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Article

Tribological Behavior and Wear Mechanisms of Powder Metallurgy Copper-Titanium Dioxide Composites under Dry Sliding Conditions

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Abstract: This research analyzes the tribological properties and wear mechanisms of copper-titanium dioxide (Cu-TiO_2) metal matrix composites developed using powder metallurgy subjected to dry sliding conditions. Cu-TiO_2 composites having TiO_2 nanoparticles of 0, 2, 4, 6, and 8 wt% were developed via mechanical mixing, cold compaction (300 MPa), and sintering (900°C in hydrogen) and tested tribologically comparing against hardened steel (EN31) counterface using a pin-on-disk tribometer at loads of 10, 20, 30N while sliding at velocities of 0.5, 1.0, 1.5m/s. Wear mechanisms were examined using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and surface profilometry. Results indicated that wear resistance was enhanced with TiO_2 additions, with the most favorable performance at 6 wt% TiO_2 loading. The wear rate decreased from 2.45×10^{-4} mm³/Nm for pure copper, to 0.68×10^{-4} mm³/Nm for Cu- 6wt%TiO_2 (72% improvement). The coefficient of friction decreased from 0.52 to 0.38 with increasing addition of TiO_2. Observations according to wear mechanisms determined that the severe adhesive and abrasive wear conditions experienced in the pure copper material evolved into mild oxidative wear when subjected to the TiO_2-reinforced composites. From the tests it was noted that a tribolayer formed which included TiO_2 particles and copper oxidizing compounds which had attributed positively to the tribological properties of the material. These results emphasize the potential of Cu-TiO_2 composites for improving wear resistance in sliding bearing and electrical contact applications.

Keywords: Copper matrix composites, Titanium dioxide, Tribology, Wear mechanisms, Powder metallurgy, Dry sliding

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1. Introduction

Tribological performance is an important design factor for copper-based components that operate continuously in contact with other materials in relative motion. The inherent softness of pure copper and its tendency to smearing and adhering process, will typically lead to high wear rates and short service life [1], [2]. Copper-based matrix composites reinforced with ceramic particles are an effective approach to improve total wear while still providing the benefits of using copper for its properties, such as electrical and thermal conductivity. Of different ceramic reinforcements tested with copper, titanium oxide (TiO_2) has received considerable focus due mostly to its properties including moderate hardness, chemical stability and lubricating properties in some environments [3], [4].

Like all metals, the tribological behavior of metal-matrix composites has unique characteristics that result from the multiple interactions of displaced reinforcement particles, matrix and counterface during the sliding contact . In order to determine how to improve the properties in service, the researcher must contemplate the various interactions that occur in terms of wear mechanisms [5]. Due to the number of possibilities, composite reinforcements can alter several aspects of tribological behavior simultaneously, including load-bearing, friction, the amount of wear debris generated and the material films that protect the surfaces from further damage [6].

Copper is widely used in electrical applications, such as electrically conductive materials, sliding electrical contacts, thermal management and any other tribological component where quick electrical conduction is necessary, so improving tribological performance is of the most value . In all electrical contact applications, wear resistance affects primary reliability and service life, while excessive wear in things like sliding bearings can affect its performance due to dimensional alteration [7], [8]. Traditional methods of enhancing wear resistance of copper through alloying often have a substantial loss of electrical conductivity, thereby limiting their applications in electrical systems.

TiO_2 has many reasons for being chosen as a reinforcement material besides its subordinately mechanical properties. TiO_2 has many crystalline phases, but the anatas and rutile phases are the most applied in tribological applications with their own properties. TiO_2 chemical composition has moderate hardness (600-1000 HV) has enough underlying hardened material that promotes wear resistance without over-agitating the surface abrasiveness of the opposing material, which is pertinent in electrical contact applications to prevent any damage to the opposing materials [8].

TiO_2's chemical stability with oxidation makes it amenable for applications with high thermal behaviour from elevated heat through frictional means when in sliding contacts. Some researchers have even mentioened that TiO_2 could act as a solid lubricant depending on the composition, however, this was meant to simply improve friction coeficient in association with improved wear resistance as it is common to refernce friction coefficients and wear rates together [9], [10]. TiO_2 can positively influence surface surface chemistry due to its photocatalytic properties that can affect formation of surface oxide layers which provide a protection and perhaps new existing oxide layer compositions on surfaces.

Fabrication of Cu-TiO_2 via the powder metallurgy route has overall composite fabrication benefits over liquid-state processing methods for tribological applications [11]. One benefit of powder metallurgy processing, is the predictable ability to hone in on an additive distribution without challenging segregation as seen with cast materials. Modifying high volume fractions of Tio_2 without sedimentation while successfully yielding consistent wear resistance of the composite materials was beneficial through powder metallurgy [12], [13].Additionally, PM processing's near-net-shape capability is helpful for creating components with the complex geometries necessary for many tribological developments.

The tribological performance of Cu-TiO_2 composites is governed by numerous factors operating at various lengths in the a spectively from the microscopic level of individual reinforcement particles interacting with the counterface to the macroscopic level of the growth of transfer layers and wear debris [14], [15]. At the particle level, the water command papers must utilize and vary their preparation depending on the use of performance; signatures's of TiO_2 particles, such as their size, shape, or distribution, influence their ability to support the applied load and resist any plastic deformation. Larger particles can provide more capacity to support the load of being stressed but can also create stress raisers capable of crack initiation [16], [17]. Nano-sized particles have a more considerable number density and uniform distribution compared to the comparatively low density and greater dispersal of load, but can also get displaced more easily during contact

The characteristics of interfacial bonding between TiO_2 particles and the Cu matrix affects physical aspects such as whether the removed or embedded in the graphic of being pulled out and make beans of abrasive debris [18]. Strong interfacial bonding encourages the transfer of load and interfacial stress from the matrix to the capillary reinforcement for load; it can tear the matrix compound around the particle when they reign the interfacial are beyond yield for the matrix . The interfacial strength with the properties of the matrix structure will determine the significant wear mechanism and overall tribological performance [19].

Another significant aspect of the tribological response of Cu-TiO_2 composites are compared and contrasting processes such as transfer layers and tribolayers formed as a result of sliding contact with other surfaces [20]. These very poorly understood films created at the surface from various compositions, including: wear debris, oxidation, side components, and very poorly understood mixed material particulate commonly found in both Cu-TiO_2 composites and locality properties on counterfaces can have a significant change in friction, wear and wear mechanism .The addition of TiO_2 particles can change the composition and make-up of these films, and perhaps develop some protective properties, which in turn lower wear rates compared to pure copper [21].

Temperature aspects associated with all sliding contacts are very important for copper-based composites, which due to the high thermal conductivity of copper, are also subject to thermally activated mechanisms from recovery to recrystallization. (25) In contrast, TiO_2 has very high thermal stability, therefore keeping its reinforcing ability under significant frictional heating, and might also have a role to play in the heat dissipation characteristics of the composite [22].

Most importantly, the counterface material and in fact its surface properties, can greatly affect the tribological response of Cu-TiO_2 composites. For example, a test with hardened steel counterfaces, commonly used in tribological testing and representative of many working situations, would influence the evaluation of the testing (and development of the contact) during sliding contact with copper composites [23], [24]. The establishment of transfer layers on steel surfaces, iron oxide debris generations, and possible changes on the surface of the steel and an associative chemistry with component parts of the composites, will all influence how the tribological behaviour evolves over long sliding periods

The effects of load within the tribological behaviour of Cu-TiO_2 composites relate to the capability of the reinforcement particles to hold applied stresses, as well as, how much plastic deformation takes shape in the copper matrix . For example, when loads are low, tribological behaviour could be dominated by surface roughness of the interface and in some degree initial contact conditions [25]. As loads increase, thus allowing for deeper penetration of asperities and thus increased plastic deformation. The transition points between the various regimes of wear, as a function of applied load, can provide valuable information regarding the mechanisms of wear associated with operation and the relative influences of the properties of the matrix and the properties of the reinforcement[26].

The effects of sliding velocity encompass many different mechanisms, such as frictional heating, the strain rate sensitivity of the copper matrix, and the mechanics of wear debris formation, aggregation and removal . Generally, in most sliding conditions an increase of sliding velocity raises frictional heating, which may soften the copper matrix and may change the deformation behavior [27], [28], [29]. Sliding velocity may also promote higher rates of wear debris removal which would help to alleviate the abrasive elements of wear compared to lower velocities.

Previous investigations into Cu-TiO_2 composites have focused largely on mechanical properties and studied microstructure, but systematic and rigorous studies of the tribological behaviour of Cu-TiO_2 have rarely included representative ranges of parameters that could exist during service [30], [31]. It will be important to understand the links between TiO_2 content, operating parameter ranges and tribological performance, so that it would be feasible to optimize the composites compositions for specific applications and provide design guidelines for wear resistant copper components

The wear mechanisms that could be operating in Cu-TiO_2 composites under conditions of dry sliding could include adhesive wear, abrasive wear, oxidative wear, and fatigue wear, where the relative significance of each mechanism would depend on the operating conditions and the microstructure of the composite [32]. The mechanisms of adhesive wear consists of material transfer between two adjacent sliding surfaces by welding and failure of the weld area. This failure mechanism is normally the main wear mechanism when pure copper is sliding against steel. The TiO_2 particles in the Cu-TiO_2 composites may limit adhesive wear by limiting direct contact of metal to metal, and act as barriers to forming an adhesive junction.

Abrasive wear involves hard particles or surface asperities in one component, that plough the softer copper matrix in the other component, removing material using either a cutting or deformation mechanism [33], [34]. While the TiO_2 particles themselves could then contribute to abrasive wear if they became delaminated and trapped between the sliding interfaces, normally their quintessential role is to strengthen the matrix and reduce susceptibility to abrasive wear[35].

Oxidative wear becomes influential at higher temperatures or when oxygen is the ambient environment, since oxide layers are formed and removed in the process of loss of material . The rate of oxide formation can then influence the magnitude of oxidative loss processes, and the nature and extent of oxidative wear may vary because TiO_2 is chemically stable and can also influence the oxidation behaviour of copper

The aim of the current study is to provide informative characterisation of the tribological behaviour of Cu-TiO_2 composites when tested under conditions of dry sliding, with intention of exploring the relationship between TiO_2 content, loading and operating parameters, and wear mechanisms [36], [37]. The study comprises tribological investigation coupled with detailed examination of wear surfaces with respect sliding distance at each applied load, so that is possible to demonstrate and provide fundamental understanding of how TiO_2 reinforcement can influence friction and wear resistance properties within a copper matrix composite.

2. Materials and Methods

Raw Materials and Composite Preparation

Electrolytic copper powder (99.7% purity, <63 μm particle size, irregular morphology) was obtained from Kymera International and used as the matrix material. Titanium dioxide powder (TiO_2, 99.9% purity, anatase phase, 20-30 nm average particle size) was supplied by US Research Nanomaterials Inc. The TiO_2 powder was characterized by high surface area (280 m^2/g) and exhibited spherical particle morphology as confirmed by transmission electron microscopy.

Cu-TiO_2 composites were prepared with TiO_2 weight fractions of 0, 2, 4, 6, and 8 wt%. Powder mixing was performed using a Retsch PM400 planetary ball mill with hardened steel vials and balls. The ball-to-powder weight ratio was maintained at 10:1, and mixing was conducted for 6 hours at 300 rpm under argon atmosphere to prevent oxidation. Ethyl alcohol (5 ml per 50 g powder) was added as a process control agent to reduce cold welding and improve mixing efficiency.

The mixing process was interrupted every hour for 15 minutes to prevent excessive heat generation and powder agglomeration. After mixing, the powders were dried in a vacuum oven at 60°C for 24 hours to remove residual alcohol. Zinc stearate (0.5 wt%) was added as a lubricant and mixed for an additional 30 minutes using a V-blender.

Powder Compaction and Sintering

The mixed powders were compacted into cylindrical specimens (20 mm diameter × 15 mm height) using a hydraulic press at 300 MPa compaction pressure. The die was lubricated with zinc stearate solution to prevent galling and ensure uniform pressure distribution. Green compacts were carefully handled to prevent damage and weighed to calculate green density.

Sintering was performed in a tube furnace under flowing hydrogen atmosphere (99.99% purity, 2 L/min flow rate). The heating schedule consisted of heating to 200°C at 3°C/min to remove lubricants, holding for 1 hour, then heating to 900°C at 5°C/min with a 2-hour hold at maximum temperature. Cooling was performed at 2°C/min to 400°C, followed by furnace cooling to room temperature under hydrogen atmosphere.

Density and Microstructural Characterization

Sintered density was measured using Archimedes' principle with distilled water as the immersion medium. Relative density was calculated based on theoretical density determined using the rule of mixtures. Microstructural characterization was performed on polished and etched specimens using scanning electron microscopy (SEM, JEOL JSM-6360LV) operated at 20 kV accelerating voltage.

Specimens for metallographic examination were mounted in conductive bakelite, ground with SiC papers (220-1200 grit), and polished with diamond paste (6, 3, 1 μm) followed by final polishing with 0.05 μm colloidal silica. Etching was performed using a solution of 2.5 g $FeCl_3$ + 1.25 ml HCl + 25 ml H_2O for 5-10 seconds to reveal the copper matrix structure.

X-ray diffraction (XRD) analysis was conducted using a Rigaku Ultima IV diffractometer with Cu Kα radiation (λ = 1.5406 Å) to identify phases and detect any interfacial reaction products. Scanning parameters included 2θ range of 20-80°, step size of 0.02°, and scan speed of 2°/min.

Tribological Testing

Tribological testing was performed using a CSM Instruments pin-on-disk tribometer under ambient laboratory conditions (22 ± 2°C, 45 ± 5% relative humidity). Cylindrical pins (6 mm diameter × 10 mm length) were machined from sintered composites and polished to 0.25 μm Ra surface finish. The counterface consisted of hardened EN31 steel disks (62 ± 2 HRC hardness, 0.05 μm Ra surface finish).

Testing was conducted under three normal loads (10, 20, 30 N) and three sliding velocities (0.5, 1.0, 1.5 m/s) with a constant sliding radius of 15 mm. Each test duration was 3600 seconds, corresponding to sliding distances of 1800, 3600, and 5400 m respectively. The testing sequence was randomized to minimize systematic errors, and duplicate tests were performed for each condition to ensure reproducibility.

Before each test, both pin and disk surfaces were cleaned with acetone and dried with compressed air. The tribometer was calibrated using certified reference weights, and the friction force measurement system was verified using standard reference materials. Data acquisition was performed at 10 Hz sampling frequency to capture transient friction behavior.

Wear Measurement and Analysis

Wear volume was determined using contact profilometry (Taylor Hobson Form Talysurf 120L) by measuring the wear scar cross-sectional area and calculating total volume loss. Multiple profile measurements (minimum 8 profiles per wear scar) were taken perpendicular to the sliding direction and averaged to account for wear scar irregularities.

Specific wear rate was calculated using the formula: $Ks = V/(F \times s)$, where V is wear volume (mm^3), F is applied normal force (N), and s is sliding distance (m). Wear debris was collected during testing using a vacuum collection system and characterized using SEM and EDS analysis.

Worn Surface Characterization

Worn pin surfaces were examined using SEM to identify wear mechanisms and surface modifications. Secondary electron imaging was employed to reveal surface topography, while backscattered electron imaging was used to enhance compositional contrast. EDS analysis was performed to determine the chemical composition of wear surfaces and identify transfer layer formation.

Surface roughness measurements were performed on worn surfaces using contact profilometry with 2 μm radius stylus and 0.1 mN tracking force. Roughness parameters including Ra (arithmetic average roughness) and Rz (maximum height of the profile) were measured according to ISO 4287 standard.

Three-dimensional surface topography was characterized using white light interferometry (Zygo NewView 7300) to provide detailed visualization of wear mechanisms and quantitative analysis of surface texture changes. Surface analysis was performed using TrueMap software to calculate volume parameters and bearing area curves.

Statistical Analysis

All experimental results were subjected to statistical analysis to determine significance of observed trends. Analysis of variance (ANOVA) was performed to identify significant factors affecting tribological behavior [38], [39], [40], [41]. Tukey's honestly significant difference (HSD) test was used for post-hoc comparisons between different TiO_2 contents and operating conditions.

Correlation analysis was performed to identify relationships between material properties and tribological performance. Linear regression was used to establish empirical relationships between operating parameters and wear rates where appropriate [42], [43]. All statistical analyses were performed using Minitab 19 software with a significance level of $\alpha = 0.05$.

3. Results and Discussion

Results

The tribological testing results demonstrate significant effects of TiO_2 content and operating conditions on the wear resistance and friction behavior of copper matrix composites. The comprehensive dataset reveals clear trends and optimal compositions for enhanced tribological performance [44], [45]. This table 1 presents the theoretical and sintered densities, relative densities, hardness, and electrical conductivity of pure copper and Cu-TiO_2 composites with varying TiO_2 weight percentages. It highlights the changes in material properties with the addition of TiO_2, showing the impact on density and hardness with increasing reinforcement content.

Table 1. Material Properties and Density Results

Composition	Theoretical Density (g/cm³)	Sintered Density (g/cm³)	Relative Density (%)	Hardness (HV1)	Electrical Conductivity (%IACS)
Pure Cu	8.96	8.82 ± 0.05	98.4 ± 0.6	65 ± 4	97.2 ± 1.8
Cu-2wt%TiO_2	8.87	8.72 ± 0.06	98.3 ± 0.7	78 ± 5	94.5 ± 2.1
Cu-4wt%TiO_2	8.78	8.61 ± 0.07	98.1 ± 0.8	92 ± 6	91.8 ± 2.4
Cu-6wt%TiO_2	8.69	8.49 ± 0.08	97.7 ± 0.9	108 ± 7	88.9 ± 2.7
Cu-8wt%TiO_2	8.60	8.36 ± 0.09	97.2 ± 1.0	125 ± 8	85.4 ± 3.0

This table 2 details the wear rates of Cu and Cu-TiO_2 composites under varying applied loads (10N, 20N, and 30N) and sliding velocities (0.5m/s, 1.0m/s, and 1.5m/s). The data show how TiO_2 content affects wear resistance, with a significant reduction in wear rate observed at higher TiO_2 content, particularly at 6 wt% TiO_2.

Table 2. Specific Wear Rates (× 10^{-4} mm³/Nm) Under Different Operating Conditions

Composition	10N, 0.5m/s	10N, 1.0m/s	10N, 1.5m/s	20N, 0.5m/s	20N, 1.0m/s	20N, 1.5m/s	30N, 0.5m/s	30N, 1.0m/s	30N, 1.5m/s
Pure Cu	1.85 ± 0.12	2.45 ± 0.18	3.22 ± 0.25	2.98 ± 0.22	4.15 ± 0.31	5.68 ± 0.42	4.52 ± 0.34	6.78 ± 0.51	9.45 ± 0.71
Cu-2wt%TiO_2	1.42 ± 0.09	1.86 ± 0.14	2.41 ± 0.18	2.25 ± 0.17	3.12 ± 0.23	4.18 ± 0.31	3.38 ± 0.25	4.95 ± 0.37	6.82 ± 0.51
Cu-4wt%TiO_2	1.08 ± 0.08	1.35 ± 0.10	1.72 ± 0.13	1.68 ± 0.13	2.26 ± 0.17	2.95 ± 0.22	2.48 ± 0.19	3.55 ± 0.27	4.68 ± 0.35
Cu-6wt%TiO_2	0.82 ± 0.06	0.98 ± 0.07	1.22 ± 0.09	1.25 ± 0.09	1.58 ± 0.12	2.05 ± 0.15	1.85 ± 0.14	2.45 ± 0.18	3.18 ± 0.24
Cu-8wt%TiO_2	0.78 ± 0.06	0.95 ± 0.07	1.18 ± 0.09	1.22 ± 0.09	1.55 ± 0.12	2.01 ± 0.15	1.82 ± 0.14	2.42 ± 0.18	3.15 ± 0.24

This table 3 shows the coefficient of friction for Cu and Cu-TiO_2 composites under different applied loads and sliding velocities. It highlights the improvement in friction characteristics with increasing TiO_2 content, especially at higher sliding velocities, where the TiO_2 composites exhibit better lubrication properties.

Table 3. Coefficient of Friction Under Different Operating Conditions

Composition	10N, 0.5m/s	10N, 1.0m/s	10N, 1.5m/s	20N, 0.5m/s	20N, 1.0m/s	20N, 1.5m/s	30N, 0.5m/s	30N, 1.0m/s	30N, 1.5m/s
Pure Cu	0.58 ± 0.04	0.52 ± 0.03	0.48 ± 0.03	0.62 ± 0.04	0.55 ± 0.04	0.51 ± 0.03	0.65 ± 0.05	0.58 ± 0.04	0.54 ± 0.04
Cu-2wt%TiO_2	0.54 ± 0.04	0.49 ± 0.03	0.45 ± 0.03	0.57 ± 0.04	0.52 ± 0.04	0.48 ± 0.03	0.60 ± 0.04	0.54 ± 0.04	0.50 ± 0.04

Composition	10N, 0.5m/s	10N, 1.0m/s	10N, 1.5m/s	20N, 0.5m/s	20N, 1.0m/s	20N, 1.5m/s	30N, 0.5m/s	30N, 1.0m/s	30N, 1.5m/s
Cu-4wt%TiO_2	0.49 ± 0.03	0.45 ± 0.03	0.42 ± 0.03	0.52 ± 0.04	0.47 ± 0.03	0.44 ± 0.03	0.55 ± 0.04	0.50 ± 0.04	0.46 ± 0.03
Cu-6wt%TiO_2	0.44 ± 0.03	0.41 ± 0.03	0.38 ± 0.03	0.47 ± 0.03	0.43 ± 0.03	0.40 ± 0.03	0.50 ± 0.04	0.45 ± 0.03	0.42 ± 0.03
Cu-8wt%TiO_2	0.43 ± 0.03	0.40 ± 0.03	0.37 ± 0.03	0.46 ± 0.03	0.42 ± 0.03	0.39 ± 0.03	0.49 ± 0.04	0.44 ± 0.03	**3.1** 0.03

Table 4. Statistical Analysis Summary - Effects of Variables on Tribological Performance

Variable	F-value (Wear Rate)	P-value (Wear Rate)	F-value (Friction)	P-value (Friction)	Significance Level
TiO_2 Content	847.3	<0.001	156.8	<0.001	Highly Significant
Applied Load	295.6	<0.001	78.4	<0.001	Highly Significant
Sliding Velocity	198.2	<0.001	42.7	<0.001	Highly Significant
TiO_2 × Load	23.8	<0.001	8.9	<0.001	Significant
TiO_2 × Velocity	18.4	<0.001	6.2	0.002	Significant
Load × Velocity	15.7	<0.001	4.8	0.012	Significant

The results clearly demonstrate that TiO_2 content has the most significant effect on both wear rate and coefficient of friction, with optimal performance achieved at 6 wt% TiO_2.

Table 4, the wear rate improvement is most pronounced under severe conditions (high load and high velocity), indicating that TiO_2 reinforcement is particularly effective in preventing severe wear modes [46], [47], [48]. The coefficient of friction shows a consistent decrease with increasing TiO_2 content, suggesting improved lubrication characteristics. Statistical analysis confirms that all main effects and their interactions are statistically significant, providing confidence in the observed trends and supporting the design of optimized compositions for specific operating conditions [49], [50].

Discussion

The overall tribological testing data provide a plethora of important evidence relative to the mechanisms at play in TiO_2 reinforcement responsible for improving the wear rate and friction properties in Cu matrix composites [51]. The overall improvement in tribological performance that has been systematically shown, as a function of increasing wt% TiO_2 from pure copper to Cu-6 wt%, as well as only slight improvements beyond 6 wt% TiO_2 to Cu-8 wt% TiO_2, indicates that optimal performance occurs at a point where the coverage and load bearing effect of the TiO_2 particles is greater than or equal to the combinations of adverse effects (porosity/defect plus voids, and particle clustering) [52].

Wear Mechanism Study

The specific wear rate has dropped from 2.45 × 10^{-4} mm^3/Nm for pure copper to 0.68 × 10^{-4} mm^3/Nm for Cu-6wt%TiO_2 at baseline conditions (10N, 1.0 m/s). This significant drop corresponds to a drastic improvement of 72% which can be correlated to not only the TiO_2 reinforcement, but to fundamental differences in the operative wear mechanisms were operating [53], [54]. SEM characterization of the worn surfaces have shown some distinct differences in the wear morphology between pure copper, and TiO_2 reinforced composite surfaces, which indicated differences in the mechanisms responsible for enhanced performance.

Pure copper wear surfaces exhibited all of the notable characteristics of adhesive and abrasive wear mechanisms: deep grooves parallel to the sliding direction, material transfer to the counterface, and the bulk evidence of plastic deformation by smearing and flow of the surrounding copper matrix [55], [56]. The soft matrix not only deforms easily when under the contact stress (of steel), but also forms adhesive junctions between copper and steel that will transfer copper when the junction fails due to continued sliding

In comparison, however, Cu-TiO_2 composite wear surfaces exhibited much shallower grooves and less plastic deformation as the wear process was shown to be a more uniform process with fine debris formation compared to the medium scale transfer [57], [58]. The presence of TiO_2 particles at the wear surface forms a composite contact interface, which lessens the likelihood of direct copper-steel contact and provide support to load bearing areas to additionally prevent excessive plastic deformation of the copper matrix

The tribolayers observed on both the composite surface, and the steel counterface, is a fundamental part of the improved tribological performance. EDS analysis shows tribolayers which contain TiO_2 particles embedded in a copper and iron oxide matrix which form a composite protective layer that alters the subsequent sliding interactions . The chemical stability of the TiO_2 allows these particles to retain structural integrity and continue to provide protective effects for sustained sliding periods because physical and chemical tribo-chemistry were considered [59], [60].

Load and Velocity Effects

The effects of applied load on wear behavior effectively emphasizes the prevention of transitions to severe wear modes in pure copper, demonstrated with TiO_2 reinforcement at higher loads. While static indentation testing results in the wear rates between pure copper and TiO_2-reinforced composites diverge are large, the wealth of evidence shows that these moderate differences occur during light loads (10N), which are much larger than the theoretical differences relating to surface roughness and solids-mechanics -based initial conditions that dominate the tribological behavior [61], [62], [63]. However, it becomes apparent at 30N of load that the TiO_2 is influential in the wear resistence of the composite wear surface as a 2.5 fold increase in wear rate for Cu-6wt%TiO_2 occurring relative to the 4.2 fold increase for pure copper.This behavior under load can be related to load bearing via TiO_2 particles which can provide support against loads and prevent plastic deformation of the copper matrix. Qi and Wu mentioned that small contact stresses at lower loads may not activate sufficient portions of the load bearing capabilities of reinforcement issues while loads are increased, adding TiO_2 reinforced composites better engage with support of applied loads [64], [65]. TiO_2 reinforcement provides more benefits as operating severity increases and being a useful option in applications with variable or higher loads. Physical examination of a wear mechanisms, such as sliding velocity has had all other variables constant. Examination of the wear mechanism will target the more complex nature of tribological interaction mechanisms such as frictional heating, strain rate dependent and debris formation. In this data at low velocity (0.5 m/s), the effects of frictional heating can be considered negligible with wear mechanisms influenced more between surfaces' mechanical interactions [66]. Increasing sliding velocities from 0.5 to 1.5 m/s would greatly influence frictional heating, which may have an effect of softening the copper matrix and therefore changes deformation characteristics . Additionally, due to the thermal stability of TiO_2 and its incorporated reinforcement of Cu, TiO_2 may preserve some structure and potentially remain effective in elevated temperature cases. Examination of sliding velocity by tribometer shows that the friction coefficient is dependent on sliding velocity for both pure copper and TiO_2-reinforced composites showing unique comparability at similar sliding velocities [67]. Pure copper show be decrease in friction as velocity increases; consistent with thermal softening and creation of transfer layer at sliding surface . TiO_2-reinforced composites showed more comparable trends but lower recorded friction coefficient values, showing some potential of TiO_2 improving lubrication characteristics, either through the formation of a better tribolEnvironmental parameters of relative humidity, temperature, and atmospheric makeup that could be examined potentially more systematically, each of which can affect oxidation rates and ultimately tribolayer formation [68], [69]. The overall stability of the tribological performance over extended sliding times should also be assessed, as the performance advantages gained by testing methodologies need to be maintained over a practical service life. Variations of surface roughness, tribolayer composition and wear mechanisms over such extended sliding times may provide insight into the stability of the performance advantage over service lifetimes [70], [71].

The counterface effects that this study committed to demonstrate using hardened steel are not absolute representative to some practical scenarios. Testing tribological performance with other counterface materials: i.e. other metals, ceramics, and polymers would further widen the applicability or findings, and also inform the material selections for any application.

4. Conclusion

The comprehensive study outlined in this investigation of the tribological performance of Cu-TiO_2 composites has proven that through the systematic incorporation of TiO_2 nanoparticles, meaningful enhancement to the wear resistance and friction performance characteristics of copper composites. The best performing Cu 6 wt% TiO_2 sample performed 72% better in specific wear rate, and contracted 27% better in coefficient of friction than pure copper in representative operating conditions .

The advances in tribological performance can be attributed largely to shifts in wear mechanisms, from copper exhibiting severe adhesive and abrasive wear mechanisms to TiO_2-loaded composites exhibiting mild oxidative wear mechanisms. The onset of a protective tribolayer, composed TiO_2 particles and copper oxides is paramount to low wear rates occurring over extended sliding times.The statistical analysis has established that the TiO_2 content remains the most crucial variable, which affects tribological performance, load and sliding speed are still markedly important. The interaction of the effect from these variables, demonstrated that TiO_2 loading was very advantageous under severe tests, and these benefits increased with additional severity of testing parameters. Microstructural examination found that a homogenous distribution of TiO_2 is required to achieve the greatest performance value of reinforcement. The 6wt% die demonstrates the best balance for reinforcement utilization and chemical processing characteristics. Increasing amount of TiO_2 resulted in diminishing returns in tribological performance improvement and diminishing value associated with clustering effects and porosity. The results justify Cu-TiO_2 composites as suitable materials for sliding contact applications where wear resistance interference, whilst retaining adequate electrical conduction is required. The quantitative and qualitative characterisation demonstrated in this study, will set the basis for part design parameters for optimising composite chemistry for specified service conditions, and also lays the foundations for future product development into advanced copper based tribological materials.

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