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THE FRICTION AND WEAR BEHAVIOR OF Cu-Ni_3Al COMPOSITES BY DRY SLIDING

TRENJE IN OBRABA Cu-Ni_3Al KOMPOZITOV PRI SUHEM DRSENJU

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The suitability of Ni_3Al intermetallics as reinforcements for Cu-base materials in tribological applications has been studied. For this purpose, Cu/Ni_3Al (5 wt %, 10 wt % and 15 wt %) composites were prepared by powder-metallurgy techniques and tested on a pin-on-ring apparatus. The effects of the applied load (83–150 N) at a constant sliding velocity of 0.4 m/s on the wear behaviour of Cu-Ni_3Al composites and wear mechanisms during dry sliding were investigated. The worn surfaces were examined by scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS). It was found that with increasing applied load, the weight loss of the composites increased to levels comparable to those of an unreinforced Cu matrix. In addition, the weight loss increased with the weight percentage of Ni_3Al particles. The coefficients of friction for the composites increased with the increasing of the applied load and increased with increasing the weight percentage of the Ni_3Al particulates. For a Cu-15wt % Ni_3Al composite the weight fraction of reinforcement was critical, as it showed the highest wear rate for all the applied loads.

Key words: metal-matrix composites; Ni_3Al; copper; wear; coefficient of friction

Raziskana je bila primernost za tribološko uporabnost kompozitov Cu-Ni_3Al. Pripravljeni so bili kompoziti (s 5 mas %, 10 mas % in 15 mas %) s tehnologijo metalurgije prahov in preizkušeni na konica – na-obroč napravi.

Raziskani so bili učinki obremenitev (83-150 N) pri konstantni hitrosti drsenja 0,4m/s na obrabo Cu-Ni_3Al in mehanizmi obrabe pri suhem drsenju. Obrabljene površine so bile pregledane v vrstičnem elektronskem mikroskopu (SEM) in analizirane v energijskem spektrometru (EDS). Ugotovljeno je bilo, da se je s postopnim povečanjem obremenitev izguba teže kompozitov povečala na raven primerljivo z neojačano Cu-matico. Izguba teže se je povečala s povečanjem vsebnosti Ni_3Al delcev. Pri Cu-15mas% Al_2O_3 kompozitu se je pokazala kot kritična vsebnost ojačitve z največjo obrabo pri vseh obremenitvah. Koeficient trenja kompozitov se je večal pri večanju obremenitve in še posebej pri večanju vsebnosti Ni_3Al.

Ključne besede: kovinski kompoziti, Ni_3Al, baker, obraba, koeficient trenja

1 INTRODUCTION

The development of metal-matrix composite (MMC) materials in recent years has been one of the most important in the field of materials. Among them, particulate composites are widely used due to the simplicity of their manufacturing. Specifically, MMCs are among the most promising materials for wear-resistant and structural applications, and the use of different possible reinforcement particles was proposed [1].

Metal-matrix composites show a combination of superior mechanical properties, such as a better elastic modulus, tensile strength, and high-temperature stability in comparison with an unreinforced matrix, yet they suffer from poor tensile ductility, fatigue-crack growth resistance and fracture toughness. The sliding wear of the composites is a complex process involving not only mechanical but also thermal and chemical interactions between the surfaces in contact [2]. Particle-reinforced metal-matrix composites are recognized as having a better wear resistance due to the presence of hard particles. These materials can be used as a reinforced part in pistons and in several wear-resistance applications [3,4]. In addition, the wear resistances of these materials are applied in internal combustion engines, as brake rotors, or in the study of the problem of die wear during the extrusion of the metal matrix composites [2]. The tribological behaviour of MMCs depends on the type of MMCs, the counter-face materials and the contact situation.

Cu-matrix composites have demonstrated a superior combination of thermal/electrical conductivity and strength, and exhibit a significant increase in the mechanical properties and an improvement in the tribological properties [5–7]. These attractive properties make such composites promising for sliding electrical contact applications where high electrical and thermal conductivity and good wear resistance are required. More recent studies have considered the possibility of adding intermetallics as a reinforcement, which seems to be a highly interesting option in terms of wear [8]. Ni_3Al is probably one of the best known and characterized intermetallics [9]. Its processing using powder metallurgy provides structural materials with high strength and reliability [10]. Nickel aluminide-based intermetallic compounds have low density, good oxidation resistance and metal-like properties, which makes them attractive materials for a wide range of applications [11,12]. The information presented in the previous paragraphs indicates that the wear behaviour and wear mechanisms of Ni_3Al-reinforced metal matrix composites, especially Ni_3Al/Al matrix composites, are starting to be understood. However, the friction and wear behaviour of Cu matrix composites reinforced with Ni_3Al have not received the attention they deserve. A better understanding of these composites will open the door to the design of new materials that are promising for sliding electrical contact applications where high electrical and thermal conductivities and a good wear resistance are required. So, the present work aims to investigate systematically the influence of load on the dry sliding wear behaviour of Cu-Ni_3Al powder metallurgical composites.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

2.1. Materials

Commercial Cu powder supplied by Merck with an average size of <63 µm was used as matrix and Ni_3Al particles supplied by Alfa (USA) with a mean size of <149 µm were used as the reinforcement. The particle-reinforced composites contained 5, 10 and 15 wt. % Ni_3Al and were fabricated by powder metallurgy (PM) techniques. The powders were mixed for 30 min. and after mixing, the powder mixtures were uniaxially cold pressed at 350 MPa and sintered at 900 °C for 30 min in an Ar atmosphere. The dimensions of the cylindrical specimens were a diameter of 12 mm and a height of 7.5 mm. The SEM in **Figure 1** illustrates a typical microstructure of the Cu-Ni_3Al composite prepared by the powder metallurgy route. This Cu-Ni_3Al composite exhibits a well-dispersed distribution of Ni_3Al particles. The bulk hardness measurements were made using a

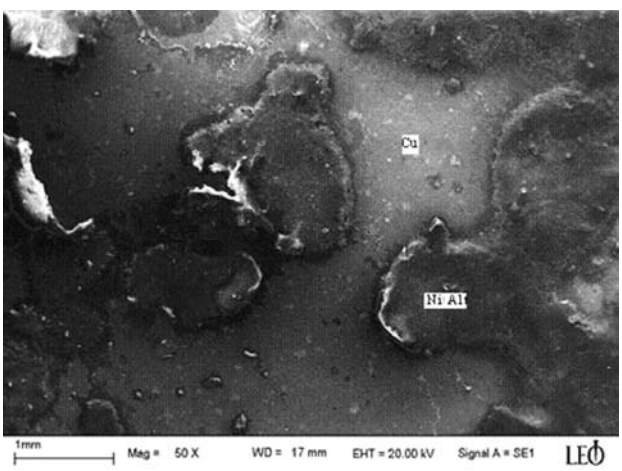

Figure 1: SEM images of a metallographic section of the Cu-10 wt % Ni_3Al composite.
Slika 1: SEM slika Cu-10 wt % Ni_3Al kompozita

Table 1: The macrohardness of the unreinforced Cu and Cu-Ni_3Al composite specimens
Tabela 1: Makrotrdota neojačanega Cu in Cu-Ni3Al kompozitov pri dolžini drsenja 1500 m in hitrosti drsenja 0,4 m/s.

Specimen	Average macrohardness (HB)
Unreinforced Cu	70
Cu-5 wt. %Ni_3Al	75
Cu-10 wt. %Ni_3Al	77
Cu-15 wt. %Ni_3Al	80

Brinell hardness tester, with a contact pressure of 15 g. The results of the hardness test on the composites are listed in **Table 1**. The hardness of the composites is much higher than that of the unreinforced Cu-matrix and it clearly increases with an increasing Ni_3Al weight percentage.

2.2 Friction and wear tests

Sliding-wear and friction tests were performed using a pin-on-ring apparatus with the composite specimen serving as the pin under dry conditions. A schematic diagram of the experimental arrangement is shown in **Figure 2**. The dry-sliding wear tests were carried out at a constant sliding velocity of 0.4 m/s and a constant temperature of 25 °C within an applied normal load in range of 83–150 N. Steel rings with a diameter of 35 mm were used as the counter-face. The counterparts in the experiments were fabricated from AISI 1050 steel as a ring which was hardened to a value of HRC 55. Prior to the tests, the contact surfaces of the composite specimens were polished using 600-, 800-, 1000- and 1200-grit SiC emery paper in running water. The specimens and rings, ultrasonically cleaned and washed in acetone, were weighed to the nearest 0.1 mg using an electronic analytical balance before and after each wear test. The coefficients of friction were obtained periodically by measuring the force on the specimen using a strain-gauge bridge. The microstructures of the specimens were examined by scanning electron microscopy (SEM) and energy-dispersive microanalyses (EDS).

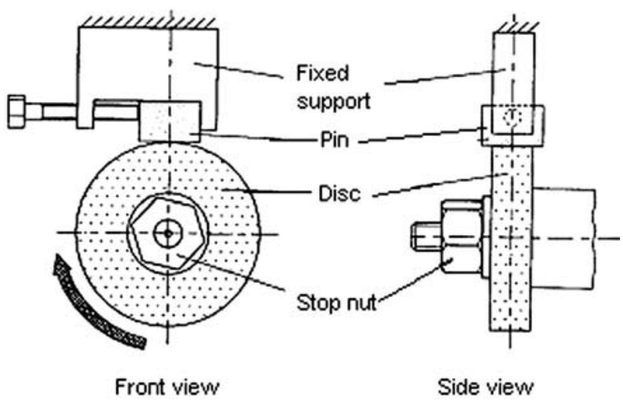

Figure 2: Schematic diagram of pin-on-ring apparatus.
Slika 2: Shematični prikaz trn-na-obroču

3 RESULTS AND DISCUSSION

The relationship between weight loss and load for various reinforcement (Ni_3Al) amounts within the sliding distance of 1500 m is given in **Figure 3**. and shows that the weight loss of all the composite specimens increased with the increasing weight percentage of intermetallics. All types of specimens suffered small weight losses after testing for the lower loads, with the exception of the Cu-15 wt. % Ni_3Al specimen. For loads of 83 and 100 N, Cu- %5 and -%10 wt. The Ni_3Al composite specimens exhibited superior wear resistance to the unreinforced Cu specimens. However, at 150 N, the reverse was true. The weight losses of the Cu-15 wt. % Ni_3Al specimen was close to that of the unreinforced Cu at 100 N. It

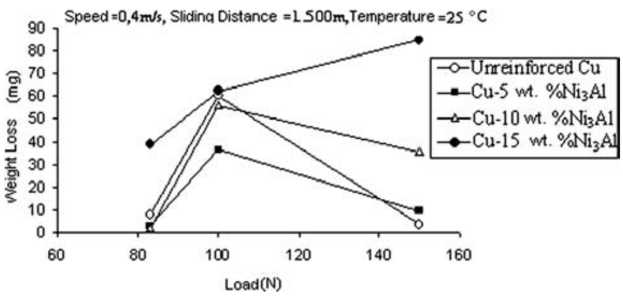

Figure 3: Variation of weight loss with load for all the specimens tested for a sliding distance of 1500 m and a sliding speed of 0.4 m/s.

Slika 3: Variacija izgube teže z obremenitvijo za vse preizkuse pri razdalji drsenja 1500 m in hitrosti 0,4m/s

increased with increasing load and showed the highest weight loss among all the specimens. The wear behaviour could lead to the conclusion that the Ni_3Al particles do not improve the wear resistance of pure Cu at the highest load (150 N). This reveals that Ni_3Al-particle-reinforced Cu matrix composites have the ability to increase the wear resistance for the lower loads (83 and 100 N). The hardness of the Ni_3Al particle is larger than that of the Cu, and the particle can keep the structural integrity of the composite at low loads. When the load is increased to reach the fracture strength of the particles, the particles began to fracture[3] and to increase the intensity of wear. For particle-reinforced composites, the particles near the contact surface may more readily induce the nucleation of cracks due to the interface debonding between the particles and the matrix in comparison to the unreinforced Cu. In the sliding wear process, these cracks may propagate and connect to form subsurface cracks. In this way, the subsurface damage process is increased by the presence of particles [3]and for all applied loads, the weight loss of the Cu-15 wt. % Ni_3Al composite is higher than that for other tested materials. Thus, the wear behaviour leads to the conclusion that Ni_3Al particles do not improve the wear resistance of the Cu matrix with the highest load (150 N).

Figure 4a and b show SEM images of the worn unreinforced specimen surfaces at loads of 83 and 150 N. At low load the surface exhibited a plastic flow occurring because of the adhesion in the wear surface of

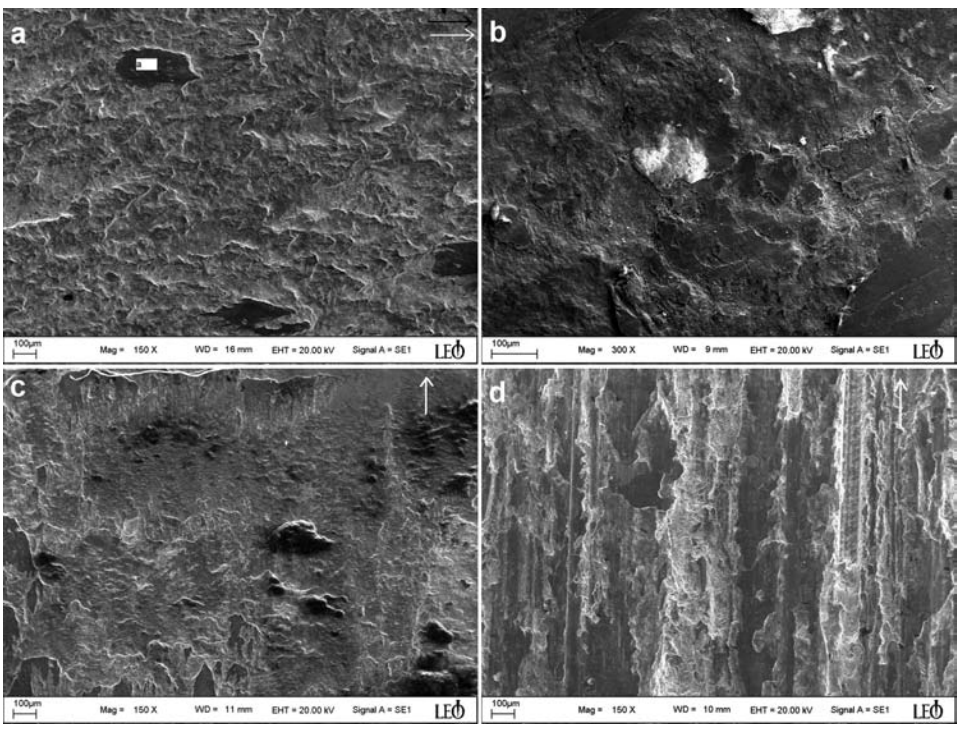

Figure 4: SEM images of the worn surfaces: (a) unreinforced Cu matrix tested at 83 N; (b) unreinforced Cu matrix tested at 150 N; (c) Cu-10 wt % Ni_3Al composite tested at 83 N; and (d) Cu-10 wt % Ni_3Al composite tested at 150 N. The arrow indicates the sliding direction.

Slika 4: SEM slike obrabljene površine: (a) neojačana Cu matica testirana pri 83 N, (b) neojačana Cu matica pri 150 N, (c) Cu-10 wt % Ni_3Al kompozita pri 83N, (d) Cu-10 wt % Ni_3Al kompozit pri 150 N. Puščica prikazuje smer drsenja.

the unreinforced Cu. The delamination, which is a common wear mechanism, was progressive. In addition, adhesive wear predominates because of the tear areas with large ripples were mostly present. As the load was increased, the occurrence of tear areas with large ripples at the highest load was not observed and large areas with large smooth grooves appeared. This explains why the weight loss of the specimen worn at 83 N was higher than that of the specimen worn at 150 N (the reason is explained with EDS results in a later paragraph). The SEM micrographs of the worn surface of Cu-10 wt. % Ni_3Al composite are presented in **Figure 4c and d**. The wear mechanisms involving plastic deformation, ripple layers and the pulling out of particles at applied loads is observed and the delamination also progressed, and at 150 N the composite surface exhibited extensive grooving, most probably produced by ploughing with the harder asperities, which pulled out the composite on the counter surface, and also showed abrasive wear characterization. On the other hand, compared with the unreinforced Cu matrix, the local plastic deformation on the worn composite surface was reduced at 83 N (nearly the same as 83N with the Cu-5wt. % Ni_3Al composite specimen). The surface was smoother than the unreinforced Cu matrix, but was still covered with grooves. The composite worn surface at 150N was generally rougher than that of the surface at 83 N.

For the composites investigated, the most important feature is the presence of Ni_3Al particles, whose hardness (HV 381) is much greater than the Cu matrix and lower than that of the steel counterpart. During the sliding wear process, the Cu-matrix surrounding them was rapidly worn away and all the contact was essential between the Ni_3Al particles and the steel counterpart [16]. The sliding wear imposed a substantial tangential force on the Ni_3Al particles in contact with the counterpart and the resulting shear stress at the particle-matrix interface. Generally, increasing the contact pressure tends to increase the shear stress. At low loads, the shear stress was too small to debond or pull out the Ni_3Al particles from the Cu-matrix or deform the matrix plastically causing cracks. So, the wear rate of composites was controlled by the wear rate of the more wear-resistant Ni_3Al phase. Thus, the wear losses of the composites were mainly dependent on the level of the applied load and the weight percentage of Ni_3Al particles. Compared with the unreinforced Cu matrix, the local plastic deformation on the worn surface (**Figure 4c, d**) was greatly reduced. This suggests that the extent of the wear was reduced by the presence of Ni_3Al, presumably because of the reduced driving force for the reaction between this phase and the counter surface. For the investigated specimens the wear surface showed a predominantly adhesive wear at the lower load (small ripples with craters) and changes to a predominantly abrasive-adhesive wear at the higher loads (large smooth areas with long grooves).

In **Figure 5** the EDS results of the worn surface of the unreinforced Cu specimen tested at 83–150 N and that of the worn surface of Cu-10 wt. % Ni_3Al composite specimen tested at 83–150 N are shown. For both loads, the EDS spectra indicated that the specimens also contained Fe and O. The higher intensity of the Fe indicates the transfer of counter-face materials to the surface of the specimens (see also **Figure 4a**). Fe and O was present in both materials, but in much greater quantities at the highest load for composite specimens, while at 150N the reverse was true for the unreinforced Cu specimen. The concentration of Ni for the composite specimen also showed some increase, reflecting the fact that worn Ni_3Al fragments spread onto the surface. The wear products coming either from the counter-face (Fe-rich oxides) or the worn surface itself penetrate into the Cu matrix. This leads to the formation of a mechanically mixed tribolayer (MML) that is basically made up of oxide particles and Cu [13,14]. Further work, including a detailed examination of the MML layer with TEM, is underway to identify the wear mechanisms and the wear results, and this will be reported at a later date. In addition, by the transfer of Fe from the counter-face to

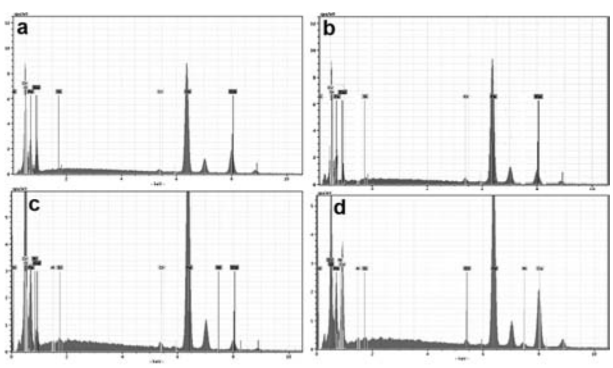

Figure 5: (a) EDS spectra of areas (labelled by "a ") of the worn surface of the unreinforced Cu specimen tested at 83 N, (b) EDS

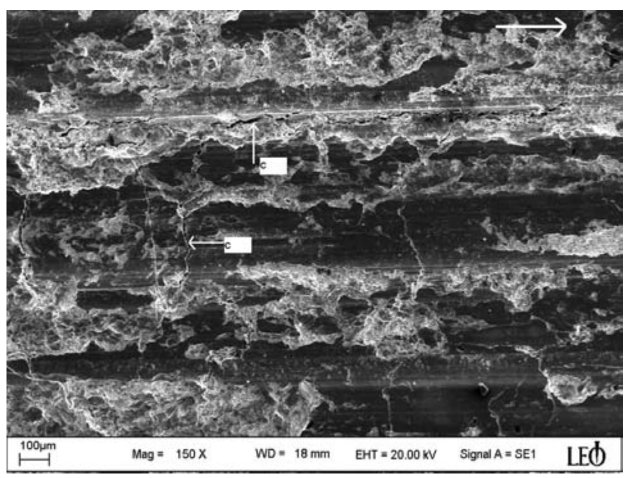

Figure 6: SEM images of the worn surfaces of Cu-15 wt. % Ni_3Al composite at 150 N ("c " showed cracks). The arrow indicates the sliding direction.

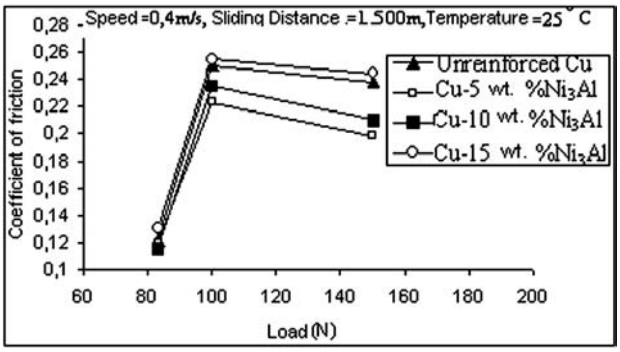

Figure 7: The coefficient of friction of unreinforced Cu and the composites for a sliding distance of 1500 m and a sliding speed of 0.4 m/s.
Slika 7: Koficient trenja neojačanega Cu in kompozitov z obremenitvijo pri drseči razdalji 1500 m in pri hitrosti drsenja 0.4 m/s.

the matrix severe plastic deformation was observed in the matrix around these particles (Fe-rich regions labelled as "a" in **Figure 4a**).

On the other hand, at a high applied load (150 N), it showed that increasing the weight percentage of the Ni_3Al particulates tends to cause an increasing weight loss of the composite (see **Figure 3**). Increasing the weight percentage of the Ni_3Al particulate causes a reduction in the extent of the plastic deformation of the matrix, and increasing the load tends to cause extensive plastic deformation of the matrix, and an increase in the number of cracks formed at the particulate-matrix interface due to poor cohesion that can cause particle decohesion. Due to the occurrence of work-hardening of the plastic deformation in the subsurface materials, cracks nucleated around the reinforcement particulate. Under repeated loading and deformation, these cracks propagated in the matrix (see **Figure 6**). This situation then occurred in the Cu-15 wt % Ni_3Al composite specimen. Eventually, the propagating cracks joined, causing the particles to pull out. The detached particles would also cause severe abrasive wear against the composite. **Figure 6** clearly revealed grooves (as "g") and to some extent cracks, which are parallel and perpendicular to the sliding direction (indicated by arrow as "c") and severely damaged regions on the worn surface of the Cu-15 wt.% Ni_3Al composite at 150 N. The wear rate of the composites containing a high volume fraction of particulate increased considerably under the high-contact-pressure conditions when applying a high load (150N). In the present tests, the results show that all the applied test loads are high for the Cu-15 wt. % Ni_3Al composite specimens.

The results of the coefficient of friction for unreinforced Al and the composites with different applied loads are shown in **Figure 7**. The coefficients of friction for the composites, with the exception of the Cu-15 wt. % Ni_3Al composite, were lower than those for the unreinforced Cu matrix. With an increasing volume fraction of Ni_3Al particulate, the coefficient of friction for the composite increased, especially at high loads (100 N and 150 N). The coefficient of friction for all the materials increased with increasing load. This result is in good agreement with the results in references [15,16]. In fact, the friction coefficient is in general determined by two contributions: the first due to the adhesive interaction between the contacting asperities and the second related to the ploughing contribution due to abrasion [16]. At high loads the contribution of the adhesion increased in importance because the greater hardness reduced the contribution of the abrasion, and the friction coefficient is increased with the load because of the increase in the real area of contact. In reality, the sliding wear will impose a substantial tangential force on the particles in contact with the steel counter surface and the resulting shear stress at the particle-matrix interface can cause particle decohesion. Thus, the wear rate will be largely controlled by the rate at which particles decohere. The effect of the shear stress is related to the friction coefficient: if the friction coefficient is low, the effect of the shear stress is low [17]. However, if the particle decohesion is easy, the contact will be between the copper matrix and the steel counter surface, and the wear rate of the composite will be comparable or even greater. Since loose hard particles can cause third-body abrasion, the friction coefficient will be high. This situation, in the present experiments, was progressive for the Cu-15 wt. % Ni_3Al composite specimens. The friction coefficient of those specimens was higher than that of the unreinforced Cu matrix for all the loads.

4 CONCLUSION

Based on the friction and wear studies for dry sliding between unreinforced Cu/Ni_3Al composites and a GCr15 steel counterpart, the following conclusions were drawn.

1. At all loads the weight loss of the composites increased with an increasing weight percentage of Ni_3Al particulate. At low loads, the wear resistance of the Cu-5% and -10 wt. % Ni_3Al composites are about an order of magnitude better than that of unreinforced Cu, which is attributed to the wear of the copper matrix directly with the steel. On the other hand, due to the poor interfacial bonding between the particles and the matrix, the Cu-15 wt. % Ni_3Al composite showed a critical weight fraction of reinforcement, and the wear results indicate that the highest wear rate was observed for the Cu-15 wt. % Ni_3Al composite specimens for all the applied loads.

2. For composite materials, a significant amount of Fe (from the counter-faces), Ni, O particles is incorporated into the Cu matrix, forming a wear surface, with its Fe, Ni, O content increasing with load.

3. The coefficients of friction for the composites were increased with increasing the applied load from 83 N to 100 N, and continued nearly with same rate to 150 N. In this relation, the coefficient of friction for the composites

also increased with increasing the weight percentage of the Ni_3Al particulate. The highest friction coefficient was observed for the Cu-15 wt. % Ni_3Al composite specimens in all the test specimens.

The overall wear tests and results presented in this manuscript for the Cu-Ni_3Al composite was made of studies of the wear of the MMC up to this time. So, an explanation of wear mechanisms mentioned in the paper matched with other studies made on other metal matrix composites labelled as references in the paper. But the results may not be matched with the other results related to MMCs.

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5 REFERENCES

[1] Da Costa, C. E., Torralba, J. M., Velasco, F., Mechanical, intergranular corrosion,and wear behavior of aluminum-matrix composite materials reinforced with nickel aluminides, Metallurgical and Materials Transactions A 33A (**2002**), 3541–3553

[2] A. T. Alpas, J. Zhang, Effect of microstructure (particulate size and volume fraction) and counterface material on the sliding wear resistance of particulate-reinforced aluminum matrix composites, Metallurgical and Materials Transactions A 25A , (**1994**), 969–982

[3] R. Chen, A. Iwabuchi, T. Shimizu, H. S. Shin, H. Mifune, The sliding wear resistance behavior of NiAl and SiC particles reinforced aluminum alloy matrix composites, Wear 213 (**1997**), 175–184

[4] M. Muratoglu, M. Aksoy, the effects of temperature on wear behaviours of Al- Cu alloy and Al-Cu-SiC composite, Materials Science and Engineering A, 282 (**2000**) 1–2, 91–99

[5] J. D. Verhoeven, F. A. Schmidt, E. D. Gibson, W. A. Spitzig, Copper-refractory metal alloys, J. Metals, (**1986**), Sept., 20–24

[6] H. L. Downing, J. D. Verhoeven, E. D. Gibson, The emissivity of etched Cu-Nb in situ alloys, J. Appl. Phys. 61 (**1987**) 7, 2621–2625

[7] P. D. Funkenbusch, T. H. Courtney, D. G. Kubisch, Fabricability of and microstructural development in cold worked metal matrix composites, Scripta Metall. 18 (**1984**), 1099–1104

[8] Z. Chen, P. Liu, J. D. Verhoeven, E. D. Gibson, Sliding wear behavior of deformation-processed Cu-15 vol.% Cr in situ composites, Wear 195 (**1996**) 1–2, 214–222

[9] J. L. Gonza´lez-Carrasco, F. Garci´a-Cano, G. Caruana, M. Lieblich, Aluminum / Ni_3Al composites processed by powder metallurgy, Materials Science and Engineering: A 183, (**1994**), L5–L8

[10] P. Pérez, J. L. González-Carrasco, G. Caruana, M. Lieblich, P. Adeva, Microstructural characterization of P/M Ni_3Al consolidated by HIP, Materials Characterization, 33 (**1994**), 349–356

[11] P. Pérez, J. L. González-Carrasco, P. Adeva, Influence of the powder particle size on tensile properties of Ni_3Al processed by rapid solidification and hot isostatic pressing, Materials Science and Engineering A, 199 (**1995**), 211–218

[12] D. B. Miracle, Overview No. 104 The physical and mechanical properties of NiAl, Acta Metallurgica et Materialia, 41 (**1993**), 649–684

[13] A. E. Anderson, Friction and wear of automobile brakes, ASM Handbook, 18 (**1992**), 569–577

[14] G. Strafellini, M. Pellizzari, A. Molinari, Influence of load and temperature on the dry sliding behaviour of Al-based metal-matrix-composites against friction material, Wear 256 (**2004**), 754–763

[15] R.D. Neobe, R.R. Bowman, M.V. Nathal, Int. Mater. Rev. 38 (**1993**), 193

[16] J. P. Tu, L. Meng, M. S. Liu, Friction and wear behavior of Cu-Fe_3Al powder metallurgical composites in dry sliding, Wear, 220 (**1998**), 72–79

[17] Y. Wang, W.M. Rainforty, H. Jones, M. Lieblich, Dry wear behaviour and its relation to microstructure of novel 6092 aluminium alloy-Ni_3Al powder metallurgy composite, Wear 251 (**2001**), 1421–1432