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RESEARCH ARTICLE

Friction and wear behavior of Cu–4 wt.%Ni–TiC composites under dry sliding conditions

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Abstract: The present study synthesized Cu–4 wt% Ni matrix composites reinforced with different percentages of TiC (0, 2, 4, 6, and 8 wt%) through high-energy ball milling, followed by compaction and sintering. The friction and wear behavior was examined at four different normal loads of 5, 10, 15, and 20 N. A constant sliding speed of 1.25 m/s was maintained while sliding against a hardened counterface made of EN31 steel (HRC 60) under ambient conditions using a pin-on-disk test rig. The composite hardness increased until the addition of 4 wt% of TiC, beyond which it was observed to decrease. Such a trend may be attributed to the TiC agglomeration in the composites containing relatively larger amounts of TiC (i.e., 6 and 8 wt%). The wear rate linearly increased with the load. However, the composites exhibited a lower rate of wear than the matrix alloy, which may have resulted from the relatively higher hardness of composites. The observed friction and wear behavior has been explained on the basis of hardness and presence of the transfer layer on the worn surface and its nature, i.e., loose or well compacted. Addition of 4 wt% TiC showed the optimum performance in terms of friction and wear caused by its higher hardness and ability to hold a transfer layer of a relatively larger thickness compared to the other materials. The wear mechanism for the Cu4Ni matrix alloy was a mix of adhesive and oxidative wear and primarily abrasive for the composites containing hard TiC particles.

Keywords: sliding wear; composites; TiC particles; friction

1 Introduction

Metal matrix composites (MMCs) have attained growing importance because of their potential applications in the automobile, aerospace, sporting goods and general engineering industries due to their excellent properties (e.g., high specific strength, elastic modulus, specific stiffness, desirable coefficient of thermal expansion, elevated temperature resistance, and superior wear resistance) [1]. Discontinuously reinforced MMCs are endowed with properties, such as low fabrication cost and utilization in various industrial purposes [2–4]. Copper-based MMCs are promising materials because of their excellent thermo-physical properties. They are also being used in several industrial applications, such as in brush and torch nozzle materials, electrical sliding contact materials in homopolar machines, and railway overhead current collector systems, where good wear resistance at a reasonable level of electrical conductivity is the prime requirement [5, 6]. Several processing techniques, including powder metallurgy, casting, and infiltration techniques, have been developed and are being used to synthesize MMCs [7]. However, the powder metallurgy route has an edge over liquid-processing methods because it overcomes the problems of porosity, non-uniform distribution of reinforcing particles, and unwanted chemical reactions, which are a part and parcel of the casting route. It also results in the production of good quality products, particularly, when the ceramic particles are reinforced into the matrix material [8]. The agglomeration of the reinforcement particles in

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the matrix, particularly in the case of small-sized reinforcement particulates, can be prevented by mechanical alloying that involves repeated deformation, cold welding, and fracture of powder using high-energy ball milling and further leads to a homogeneous distribution of the reinforcement phase in the matrix [9].

Researchers have reinforced various oxides, carbides, and borides in copper to enhance its mechanical and wear resistance properties [10−13]. Among these reinforcements, titanium carbide is considered attractive because of its higher modulus, hardness, and melting temperature [14]. TiC particles reinforced with copper-based composites have recently been explored because of their numerous industrial applications in electrodes, switches, motors, etc. [15–19]. Ni is used in the present investigation as a binding agent between Cu and TiC [20].

A critical review of the literature presented above clearly reveals that various studies were conducted on the mechanical and physical properties of Cu-based composites containing different reinforcements. However, only limited investigations were made toward understanding the friction and wear behavior of TiC-reinforced Cu-based composites. Hence, the present study aims to highlight the Cu-based composites through high-energy ball milling, followed by compaction and sintering containing different amounts of TiC particles. The main focus of the investigation is to evaluate and understand the friction and wear performance of the synthesized composites containing different amounts of reinforcement by performing dry sliding wear tests using a pin-on-disk tribometer under different normal loads of 5, 10, 15, and 20 N and maintaining a constant sliding speed of 1.25 m/s. The exploration equally attempts to study the effective mechanisms of wear taking place in the present circumstances.

2 Experimental procedure

2.1 Materials

Copper and nickel with 99% purity (Loba Chemie Pvt. Ltd., India) having an average particle size of 200 mesh and TiC particles (325 mesh, 98%, Sigma Aldrich, Germany) as the reinforcement were used to make the Cu–4 wt% Ni–x wt% TiC (x = 0, 2, 4, 6, and 8) metal matrix composite. These composites were designated as Cu4Ni, Cu4Ni–2TiC, Cu4Ni–4TiC, Cu4Ni–6TiC, and Cu4Ni–8TiC, respectively. Formulated composite powders were ground in a high-energy ball mill for 120 min at 400 rpm in the presence of toluene, which acted as the process control agent and restricted the generation of intermetallic compounds. Hardened stainless steel vial was used to seal the powders, and the ball-to-powder ratio was 10:1. The high-energy wet ball milling was rested periodically for every 20 min, then resumed for another 20 min to avoid overheating. The ground mixes were compacted by cold uniaxial pressing in a rigid cylindrical die at an optimized pressure of 650 MPa. For the friction-free punch movement, stearic acid was applied on the inner surface of the die as a lubricant. The compacted samples measured 12 mm × 11 mm. Green pellets were sintered in an argon atmosphere at an optimized sintering temperature of 850 °C for a soaking time of 60 min.

2.2 Characterization

The phase evolution of the sintered composites was studied using a Rigaku Desktop Miniflex II X-ray diffractometer with Cu-Kα (λ = 15.406 nm). The composite microstructure was examined using a ZEISS (model no. EVO/18) scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS). The sintered density of the samples was measured using Archimedes' principle. The Vickers micro-hardness test was performed for 15 s using a Vaiseshika electron micro-hardness tester (DHV-1000) with a load of 100 g. A minimum of ten different measurements was taken. The average value of the micro-hardness was reported accordingly.

2.3 Friction and wear tests

The friction and wear tests were conducted according to the ASTM G99-05 standard using a pin-on-disk tribometer (Magnum Engineers, Bangalore, India) with a counterface of the EN31 steel hardened to 60 HRC at an ambient temperature. Figure 1 shows a schematic diagram of the pin-on disk wear tester. The pin-shaped specimens were ground with a 800-grit SiC paper prior to the wear test. The applied normal

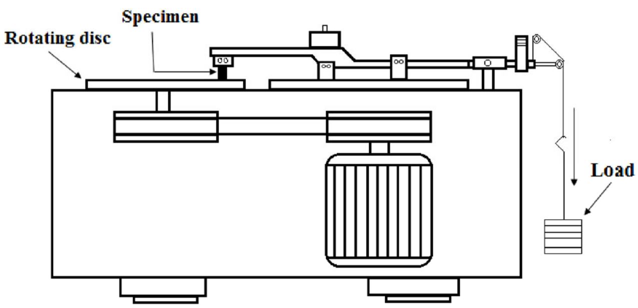

Fig. 1 Schematic of pin-on-disc wear test machine.

loads were 5, 10, 15, and 20 N, and the sliding speed was fixed at 1.25 m/s. The total sliding distance covered during the wear test was 2,250 m. The weight loss during the wear test of each specimen was measured prior to and after the test using an electronic balance with an accuracy of 0.1 mg. Meanwhile, the volume loss of the samples was calculated through weight loss divided by Archimedes' density of the material. The control panel equipped with the tribometer displayed the frictional force. The same was used to calculate the friction coefficient by dividing it by the normal load. Each test for a particular condition of load and speed was conducted thrice. The average value of three tests was reported in the present investigation. The worn surface of the specimens was subjected to SEM and EDS analyses to explore the nature of the wear mechanism.

3 Results and discussion

3.1 Microstructural characterization

Figure 2 shows the X-ray diffraction patterns of the matrix alloy and the TiC-reinforced composites revealing the occurrence of the Cu and TiC peaks, which indicated that no intermetallic compounds or other oxide phase formation took place during the sintering process. The spectra also evidently illustrated that the TiC peaks became distinct only beyond a certain amount of its addition. The peaks corresponding to the presence of Ni could not be detected in the spectra because it goes into making a solid solution due to complete solubility in copper.

Figure 3 presents the SEM morphology of the Cu4Ni matrix alloy and the other composites developed via high-energy ball milling followed by compaction and

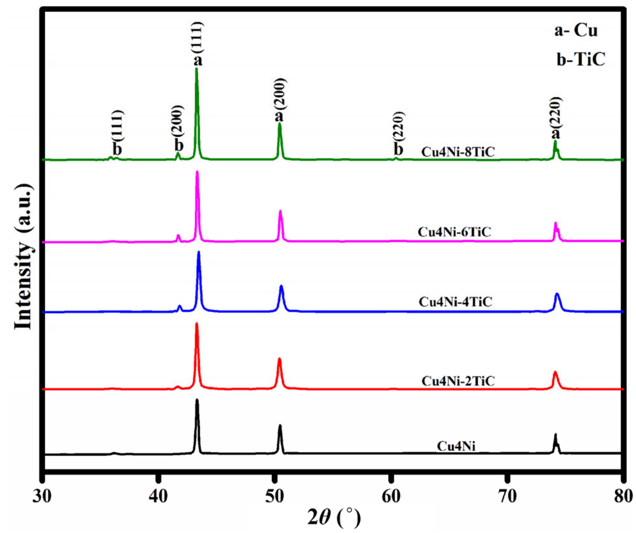

Fig. 2 XRD patterns of Cu4Ni–*x* wt% TiC (*x* = 0, 2, 4, 6 and 8) composites sintered at 850 °C.

sintering. The micrographs showed light and dark gray areas and sharp-edged particles representing copper, porosity, and TiC particles, respectively. The TiC particles appeared to be uniformly distributed in the matrix alloy, as seen from Figs. 3(b) to 3(e). No cracks could be observed in the micrographs. A uniform distribution of the reinforced particles resulted in the improvement of the composites' mechanical properties [21]. Furthermore, the addition of a relatively higher amount of TiC particles may result in the agglomeration leading to the formation of pores in the composites, which could also be observed from the micrographs in Figs. 3(b)–3(e) in round circles [22]. The agglomeration can be seen in the inset of Fig. 3(e). Figures 4(a) and 4(b) present the EDS analysis of the marked portion of the micrographs: (a) Cu4Ni-4TiC and (b) Cu4Ni-8TiC. The EDS analysis in Fig. 4(a) clearly demonstrated that the Cu, Ni, Ti, and C peaks appeared in the EDS spectra, whereas those of Ti and C appeared in the EDS spectra in Fig. 4(b). The TiC was present in the composite, and no oxygen peak was observed in the spectra, suggesting that no oxidation occurred during the sintering process.

3.2 Density and micro-hardness behavior

Figure 5 depicts the effect of the TiC addition on the matrix alloy density. The density enhanced to 7.96 gm/cm^3 when the TiC content was 4 wt% and deteriorated, afterward. A decrease in the density with

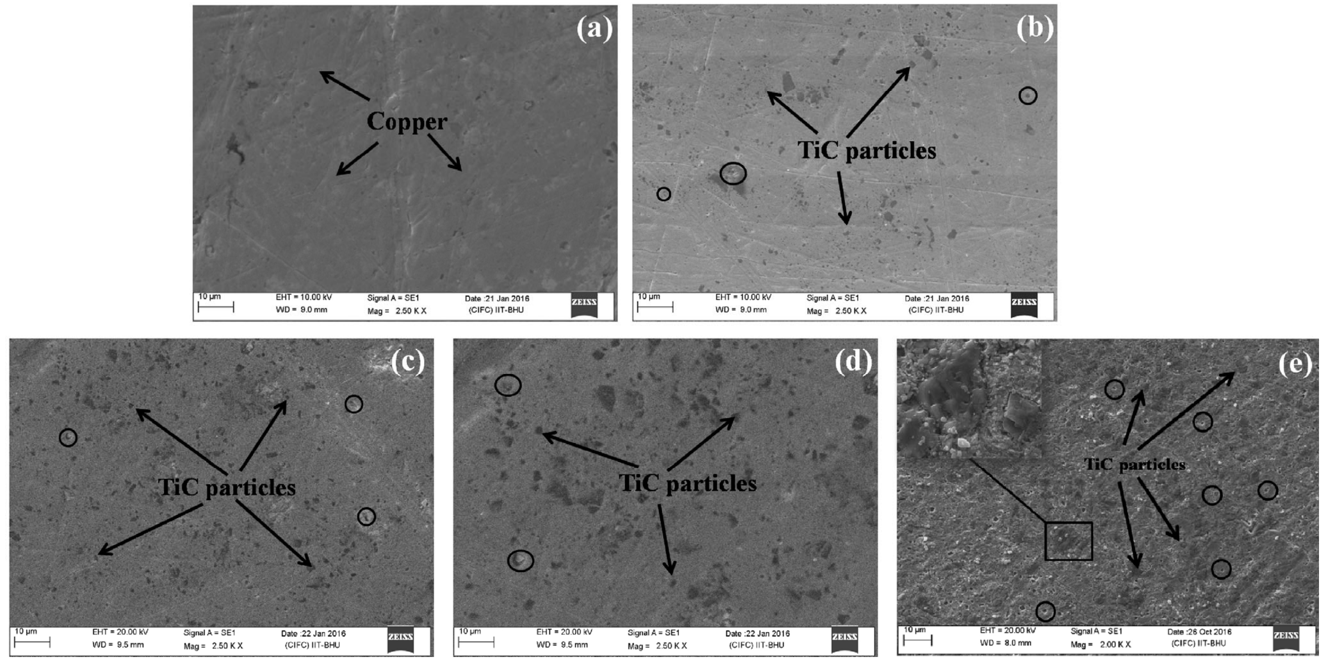

Fig. 3 SEM micrographs of (a) Cu4Ni matrix alloy, (b) Cu4Ni-2TiC, (c) Cu4Ni-4TiC, (d) Cu4Ni-6TiC, and (e) Cu4Ni-8TiC.

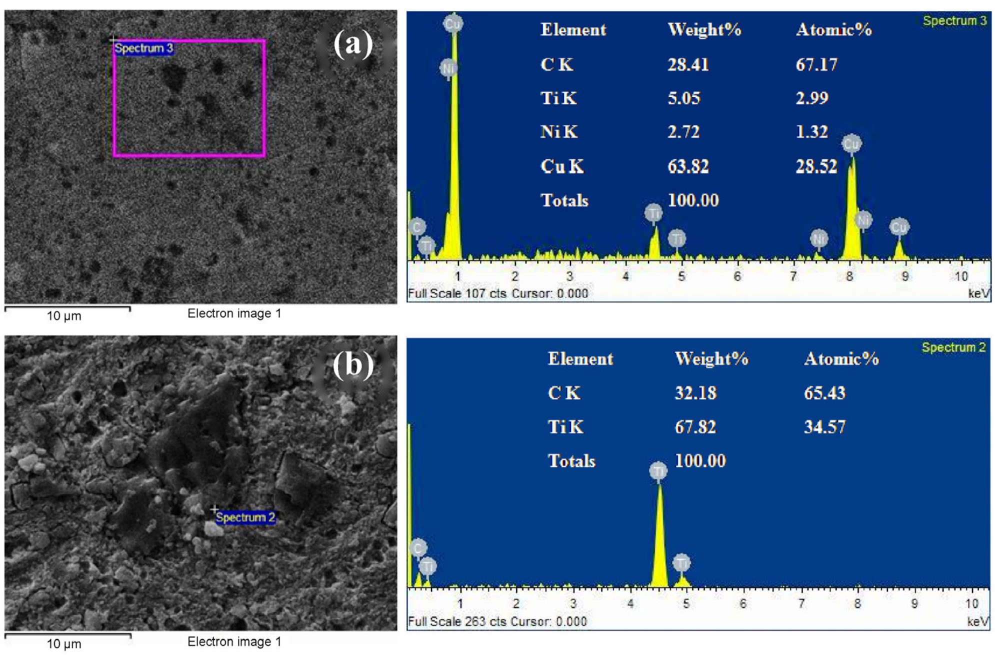

Fig. 4 EDS analysis of the marked portion of the micrographs (a) Cu4Ni-4TiC and (b) Cu4Ni-8TiC.

the increasing amount of TiC may be attributed to the TiC particle agglomeration, which promoted the pore formation and resulted in a reduced density [22].

The variation of the micro-hardness with the TiC content depicted in Fig. 6 showed that the hardness of the composite increased with the addition of TiC until 4 wt%, beyond which, it started decreasing. Relatively higher hardness values were obtained for 4 wt% TiC-reinforced composite with a hardness value of 109 HV. These values were almost 82% more than the matrix alloy. The hardness increase with the increase in the TiC amount from 2 wt% to 4 wt% can be caused by the dispersion strengthening effect of the TiC particles. The thermal disparity between the reinforcing ceramic particles (TiC) and the matrix alloy resulted in the internal stresses that generated the dislocations leading to the increase of the dislocation density, which ultimately contributed to the improvement of the composite hardness [23]. After a certain amount of reinforcing particles (4 wt% in the present study), the composite hardness decreased, because of the increasing tendency of the TiC particle agglomeration that also resulted in the diminished load bearing capacity of the TiC. Another reason may be the increase in the actual inter-particle distance that adversely affected the hardness [24].

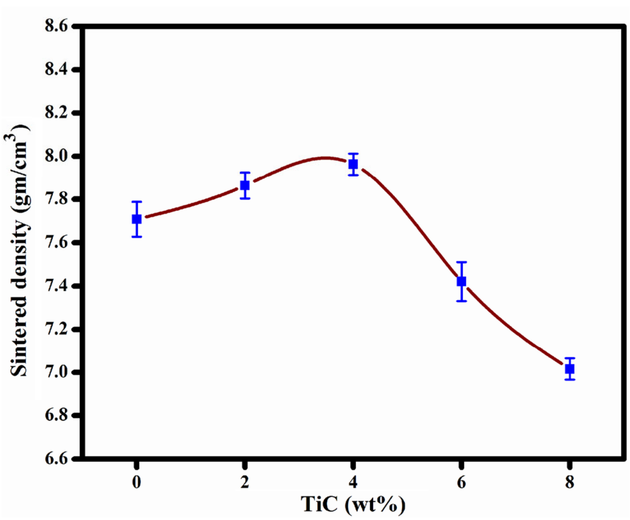

Fig. 5 Effect of TiC reinforcement on the density.

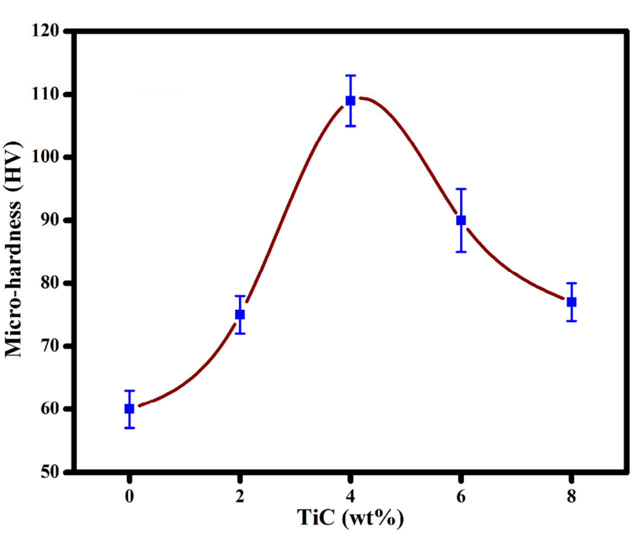

Fig. 6 Variation of micro-hardness with TiC content.

3.3 Friction and wear behavior

Figures 7(a) to 7(d) show the variation of the cumulative volume loss with the sliding distance for all the materials investigated in the present study under different loads of 5, 10, 15, and 20 N and at a constant sliding speed of 1.25 m/s. An almost linear increase in the cumulative volume loss with the increase in the sliding distance took place and confirmed through curve fitting by the linear least square fit. However, the data points were shown to join point by point in Fig. 7. Moreover, the volume loss of the matrix alloy (i.e., Cu4Ni) was consistently higher at all the normal loads in comparison to the composites. This result was not surprising because the hard TiC particles provided a shield to the relatively softer matrix during sliding and enhanced the load bearing capacity of the composites [25]. The volume loss among the composites decreased as the TiC amount increased from 2 to 4 wt%, beyond which, it again increased with the increase in TiC to 6 and 8 wt% at all the normal loads (Figs. 7(a) to 7(d)). Hence, Cu4Ni–4TiC showed the least volume loss, whereas Cu4Ni–2TiC exhibited the largest loss of volume among all the composites at all loads. This result may be attributed to a relatively higher hardness of the composite containing 4 wt% TiC in comparison to other composites.

The wear rate at a particular load was calculated from the slope of the variation of the cumulative loss with the sliding distance (Fig. 7) for Cu4Ni and the composites by fitting the data points through the linear least square fit. Figure 8 shows the wear rate variation with the normal load. The wear rate increased almost linearly with the load following Archard's law, which states that wear rate is directly proportional to the normal load, but inversely proportional to the hardness of the softer of the two mating materials [26]. The composites had a lower wear rate than the matrix alloy at all the loads, which may be credited to the higher hardness of the composites in comparison to the Cu4Ni matrix alloy. Among the composites, Cu4Ni–4TiC showed the lowest wear rate at all the normal loads used in the investigation, which may again be attributed to its hardness that was the highest in the present study. The wear rates shown by the other composites appeared to fall in the same band

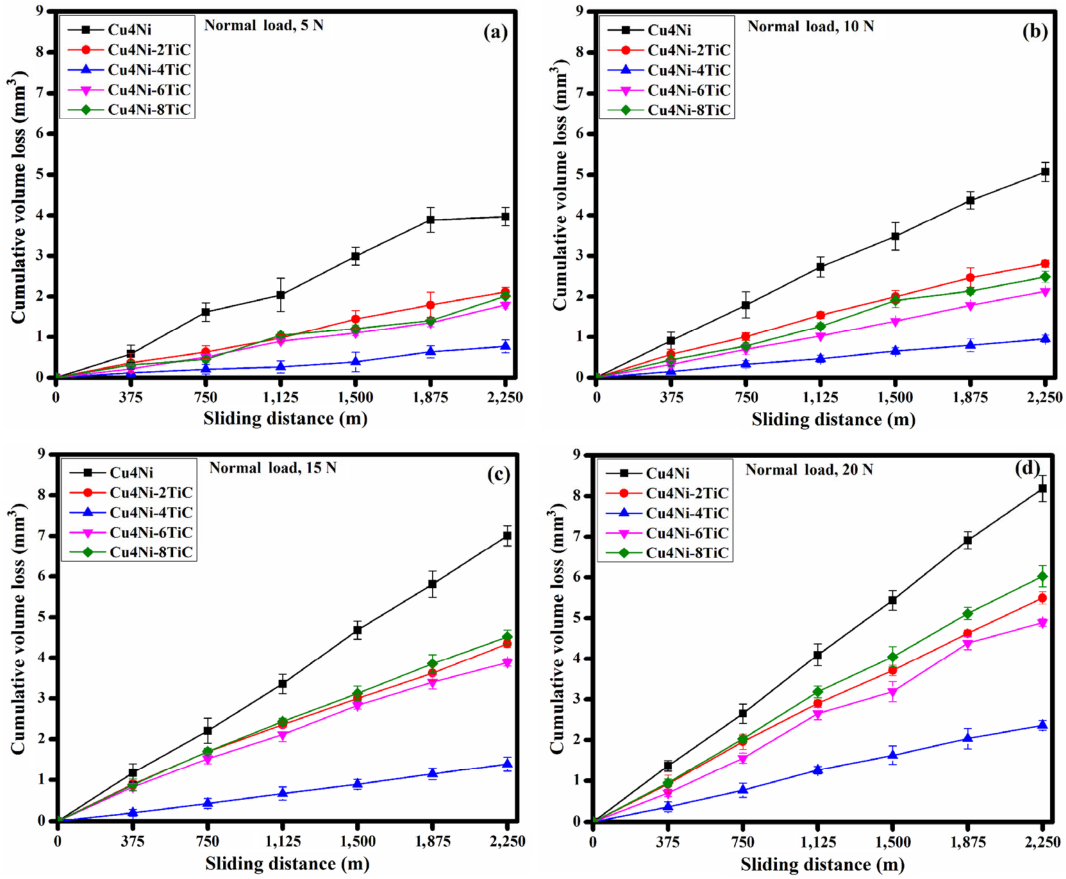

Fig. 7 Variation of cumulative volume loss with sliding distance at normal load of (a) 5 N, (b) 10 N, (c) 15N, and (d) 20 N for a constant sliding speed of 1.25 m/s.

at relatively lower loads. However, the difference appeared to increase with the increasing load, especially for Cu4Ni–8TiC (Fig. 8).

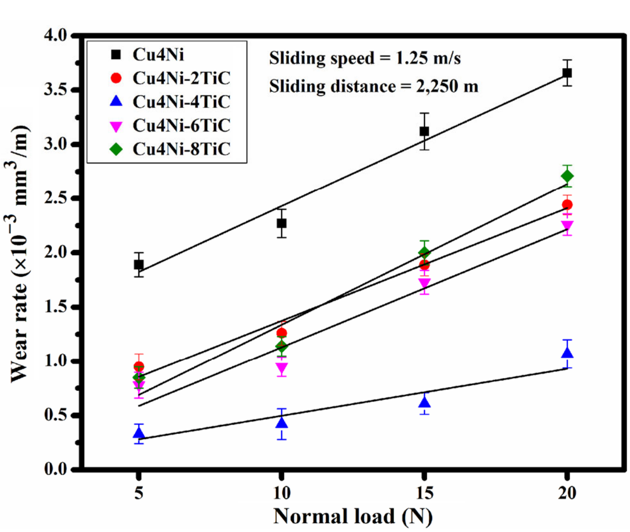

Fig. 8 Variation of wear rate with normal load.

Figure 9 shows the variation of the friction coefficient averaged over the distance slid (i.e., 2,250 m) with the normal load and at a constant sliding speed of 1.25 m/s for both Cu4Ni and composites. The average friction coefficient increased with the increasing load for all the composites synthesized in the present study. However, the friction coefficient for the Cu4Ni matrix alloy increased as the load increased from 5 to 10 N, then decreased as the load increased to 15 N, beyond which, it again increased until a 20 N load. Figure 9 illustrates that the friction coefficients shown by all the materials were from 0.78 to 0.92. The friction coefficient shown by Cu4Ni was the lowest, whereas that by Cu4Ni-8TiC was the highest at all the normal loads. The similar observations were reported by Celikyurek et al. [27].

One could observe that the friction coefficient increased with the increasing TiC content in the composites at a particular load, which may be attributed

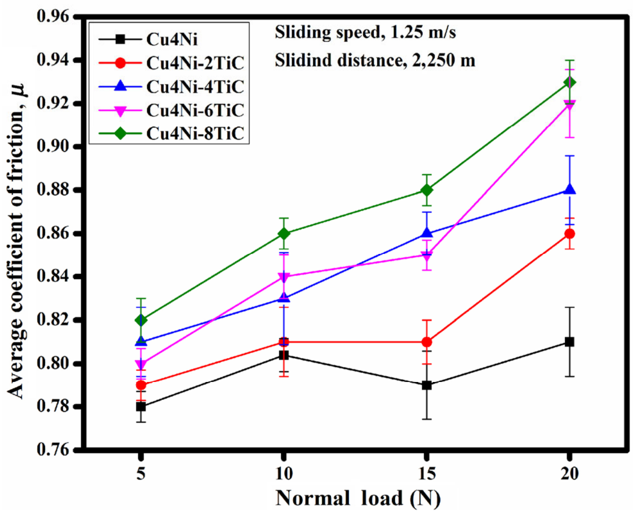

Fig. 9 Variation of average coefficient of friction with normal load.

to the abrasion caused by the TiC particles that get detached from the matrix with the increasing load and trapped between the contacting surfaces, which promoted the three body abrasion and resulted in an increased friction coefficient in the composites. An increase in the TiC content further aggravated the situation as more number of particles now get detached, thereby aiding abrasion. Hence, the friction coefficient increased with both the load and the TiC content. A relatively lower friction coefficient shown by Cu4Ni may be attributed to the relatively soft nature of the matrix in comparison to the composites as well as the absence of any abrasive action.

3.4 Worn surface analysis

Figures 10(a) to 10(c) show the SEM micrographs of the worn surfaces of the tested specimens at a normal load of 20 N after sliding a distance of 2,250 m. The SEM micrograph corresponding to the worn surface of Cu4Ni given in Fig. 10(a) exhibited the presence of the transfer layer of oxide containing the material transferred from the counter face. The extent of cover provided by this layer may explain the absence of the wear tracks, typical of the sliding process, which were not visible on the micrograph. However, this layer appeared to have been detached at some places (marked by arrow on the micrograph) from the substrate. The layer inhibited a metal–metal contact and provided a low shearing strength junction at the interface, thereby resulting in a reduced friction coefficient in comparison to the composites (Fig. 9). Figure 10(b) corresponding to the Cu4Ni–4TiC composite shows some fine wear tracks covered by the transfer layer of a well-compacted wear debris at some places along with particle pull-out at some locations. The SEM micrograph of the worn surface of Cu4Ni–8TiC depicted in Fig. 10(c) also showed the presence of a transfer layer that appeared to be a bit loose against the well-compacted layer in Fig. 10(b). However, no grooves were visible on the specimen surface, which may be caused by the filling of these groves by the loose wear particles, because Cu4Ni–8TiC has shown the largest volume loss among the composites. This could be confirmed from Fig. 7. The similar features were observed for the other composites, namely, Cu4Ni-2TiC and Cu4Ni-6TiC, with varying degrees of compaction and extent of cover provided by the transfer layer. However, these results were not shown herein. The presence of the fine grooves in Fig. 10 indicated an abrasive mechanism of wear in the composites, which might have been caused by the hard TiC particles pulled out from the matrix because of the poor bonding between TiC and the matrix despite the addition of Ni expected to improve the bonding. Furthermore, investigations must be conducted to examine the problems related to bonding. The pulled-out particles gave rise to abrasion until they were loose. However, during sliding, they get mixed with the other oxide and metallic particles that included the material transferred from the counterface and formed a transfer layer, which became compact because of frictional heating (Fig. 10(b)). A relatively higher friction coefficient shown by the composites in comparison to Cu4Ni may be caused by the abrasive action of these TiC particles. The friction coefficient among the composites increased with the increasing content of TiC (Fig. 9), which may be explained based on the chances of the TiC pull-out that are more in a composite containing relatively higher amount of TiC. These particles led to an enhanced abrasion resulting in a higher friction coefficient in composites containing a relatively larger amount of TiC. Despite a relatively lower friction coefficient, the wear rate shown by Cu4Ni was the largest and may be credited to a comparatively lower hardness of Cu4Ni in comparison to the composites. The frictional heat during sliding aided the formation of oxide, which gets mixed with the detached wear particles and results in the formation of a transfer layer containing mixture oxides and metallic debris particles. This layer reached up to a critical thickness, after which it became unstable and got detached from the surface. It has been reported that a harder substrate is able to support a layer of larger thickness [28]. Cu4Ni has a relatively lower hardness compared to the composites. Hence, it can only support a transfer layer with a relatively smaller thickness before it detaches. This may explain the higher rate of the wear observed for Cu4Ni in comparison to the synthesized composites. Among the composites, Cu4Ni–4TiC has the lowest rate of wear, which again may be explained based on its relatively higher hardness and ability to hold a thicker transfer layer as explained earlier. The other contributing factor may be the presence of the well-compacted transfer layer in Fig. 10(b), which effectively reduced the metal–metal contact and resulted in a lower rate of wear as well as the friction coefficient in Cu4Ni–4TiC, against the loose transfer layer that appeared to have got detached at some locations (marked by arrows) illustrated in Fig. 10(c) corresponding to Cu4Ni–8TiC.

Figure 11 depicts the typical EDS analysis of the marked portion of the worn surface micrograph of the Cu4Ni–4TiC pin. The presence of Fe in the EDS spectra confirmed that the metal transfer took place from the counter face. The presence of oxygen in the spectra indicated the possibility of oxidation that might have occurred during sliding.

From the above discussion, one can summarize that the addition of 4 wt% TiC in the Cu4Ni matrix alloy showed optimum hardness and tribological performance under the conditions of the load and the speed used in the present study. The operative mechanism was primarily abrasive in all the composites and a combination of adhesive and oxidative wear in the Cu4Ni matrix alloy. The TiC pull-out may be attributed to the weak bonding between the matrix and the reinforced particle in spite of the addition of Ni to improve the binding characteristics. Further investigations are required to examine the bonding-related problems.

4 Conclusions

1. The Cu4Ni–TiC composites were successfully synthesized by high-energy ball milling, followed by

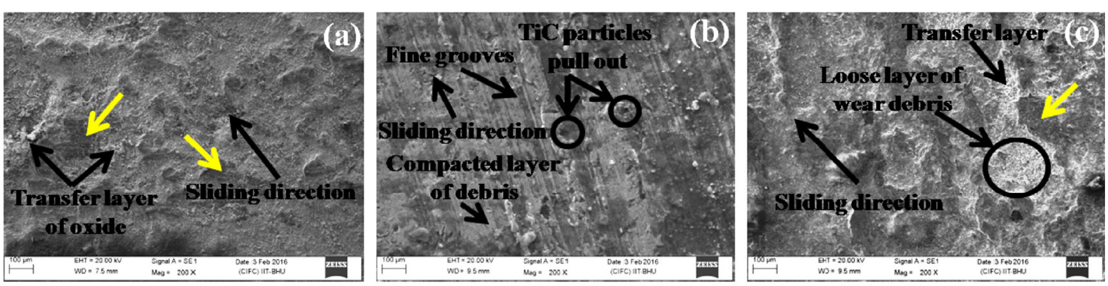

Fig. 10 SEM micrographs of worn surface of (a) Cu4Ni matrix alloy, (b) Cu4Ni-4TiC, and (c) Cu4Ni-8TiC at 20 N.

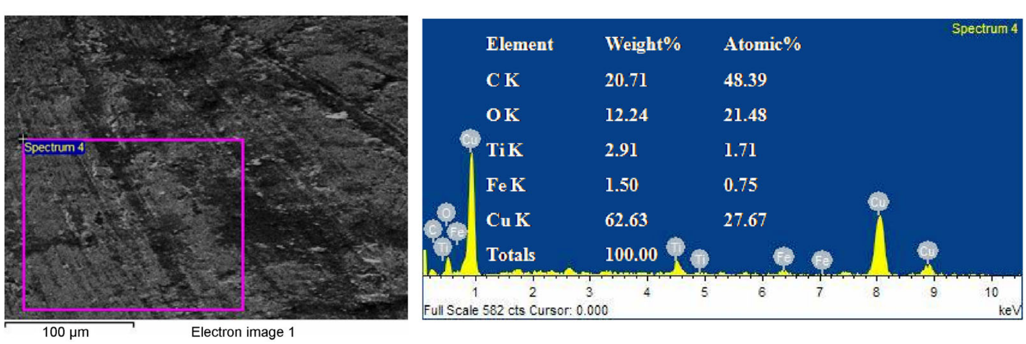

Fig. 11 Typical EDS analysis of the marked portion of the worn surface micrograph of Cu4Ni-4TiC pin.

compaction and sintering. The uniform distribution of the TiC particles can be observed from the microstructure. The hardness of the composite increased until the addition of 4 wt% of TiC, beyond which, it decreased.

2. The wear rate for the composites and the Cu4Ni matrix alloy increased linearly with the load. However, the composites showed a lower wear rate than the matrix alloy, which was correlated with the estimated hardness. The additions of 4 wt% TiC illustrated a better performance in terms of friction and wears, which was attributed to its relatively higher hardness and ability to hold a transfer layer of a relatively larger thickness in comparison to the other materials.

3. The average friction coefficient increased with the increasing load. However, the Cu4Ni matrix alloy exhibited the minimum value of the friction coefficient among all the materials investigated because of its relatively soft nature compared to the composites and the presence of the oxide layer over its surface that provided low shearing junctions at the interface. A relatively higher friction coefficient in the composites was credited to the abrasive action of the hard TiC particles.

4. The wear mechanism for the Cu4Ni matrix alloy was a mix of adhesive and oxidative wear and primarily abrasive for the composites containing hard TiC particles.

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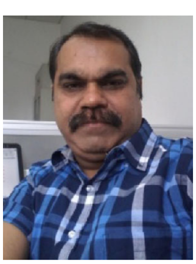

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