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Kumar, Harsh
Department of Mechanical Engineering, National Institute of Technology Kurukshetra

Kumar, Vikas
Department of Mechanical Engineering, National Institute of Technology Kurukshetra

Kumar, Dinesh
Department of Mechanical Engineering, National Institute of Technology Kurukshetra

Singh, Satnam
Department of Mechanical Engineering, National Institute of Technology Kurukshetra

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Wear Behavior of Friction Stir Processed Copper-Cerium Oxide Surface Composites

Harsh Kumar[1], Vikas Kumar[1], Dinesh Kumar[1*], Satnam Singh[1]
[1]MED, NIT Kurukshetra, India

*E-mail: dinesh_61900120@nitkkr.ac.in

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Abstract: Today's surface modification methods include friction stir processing (FSP). using a combination of heat generated by the friction between the tool and the workpiece, intense plastic deformation, and stirring to mix the matrix material. To create a consistent and dense microstructure, the FSP continuously improves the material's surface characteristics. In addition, this unique method enables the creation of surface material matrix composites by incorporating various reinforcement particles (MMC). The importance of various types of reinforcing particles during FSP and their effects on surface properties like hardness, tensile strength, and wear behaviors have recently been the subject of a lot of research. Under various applied weights, sliding distances, and sliding velocities, the manufactured copper-cerium oxide surface composite was put through a sliding wear test. The FSP-ed surface composites had the lowest wear rate of 0.0039 mm3/N-m, and SEM analysis shows that the delamination layer and peeled-off behavior were seen on the worn-out surfaces.

Keywords: copper, cerium oxide, friction stir processing, surface modification, wear.

1. Introduction

Due to its improved thermal conductivity and electrical conductivity, copper (Cu) has been employed in a number of industries, including those that produce thermal contacts, welding electrodes, and electronic packaging[1)]. However, everyone is aware that pure copper lacks good tensile, yield, creep, and hardness properties[2)]. However, adding ceramic, carbide, and oxide elements to the copper matrix as reinforcements can improve the aforementioned qualities of the resulting MMCs[3)]. In electrical machines, the system's primary job is to transmit current from the fixed conductor to the moving conductors, and for that job, the biggest challenge was doing so effectively[4)]. The most common method of current transfer interface used nowadays is when two conductors are sliding. Sliding force and wear from current transfers are two sorts of issues that affect sliding interfaces[5)].

Due to their size, diffusivity, spacing, distribution, low solubility, and thermodynamic stability, the reinforcement particles' integration into the matrix material improves the strengthening mechanism, creep resistance, and hardness of the resulting MMCs[6)]. Authors have covered the characterization and fabrication of ceramic-based copper composites in earlier research. Metal matrix nanocomposites have been the subject of a few studies, which have improved the generated MMCs' characteristics. Cerium oxide is used as a nano-oxide reinforcement in the current investigations to create nano-oxide metal matrix composites. Some uses for the aforementioned copper-cerium oxide MMCs include brushes for motors, pantographs, railway collector shoes, sliding connections, and bearing materials.

Yuvaraj et al. produced a copper metal matrix composite using the FSP process using a copper alloy that was reinforced with 2 and 4 weight percent of yttrium oxide. SEM was used to establish that the Y_2O_3 particles were evenly dispersed and had solid contact with the matrix[7)]. Mohanad Lateef Hamada and colleagues discussed the behavior of Cu reinforced with varying weight percentages of Y_2O_3 from 0% to 20% over a five-day period. The composites were made using the FSP method. The reinforcing distribution was good up to 10wt%, but beyond that, some yttria particles formed agglomerations and clumped together, increasing porosity for 15wt% and 20wt% composites[8)]. Hafeez Ahamed and V. Senthil Kumar created a copper hybrid nanocomposite that also contained a particular amount of nanosized Al_2O_3 and Y_2O_3 powder. Prior to compaction and sintering, the samples of Cu, Cu/1.5 Al_2O_3, Cu/1.5 Y_2O_3, and Cu/0.75 Al_2O_3/0.75 Y_2O_3 were prepared using the FSP process. According to reports, ultrafine grains were created using high-pressure mechanical milling [9)]. W. B. Bouaeshi et al. doped yttrium oxide on the surface of copper metal to enhance surface characteristics. It is likely that the yttria particles may have melted or broken down because the temperature of the arc-melting (3700C) was greater than the yttria's melting point and there was no sign of Y_2O_3 particles in the microstructure analysis of the yttria-Cu samples (2430C). A new phase known as Al3Y has been established by the samples' XRD pattern. The Cu-20wt% Y_2O_3 sample showed stronger and superior wear resistance because the Cu3Y phase was formed, and the microstructure was changed. This was also observed in samples made of yttria, which had improved corrosion resistance[10]. Barmouz et al. processed copper and silicon carbide surface composite using the friction stir processing route. The strength was decreased after the addition of Sic particles in pure copper metal matrix and also concluded lower wear resistance in fabricated MMCs compare to pure copper[11]. Dinaharan et al. utilized the FSP method to fabricate Cu/TiB_2 surface composite. The author concluded that the hardness value of 128 HV was noted with an 18% volume addition of TiB_2 particles in the copper matrix. The lower wear rate of 148 x 10^{-5} mm^3/m was also attained with the same weight percentage of the reinforcement in CMMCs[12]. Very less literature was found on this combination. In most of the research papers, either cerium oxide was used as single reinforcement or in combination with different reinforcement like SiC, Al_2O_3, CNT, TiO_2, etc.[5-12]

2. Material and Methods

According to the industry, copper, aluminum, magnesium, and their different alloys are the materials most frequently utilized in the FSP process[13]. Copper alloys are simple to cast and produce for various automobile industry components. Electrical cables, semiconductor device bushes, electrical contacts, wind turbines, railway technologies, and bearing inner lining materials all utilized copper. The material for use in the project was copper. Using a hand cutter, the copper samples were divided into tiny fragments that measured 150 mm x 40 mm x 5 mm. The plate joining area was filed to create the surface's smoothness and alignment[14]. The composition of pure copper was also mentioned in table 1.

In this study, pure copper plates with dimensions of 150 mm x 40 mm x 5 mm were prepared and used as the base material. A square section measuring 1 mm x 1 mm was machined along the work plate's focal point. Although the deliberate typical size of the powder is around 5 m, crude cerium oxide was purchased and powdered through a treated steel ball plant at a speed of 142 m/sec with a handling season of 45 min. For easier handling, the cerium oxide powder is tightly packed into the notch. The H13 steel tube-shaped FSP device with pin dimensions of 4.7 mm in diameter and 4.7 mm in length was retrofitted into a 1.5-ton stacking capacity native make CNC processing machine at SIEMENS.

Table 1: Composition of Pure Copper

Element	Nb	V	Si	P	Ni
Wt.%	0.0002	0.0002	0.0073	0.0021	0.0038
Element	Ti	Mn	Sb	Co	Cu
Wt.%	0.0002	0.0251	0.005	0.002	99.96

The groove was initially sealed using the pin-less tool to prevent the sprinkling of reinforcement particulates. The examples were handled at a variety of interaction boundaries, including a device tilt angle of 0.5°, instrument rotational speed of 1000–1200 rpm, and translational speed of 25–45 mm/min. These limits were established after a series of preliminary tests using examples without deformities. For consideration, nine examples were chosen. Sequential passes typically result in significant imperfections. Copper base metal and the handled example (FSP-ed) without any reinforcements were also taken into consideration for examination. Figure 1 shows the experimental setup and surface composite specimens.

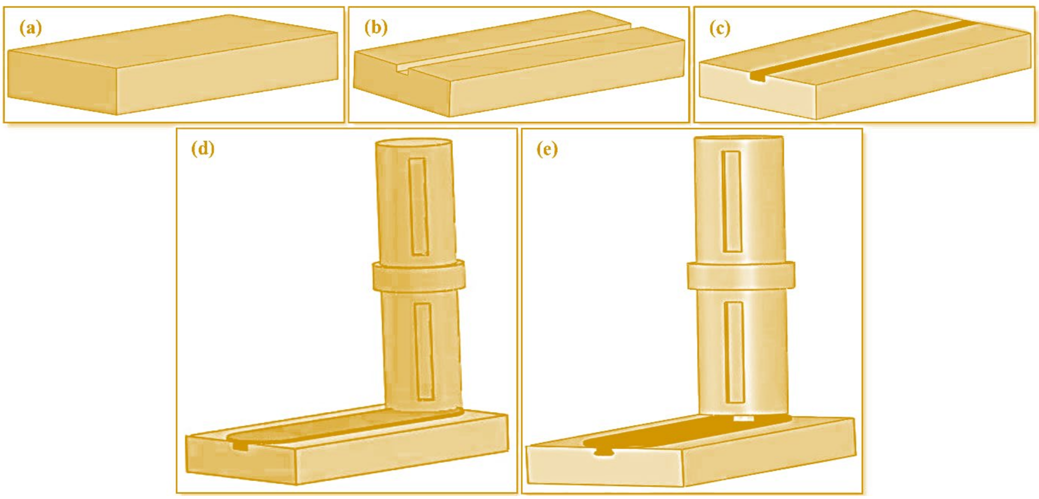

Figure 1 (a-e): Representation of FSP; (a) Copper as base metal, (b) Formation of groove, (c) Cerium oxide as reinforcement packing in the groove, (d) Use of pin-less tool to close the groove, and (e) Fabrication of FSP-ed surface composite with tool-pin

3. Wear test

On a Single-sample wear tester (SSWT), a copper alloy composite loaded with cerium oxide, abrasion tests are carried out utilizing a pin-on-disc arrangement for wear test against the steel surface complied with the ASTM G99 standard. It was a hardened steel disc with 68 HRC. On a fixed sample holder, samples (20 x 8 x 8 mm in size) were loaded vertically. Wear on the FSP-ed SC3 specimen was observed with the pin-on-disc instrument. The weight loss was measured before and after the test, in addition to the friction data, vibration behavior, and noise behavior, which were all recorded. To get rid of material remnants and wear accumulation, the specimen's contact surfaces are polished with 200, 320, 420, and 600 Grits sandpaper for a few minutes at the start of each run of the tests. After being taken out, it is alcohol-rinsed. After being cleaned with alcohol, the weight of each specimen was measured for all tests with an electronic balance that was calibrated to an accuracy of 0.001 mg (TL-201, manufactured by Top-lab India Pvt. Ltd.). The information that was gathered and examined includes specific wear rates expressed as weight loss values. To measure the abrasion wear of FSP-ed SCs samples, gravimetric measurement (gram (g) using precision electronic balances) and sample height loss (micrometer units for LVDT sensors) were both employed. Precision 0.001 mg; groove diameter 40 mm.

$$\mathrm{Ws} = \Delta m/(\rho * Vs * t * fn)$$

Where m denotes the mass loss of the models (in grams), q the model density (in grams per cubic centimeters), vs the sliding velocity (in meters per second), t the test period (in seconds), and fn the normal load (N).

3. Results and discussion

3.1 Hardness and Tensile Strength

Hardness and tensile strength were measured using Vickers hardness tester and Universal testing machine respectively.

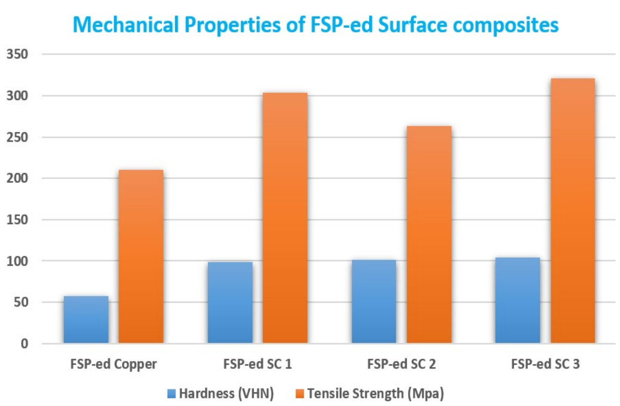

Figure 2: Mechanical properties of FSP-ed SCs

The FSP-ed copper means friction stir processed of copper (base material) without reinforcement addition. FSP-ed SC1, FSP-ed SC2, and FSP-ed SC3 show the friction stir processing with the addition of cerium oxide as reinforcement with one pass, second pass, and third pass of the pin-tool. Figure 2 shows that FSP-ed SC3 possesses higher hardness and tensile strength compared to all the other specimens. It also shows that the addition of reinforcement gives enhancement in the hardness and tensile strength compared to base alloy after one pass, second pass, and third pass.

3.2 Wear Behavior

The wear test analysis was done on the DUCOM tribometer present in the tribology lab (Mechanical Engineering Department) of NIT Kurukshetra.

Wear is also a significant parameter to develop a new material because it gives us the life or span of the material under different environmental or loading conditions. In the current study, a wear test was done on samples having higher hardness. The composition of the sample was copper as a matrix material reinforced with 5 vol.% of cerium oxide using friction stir processing with different parameters as mentioned earlier. The test was conducted under different loads, sliding velocities, and distances[13]. The values of the wear rate were mentioned in table 2. The main effect graphs of individual parameters during the wear test were also drawn as represented in figures 3 (a, b, and c).

Table 2: Wear rate under different conditions

Load (N)	Sliding Distance (m)	Sliding velocity (m/s)	Wear rate (mm^3/N-m)
5	500	0.5	0.0045
5	1000	1	0.0042
5	1500	1.5	0.0048
10	500	1	0.0075
10	1000	1.5	0.0071
10	1500	0.5	0.0039
15	500	1.5	0.0090
15	1000	0.5	0.0083
15	1500	1	0.0069

The three parameters were selected for the wear test: applied load, sliding distance, and velocity. The combination was prepared according to the design of the experiment. The effect of the individual parameter was observed for the wear of the specimens as discussed below:

3.1.1 Influence of Applied load on wear rate for Cu-CeO2 Composite

Under sliding distance and velocity conditions with three levels each, the influence of applied stress on the wear rate of the constructed composites was observed. The relationship between applied load and wear rate during the wear test is depicted in Figure 3(a). 5, 10, and 15 N were the three levels of load that were applied. The graph shows how the wear rate grew steadily as the load did. Since wear resistance and wear rate are inversely related, greater wear rates imply poorer wear resistance. Compared to loads of 10 and 15 N, the 5 N load exhibits a low value of wear rate. In copper-cerium oxide composites, the load increment induces wear severity, which in turn creates wear debris and delamination in the specimen[15–17].

3.1.2 Influence of Sliding distance on wear rate for Cu-CeO2 Composite

Figure 3 (b) illustrates how the wear rate varies with sliding distance. With the increase in sliding distance, a decrease in wear rate was seen. At a 1500 m sliding distance, the highest wear rate was observed. It was discovered that the wear rate consistently decreased. The produced composite's enhanced wear resistance is caused by the homogeneous mixing and bonding of copper and cerium oxide in the composite[18–21].

3.1.3 Influence of Sliding velocity on wear rate for Cu-CeO2 Composite

The wear rate of the copper and cerium oxide composite is shown in Figure 3 (c) as a function of sliding velocity during the wear test. Similar behavior to that seen with the imposed load is depicted in the image. The increase in sliding velocity from 0.5 m/s to 1.5 m/s resulted in an increase in wear rate. The material experiences less wear and more wear resistance at a sliding speed of 0.5 m/s. The material loss in the wear test is caused by abrasive and adhesive wear. The specimens have significant volume loss as a result of the disc and manufactured material rubbing against one another[22–25].

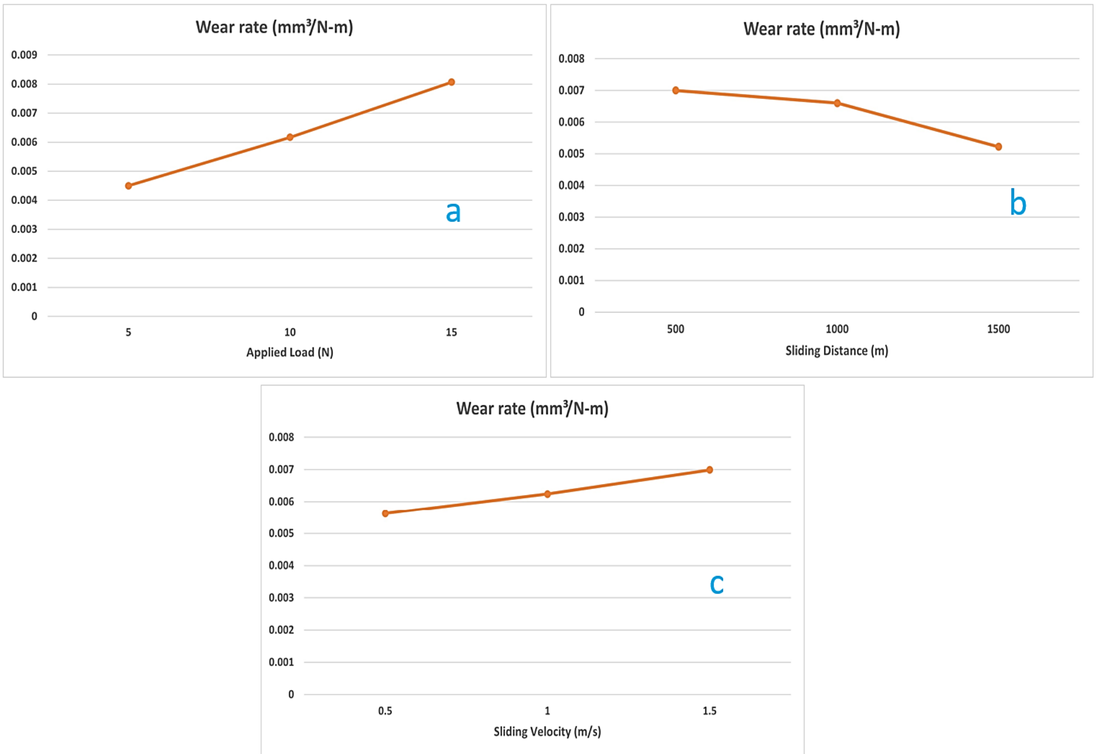

Figure 3 (a-c): (a)Effect of load, (b) sliding distance, and (c) sliding velocity on the wear rate

3.2 Morphology of Worn-out surfaces

The sliding wear behavior was analyzed under different conditions and worn-our surfaces were observed using a scanning electron microscope (JSM-6390LV, manufactured by JOEL USA). The applied load affects the wear rate most effectively out of all the parameters and due to this reason, the worn-out surfaces were analyzed at 5, 10, and 15 N of applied loads. The peeled-off particles, delamination, and abrasive wear were noticed under 5 N load as mentioned in figure 4 (a) [12,26,27]. The oxidation and adhesive wear were observed when tested under 10 N load as shown in figure 4 (b). The delamination and small particles are peeled out from the surface of the FSP-ed composites as displayed in figure 4 (c) [28–30]. The addition of cerium oxide particles to the copper boosts the manufactured specimens' hardness and wear resistance.

However, a rise in the hardness of the surfaces that touch each other causes the material to deteriorate and erode. Additionally, during the sliding wear of the specimens, there is a chance that a heterogenous dispersion layer may emerge, producing debris in the form of copper, iron, and cerium oxide particles. The composites' rate of wear is decreased by the flat surfaces and high hardness produced through plastic deformation. Under the load of 10 N, 1500 m, and 0.5 m/s sliding distance and velocity, respectively, the minimal wear rate of 0.0039 mm3/N-m was noted.

The EDS analysis confirms the presence of copper and cerium oxide in the produced FSP-ed surface composite. Figure 4 (d) shows the constituent weight percentages of the FSP-ed surface composite.

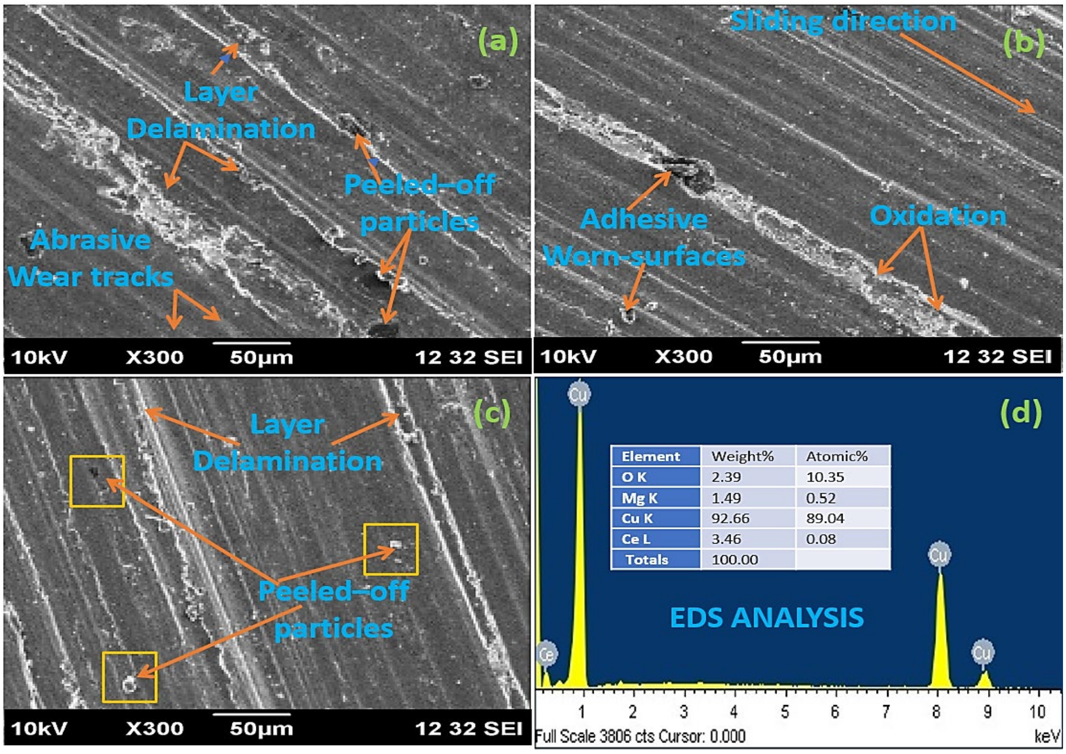

Figure 4 (a, b, c, and d): Worn-out surfaces at applied loads; (a) 5 N, (b) 10 N, (c) 15 N, and (d) EDS analysis

6. Conclusions

The friction stirs processing of copper matrix surface composites showed the impact of cerium oxide, and the FSP-ed surface composite also showed wear behavior. The conclusions are listed below.

- Copper matrix surface composites reinforced with a consistent quantity of cerium oxide were prepared using friction stir processing.
- The enhancement in hardness (103 VHN) and tensile strength (321 MPa) were achieved in the FSP-ed surface composite after the third pass.
- The manufactured copper-cerium oxide surface composite was subjected to sliding wear tests at various applied weights, sliding distances, and sliding velocities.
- The wear rate rose when the applied force was increased, and a low wear rate was achieved with an applied load of 10 N, a sliding distance of 1500 m, and a sliding velocity of 0.5 m/s.
- The lowest wear rate was determined to be 0.0039 mm3/N-m, and SEM examination shows that worn-out surfaces of the FSP-ed surface composites exhibited delamination layer and peeled-off behavior.

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