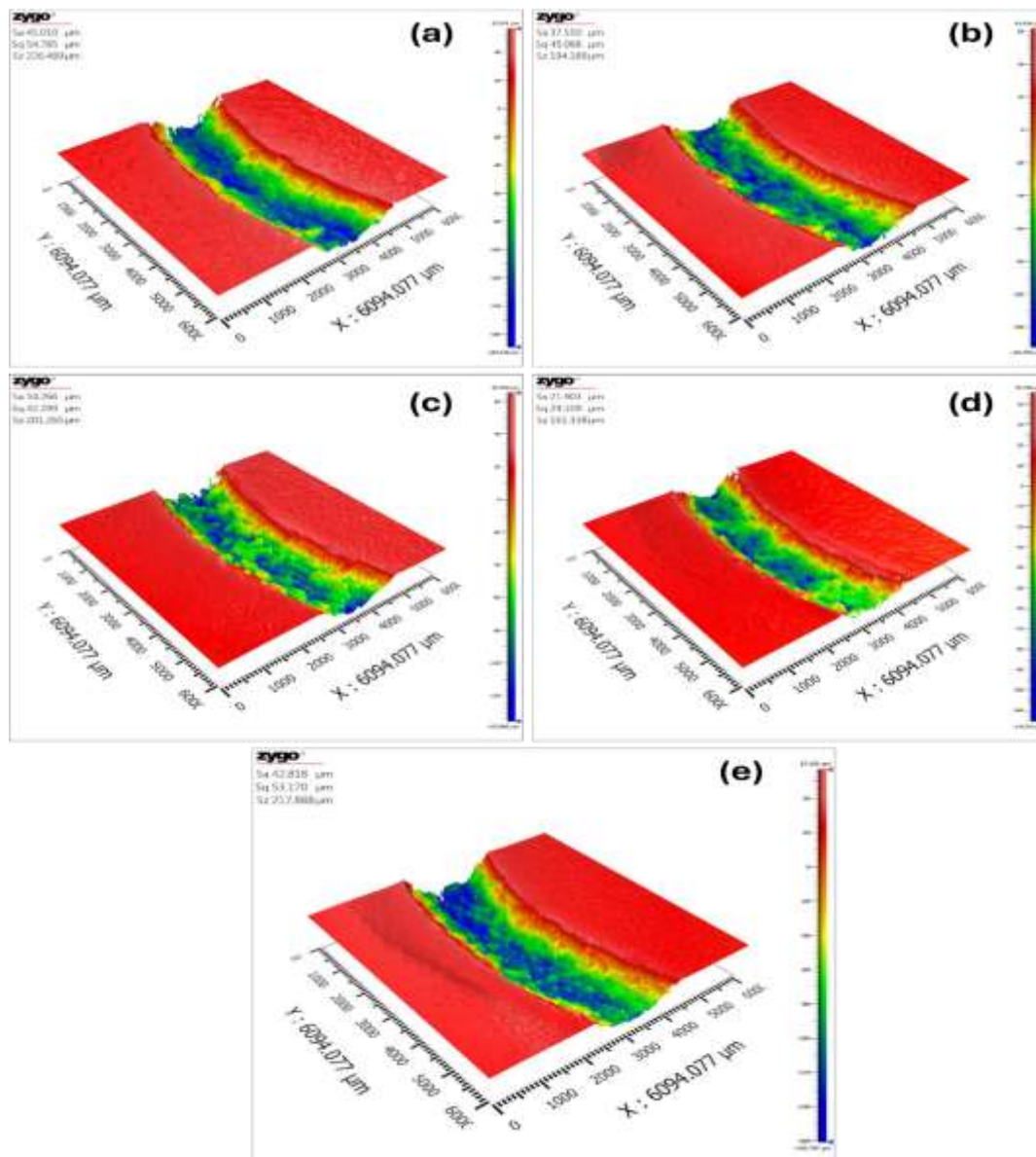


Figure 5. 3D surface topography images: (a) Cu, (b) 99.5% Cu-0.5% Mx, (c) 99%Cu-1%Mx, (d) 98.5%Cu-1.5%Mx, and (e) 98%Cu-2.0% Mx

4. Conclusion

Cu-MXene composites were successfully prepared using the powder metallurgy route, and the effect of MXene addition in different proportions was systematically investigated. Experimental investigations revealed a clear trend where increasing concentrations of MXene in copper composites lead to progressively smoother and more uniform surface topographies, indicating enhanced surface refinement. This enhancement is likely due to MXene's ability to

fill voids and modify the microstructural features of the copper matrix, improving its overall surface characteristics for potential applications in environments requiring precise and uniform surface properties. SEM images reveal that as MXene content increases, the copper surface transitions from rough and irregular to smooth and highly aligned. The influence of MXene is not merely additive but transformative, suggesting that its incorporation into the copper matrix could be strategically utilized to engineer the surface properties of copper-based materials for specific applications. Optical images clearly demonstrate how increasing the MXene content progressively refines and densifies the copper's grain structure. The pure copper sample shows the most irregular and porous structure, while the 2% MXene composite exhibits the highest degree of uniformity and structural integrity. This transformation suggests that MXene not only fills the voids but also facilitates the rearrangement and stabilization of copper grains, likely contributing to improved physical properties like strength and durability. The analysis of the wear loss, density, and hardness data for copper and its MXene composites clearly indicates that increasing the MXene content significantly enhances the material's density and hardness, resulting in markedly improved wear resistance. This trend demonstrates that MXene acts effectively as a reinforcing agent in the copper matrix, offering potential for developing highly durable and mechanically robust materials for industrial applications.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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