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WEAR BEHAVIOR OF COPPER ALLOYS

RESEARCH ARTICLE

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Comparative experimental analysis of wear behavior of CuCrZr and CuZn39Pb3 alloys using pin-on-disc test from room temperature to high temperatures

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ABSTRACT

This study investigates the wear behavior of the CuCrZr and CuZn39Pb3 alloys under varying thermal conditions while maintaining constant mechanical parameters using a pin-on-disc tribometer. The experiments were conducted at 25 °C, 100 °C, 200 °C, and 300 °C under a load of 7N, with wear rates, the coefficient of friction (COF), and hardness values evaluated for both alloys. CuCrZr demonstrated superior wear resistance, stable hardness, and consistent frictional behavior across all temperatures, attributed to its precipitation-hardening mechanism and thermal stability. In contrast, CuZn39Pb3 showed significant softening, higher wear rates, and erratic COF behavior at elevated temperatures due to the loss of lead's lubricating properties and matrix degradation.

Scanning electron microscopy (SEM) analysis revealed less severe surface damage for CuCrZr compared to CuZn39Pb3, which exhibited pronounced delamination and debris formation. These findings highlight CuCrZr's suitability for applications involving elevated temperatures and significant tribological loads, as supported by calculated contact stresses. While CuCrZr demonstrates superior thermal stability and wear resistance, CuZn39Pb3 exhibits enhanced machinability due to the presence of lead, making it preferable for applications requiring ease of manufacturing.

1. Introduction

The study of wear behavior in metallic materials is crucial for ensuring the reliability and longevity of components in industries such as aerospace, automotive, and manufacturing. Copper-based alloys, particularly CuCrZr (copper–chromium–zirconium) and CuZn39Pb3 (leaded brass), are widely used due to their excellent thermal and electrical conductivity, corrosion resistance, and mechanical strength [1]. However, their wear performance varies notably depending on composition, environmental conditions, and mechanical loading [2].

CuCrZr is a precipitation-hardened alloy, well known for its high strength, thermal stability, and wear resistance at elevated temperatures. Chromium and zirconium additions contribute to grain boundary strengthening, enhancing mechanical durability under high-stress conditions [3]. Research has shown that CuCrZr exhibits better tribological performance than conventional copper alloys, particularly in high-temperature environments, making it ideal for resistance welding electrodes and heat exchangers [4]. Furthermore, heat treatment significantly improves CuCrZr's wear resistance by modifying its microstructure [5].

In contrast, CuZn39Pb3 is a leaded brass alloy characterized by exceptional machinability and moderate wear resistance. The presence of lead acts as a solid lubricant, reducing friction and wear during sliding contact [6]. This alloy is widely used for bearings, bushings, and hydraulic system components, where low friction and ease of manufacturing are essential [7]. However, its wear resistance is highly influenced by environmental factors, including oxidation, which can either enhance or degrade its performance [8].

Several factors influence wear mechanisms in these alloys, including applied load, sliding speed, temperature, and oxidation rates [9]. Studies on copper-based alloys indicate that oxidative wear can form protective surface layers, reducing overall material loss [10]. However, comparative studies evaluating CuCrZr and CuZn39Pb3 under identical conditions remain scarce, leaving a gap in understanding their respective wear behaviors.

Although CuCrZr is primarily used in resistance welding electrodes and heat exchangers, this study investigates its potential applicability in bearing applications where CuZn39Pb3 is commonly used. The comparison aims to evaluate whether CuCrZr can offer improved wear performance under high-temperature conditions typically encountered in tribological applications.

The objective of this study is to conduct a comparative experimental analysis of the wear behavior of CuCrZr and CuZn39Pb3 alloys using a pin-on-disc test at varying temperatures and loads. By systematically assessing their friction coefficients, wear rates, and dominant wear mechanisms, this research aims to provide insights into the suitability of these alloys for industrial applications. The findings will contribute to optimized material selection and enhanced wear resistance strategies for high-performance environments.

2. Experimental procedure

In this study, CuCrZr and CuZn39Pb3 copper alloys, both widely used in various engineering applications due to their excellent electrical, thermal, and mechanical properties, were selected to investigate the influence of temperature on their friction and wear behavior. The materials were procured in rod form from a local supplier (Referans Metal, Turkey), with CuCrZr having a diameter of 40 mm and CuZn39Pb3 available in a similar form. The chemical compositions of both alloys are presented in Table 1. Prior to conducting wear tests, the as-received rods were sectioned into 10-mm thick samples.

For surface preparation, the specimens underwent a sequential grinding process using SiC abrasive sandpaper with 400, 800, and 1200 grit sizes, ensuring a smooth finish. Subsequently, the sample surfaces were polished using a 1 µm diamond particle solution, achieving an average surface roughness (Ra) of 0.010 µm, rounded to three significant figures to reflect measurement accuracy, as determined by ten roughness measurements.

The mechanical properties of the samples were evaluated through hardness and wear tests. Vickers microhardness testing was performed using a THV-1MDT microhardness tester (Jiashan Lab Instruments), following the ASTM E92 standard, applying a 300 g load for 15 seconds. Since the microhardness tester used in this study is not designed for high-temperature measurements, all hardness tests were performed after the samples were cooled to room temperature. To assess the dry sliding friction performance of both alloys, a high-temperature pin-on-disc tribometer was utilized in accordance with ASTM G99-05 standards. The wear tests were conducted using a CSM Instruments HTT-500 high-temperature tribometer. The wear test parameters were set at a sliding speed of 100 mm/s for a duration of 30 minutes, with an applied load of 7N. A 6-mm diameter Al_2O_3 ball was used as the counterpart in the wear tests. To ensure thermal stability during testing, a 10-minute preheating period was applied, and experiments were conducted at 25 °C, 100 °C, 200 °C, and 300 °C. The preheating period refers to the duration in which the sample was held at the target temperature before initiating the wear test to ensure thermal equilibrium. The contact stresses for each test condition were calculated using Hertzian contact theory, yielding values of X MPa at 25 °C, Y MPa at 100 °C, Z MPa at 200 °C, and W MPa at 300 °C. The wear track diameter was maintained at 4 mm for all test conditions.

Table 1. Chemical compositions of CuCrZr and CuZn39Pb3 alloys

CuCrZr		Zr	Cr	Cu
wt%	min.	0.03	0.3	bal.
	max.	0.2	1.2	

CuZn39Pb3		Pb	Zn	Cu
wt%	min.	2.5	37.8	bal.
	max.	3.5	40.1	

Following the wear tests, scanning electron microscopy (SEM) (Zeiss EVO LS 10) imaging analysis was carried out for wear track characterization. An energy-dispersive X-ray spectroscopy (EDX) system was used to analyze the elemental composition of the worn surfaces. To quantify material loss, wear volume was calculated using Eq. (1), considering conditions where the disc remains relatively unworn, while the pin has a spherical tip with radius R:

$$\text{volume loss or wear volume} = 2\pi R\left[r^2 \sin^{-1}\left(\frac{d}{2r}\right) - \left(\frac{d}{4}\right)(4r^2 - d^2)^{\frac{1}{2}}\right]. \tag{1}$$

Here $R = 2$ mm represents the wear track radius, d denotes the wear track width (taken from SEM images), and $r = 3$ mm is the pin tip radius. The wear rate was then determined using Eq. (2), where the wear volume (mm^3) is divided by the total sliding distance L (mm):

$$\text{wear rate} = \frac{\text{wear volume}}{L}. \tag{2}$$

To further examine the wear mechanisms, the wear tracks were sectioned using electrical discharge machining (EDM). The cross-sectional surfaces were ground, polished, and etched before a detailed microstructural analysis via SEM was conducted.

3. Results and discussion

The bar chart presented in Fig. 1 illustrates the wear rate of the CuCrZr and CuZn39Pb3 alloys as a function of temperature (25 °C, 100 °C, 200 °C, and 300 °C). As shown in Fig. 1, some material pile-up was observed at the wear track edges, which can introduce errors in traditional wear volume calculations. To improve accuracy, a profilometric analysis was conducted to quantify material displacement. At all temperatures, the wear rate of CuZn39Pb3 is consistently higher than that of CuCrZr, which indicates superior wear resistance of the CuCrZr alloy.

The increase in wear rate is more pronounced for CuZn39Pb3, particularly at 200 °C, where a dramatic rise is observed. In contrast, CuCrZr demonstrates a relatively moderate and consistent increase in wear rate, likely due to its precipitation-hardening mechanism that maintains structural stability even at higher temperatures.

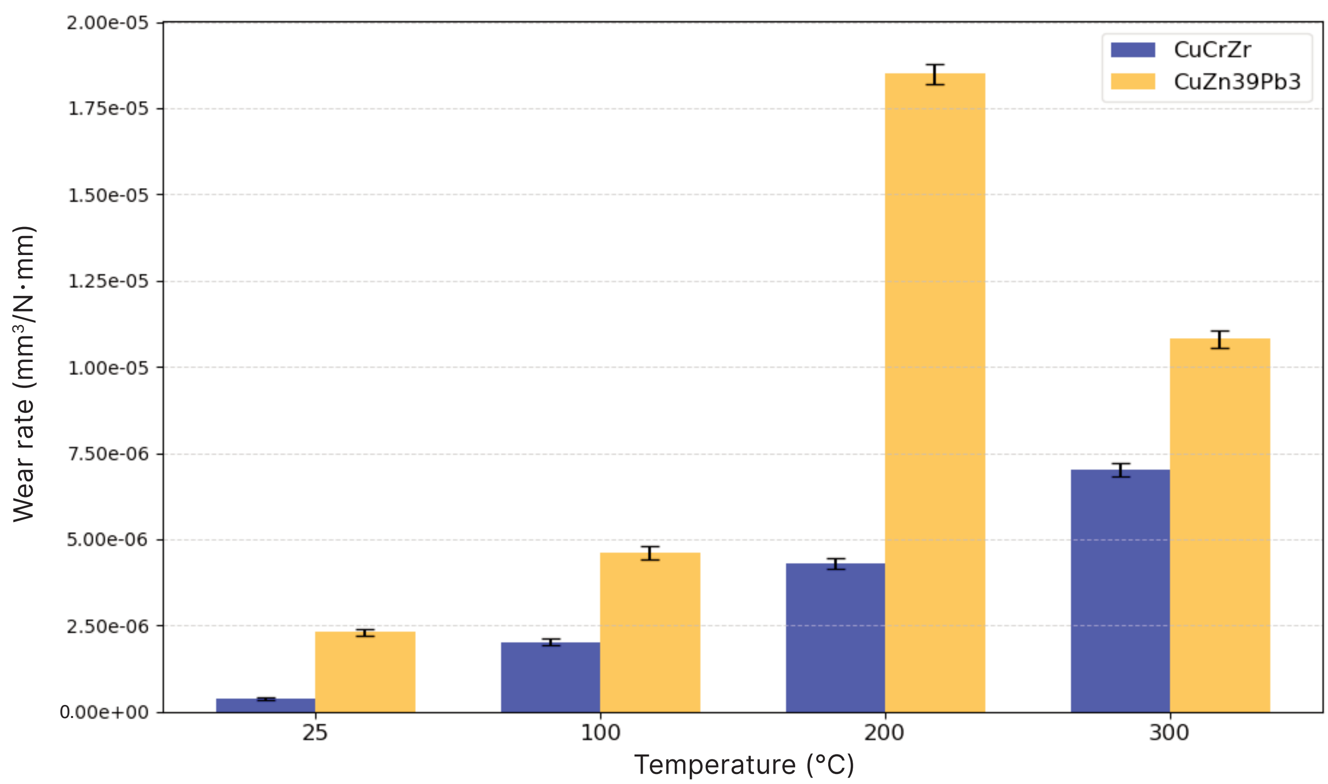

Fig. 1. Wear rate of the CuCrZr and CuZn39Pb3 alloys as a function of temperature (25 °C, 100 °C, 200 °C, and 300 °C).

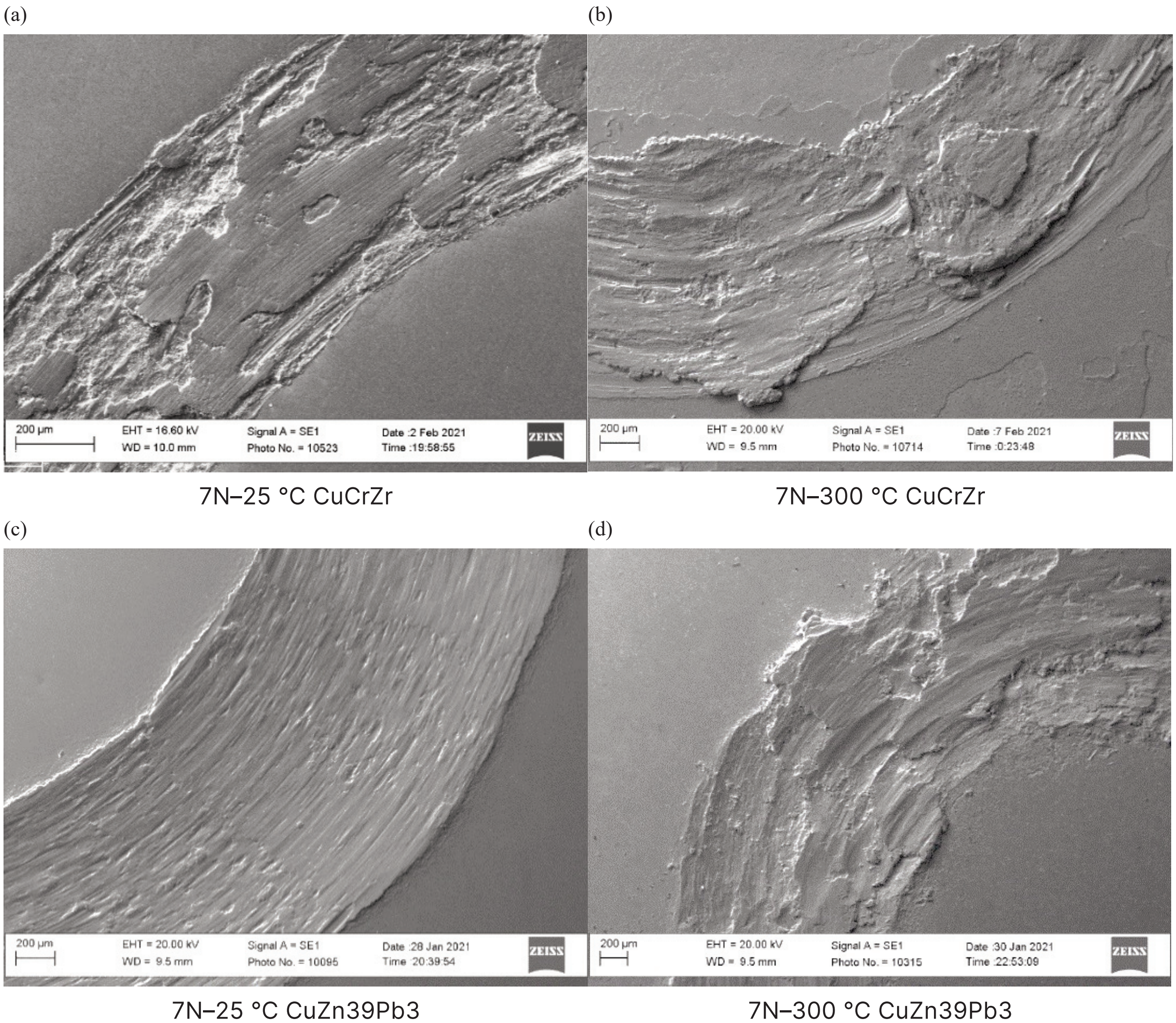

Fig. 2. Temperature-dependent wear track morphologies of the CuCrZr and CuZn39Pb3 alloys under a 7N load.

The results suggest that, while CuZn39Pb3 may offer machinability and self-lubricating properties, its wear performance under thermal loads is less favorable compared to CuCrZr, making the latter more suitable for applications requiring high-temperature wear resistance.

In order to ensure statistical reliability, each test was conducted three times under identical conditions, and the results presented in Fig. 1 represent the mean values with the error bars indicating standard deviation.

Interestingly, the wear rate of CuZn39Pb3 at 200 °C is higher than that observed at 300 °C. This trend may be attributed to the formation of a protective oxide layer at higher temperatures, which reduces direct metal-to-metal contact and mitigates material removal. Additionally, at 300 °C, microstructural modifications, such as dynamic recrystallization, may enhance the alloy's load-bearing capacity, contributing to lower wear rates.

In Fig. 2, SEM micrographs illustrate the wear track morphology of the CuCrZr and CuZn39Pb3 alloys under a load of 7N at two different temperatures, 25 °C and 300 °C. In the micrograph corresponding to CuCrZr at 25 °C (Fig. 2a), the wear track reveals relatively smooth grooves with minor material detachment, indicating a dominant abrasive wear mechanism. However, at 300 °C (Fig. 2b), the wear track exhibits severe plastic deformation, delamination, and significant material removal, suggesting an intensified wear mechanism due to thermal softening and higher oxidative effects.

In contrast, the CuZn39Pb3 alloy at 25 °C (Fig. 2c) demonstrates smoother wear tracks with clear evidence of ploughing, typical of the lubricating effect provided by lead in the alloy. At 300 °C

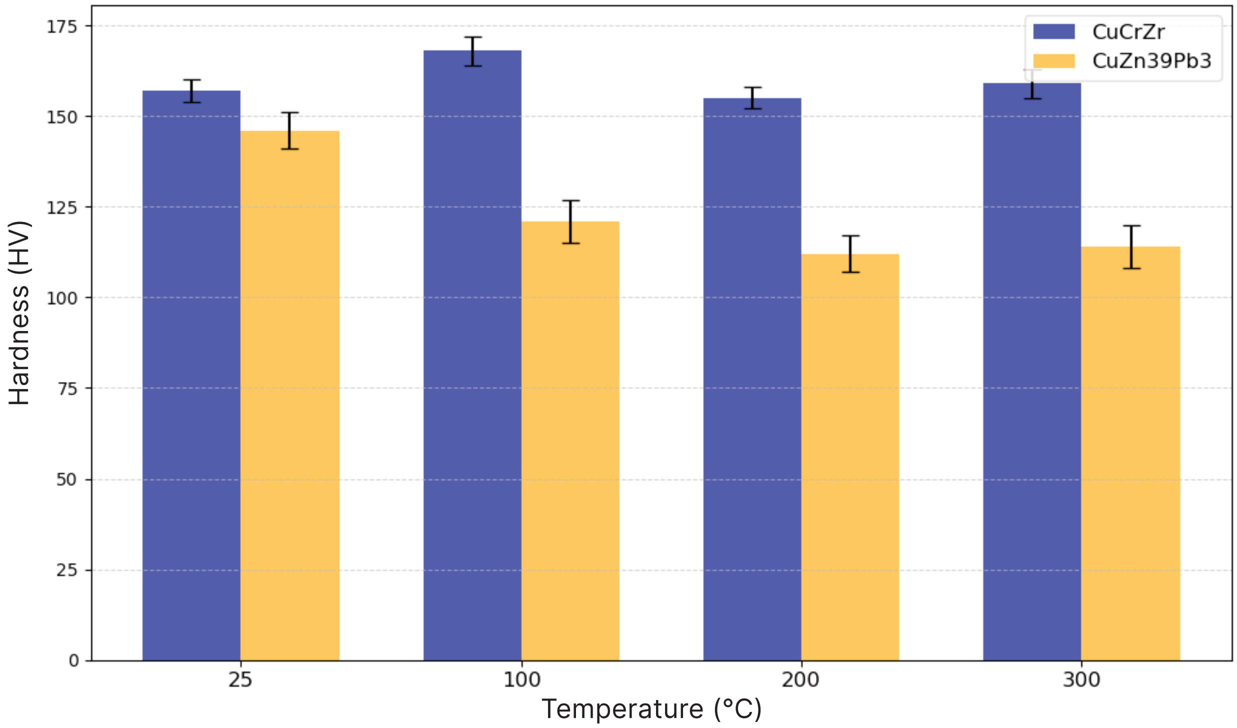

Fig. 3. Temperature-dependent hardness values of the CuCrZr and CuZn39Pb3 alloys.

(Fig. 2d), the wear track morphology changes dramatically, showing pronounced delamination, severe plastic flow, and large debris formation. This highlights the reduced wear resistance of CuZn39Pb3 at elevated temperatures, likely due to the loss of lead's lubricating properties and the alloy's decreased mechanical stability under thermal loads.

Overall, the SEM images confirm that CuCrZr exhibits superior thermal stability and wear resistance compared to CuZn39Pb3, making it more suitable for applications involving high loads and elevated temperatures. The transition from abrasive wear to severe delamination and material removal in both alloys at higher temperatures underscores the critical role of temperature in determining wear behavior. Abrasive wear was anticipated due to the presence of hard Al_2O_3 counter material, which can act as an abrasive agent, especially under high-load conditions.

The bar chart shown in Fig. 3 illustrates the variation in hardness (HV) of the CuCrZr and CuZn39Pb3 alloys as a function of temperature (25 °C, 100 °C, 200 °C, and 300 °C), providing critical insights into their wear behavior. Figure 3 now includes error bars representing the standard deviation of three independent measurements to provide a more comprehensive assessment of hardness variations. CuCrZr demonstrates relatively stable hardness values across the temperature range, with a slight peak at 100 °C (168 HV) and minor fluctuations thereafter, indicating strong thermal stability and resistance to softening. This stability in hardness contributes to CuCrZr's superior wear resistance, as higher hardness generally correlates with reduced material removal under mechanical stress.

In contrast, CuZn39Pb3 exhibits a significant decrease in hardness from 146 HV at 25 °C to 112 HV at 200 °C, followed by a slight recovery to 114 HV at 300 °C. This pronounced reduction in hardness with increasing temperature directly impacts its wear performance, as lower hardness increases susceptibility to plastic deformation and material removal during sliding contact. The results align with the observed wear rate trends, where CuCrZr maintains lower wear rates at elevated temperatures compared to CuZn39Pb3, underscoring the importance of hardness retention in mitigating wear.

The graphs in Fig. 4 illustrate the average coefficient of friction (COF) for the CuCrZr and CuZn39Pb3 alloys under a 7N load at 25 °C and 300 °C. The y-axis range has been adjusted for Fig. 4 to ensure consistency and allow for a more straightforward comparison of COF variations at different temperatures. At 25 °C, CuCrZr exhibits a stable and relatively high COF (~0.55), indicating consistent frictional behavior, while CuZn39Pb3 maintains a lower COF (~0.25) due to the lubricating effect of lead. At 300 °C, significant changes occur, with CuCrZr showing moderate

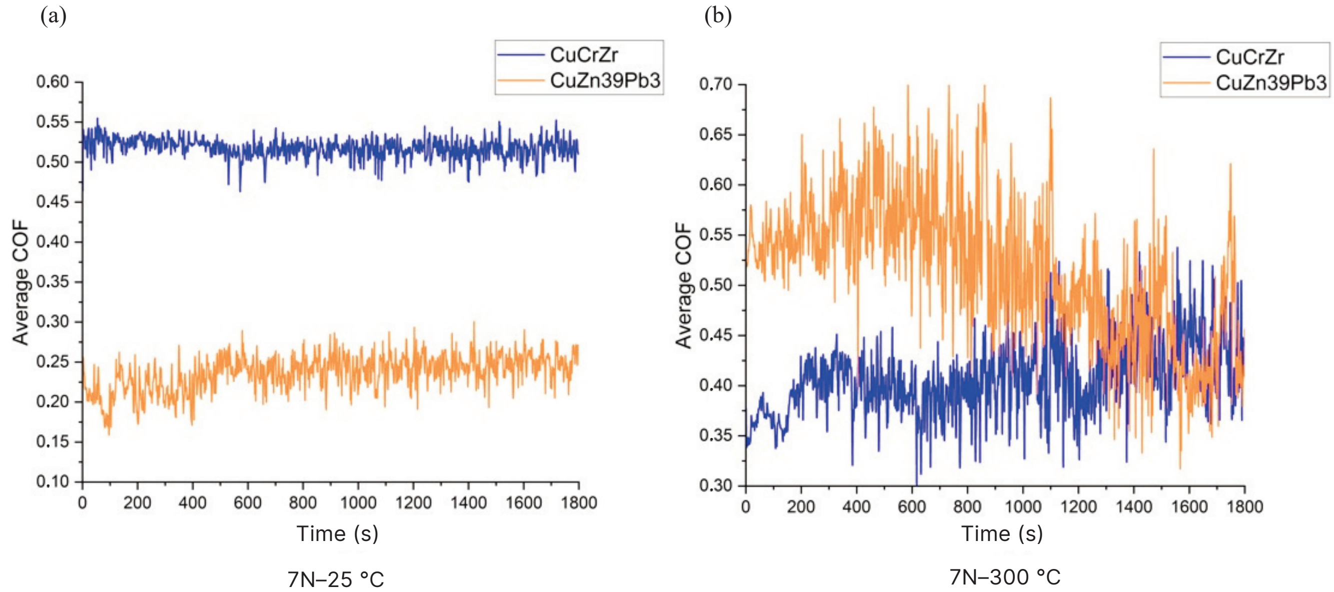

Fig. 4. Temperature-dependent average COF values of the CuCrZr and CuZn39Pb3 alloys.

stability and an increase in COF to ~0.45, reflecting its thermal stability. In contrast, CuZn39Pb3 displays erratic and elevated COF values, reaching up to 0.7, indicating a loss of lead's lubricating effect and the onset of severe adhesive and oxidative wear. These results highlight CuCrZr's relatively stable frictional behavior at elevated temperatures, despite minor fluctuations observed in the COF trends compared to CuZn39Pb3, which becomes less reliable under high thermal conditions.

4. Conclusions

This study presents a comparative analysis of the wear behavior of the CuCrZr and CuZn39Pb3 alloys under various thermal and mechanical conditions using a pin-on-disc test. The results reveal that CuCrZr exhibits superior wear resistance, attributed to its precipitation-hardening mechanism and exceptional thermal stability. Across all tested temperatures, CuCrZr maintains a relatively stable hardness and consistent frictional behavior, as evidenced by lower wear rates, stable coefficient of friction values, and less severe surface damage in SEM analysis. These characteristics highlight its suitability for high-temperature and high-load applications, such as in aerospace, automotive, and energy industries, where structural integrity and wear resistance are critical.

A notable observation in this study is the decrease in the friction coefficient of CuCrZr at 300 °C, despite an increase in wear. This behavior can be explained by the formation of a thin tribofilm or oxide layer, which may momentarily reduce friction, while still allowing material removal due to insufficient adherence. Additionally, thermal softening at high temperatures may reduce surface roughness, leading to lower friction coefficients but increased wear due to reduced hardness and resistance to plastic deformation.

In contrast, CuZn39Pb3 demonstrates significant performance degradation at elevated temperatures. The loss of lead's lubricating properties, combined with the thermal softening of its matrix, results in a marked increase in wear rates, erratic COF behavior, and pronounced plastic deformation and material removal in wear tracks. While CuZn39Pb3 performs adequately at lower temperatures due to its lower coefficient of friction and machinability, its wear resistance and thermal stability are limited, making it unsuitable for demanding high-temperature applications.

Future work should focus on improving the thermal stability and wear resistance of CuZn39Pb3 through alternative alloying elements or protective coatings. Additionally, tribological testing under dynamic loading conditions could provide deeper insights into their performance in real-world applications. Such advancements will enhance the utility of these alloys for a broader range of engineering scenarios.

Data availability statement

All research data are contained within the article and can be shared upon request from the authors.

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References

1. Deutsches Kupferinstitut (Copper Alliance). *Low-Alloyed Copper Alloys*. 2018. https://kupfer.de/wp-content/uploads/2019/11/RZ_Niedriglegierte_Kupferwerkstoffe_i8_EN_Einzelseiten.pdf (accessed 2025-02-02).
2. De Gee, A. W. J. and Zaat, J. H. Wear of copper alloys against steel in oxygen and argon. *Wear*, 1962, **5**(4), 257–274. https://doi.org/10.1016/0043-1648(62)90129-1
3. Qi, W. X., Tu, J. P., Liu, F., Yang, Y. Z., Wang, N. Y., Lu, H. M. et al. Microstructure and tribological behavior of a peak aged Cu–Cr–Zr alloy. *Mater. Sci. Eng. A*, 2003, **343**(1–2), 89–96. https://doi.org/10.1016/S0921-5093(02)00387-8
4. Tang, X., Chen, X., Sun, F., Li, L., Liu, P., Zhou, H. et al. A study on the mechanical and electrical properties of high-strength CuCrZr alloy fabricated using laser powder bed fusion. *J. Alloys Compd.*, 2022, **924**, 166627. https://doi.org/10.1016/j.jallcom.2022.166627
5. Wegener, T., Koopmann, J., Richter, J., Krooß, P. and Niendorf, T. CuCrZr processed by laser powder bed fusion – processability and influence of heat treatment on electrical conductivity, microstructure and mechanical properties. *Fatigue Fract. Eng. Mater. Struct.*, 2021, **44**(9), 2570–2590. https://doi.org/10.1111/ffe.13527
6. Küçükömeroğlu, T. and Kara, L. The friction and wear properties of CuZn39Pb3 alloys under atmospheric and vacuum conditions. *Wear*, 2014, **309**(1–2), 21–28. https://doi.org/10.1016/j.wear.2013.10.003
7. Amirat, M., Zaïdi, H., Djamaï, A., Necib, D. and Eyidi, D. Influence of the gas environment on the transferred film of the brass (Cu64Zn36)/steel AISI 1045 couple. *Wear*, 2009, **267**(1–4), 433–440. https://doi.org/10.1016/j.wear.2008.12.059
8. Kwok, C. T., Wong, P. K., Man, H. C. and Cheng, F. T. Effect of pH on corrosion behavior of CuCrZr in solution without and with NaCl. *J. Nucl. Mater.*, 2009, **394**(1), 52–62. https://doi.org/10.1016/j.jnucmat.2009.08.006
9. Zhou, W., Kousaka, T., Moriya, S.-I., Kimura, T., Nakamoto, T. and Nomura, N. Fabrication of a strong and ductile CuCrZr alloy using laser powder bed fusion. *Addit. Manuf. Lett.*, 2023, **5**, 100121. https://doi.org/10.1016/j.addlet.2023.100121
10. UKAEA (UK Atomic Energy Authority). *Development of the material property handbook and database of CuCrZr alloy for fusion applications*. 2019. https://scientific-publications.ukaea.uk/wp-content/uploads/UKAEA-CCFE-PR1927.pdf (accessed 2025-02-02).

CuCrZr ja CuZn39Pb3 sulamite kulumiskäitumise eksperimentaalne võrdlus pin-on-disc meetodil toatemperatuurist kõrgematel temperatuuridel

Isik Cetintav ja Mehmet Ceviz

Uuringus analüüsitakse CuCrZr ja CuZn39Pb3 sulamite kulumiskäitumist erinevates termilistes tingimustes, hoides mehaanilised parameetrid konstantsetena ja kasutades tihvt-ketta tribomeetrit. Katsed viidi läbi temperatuuridel 25 °C, 100 °C, 200 °C ja 300 °C, koormusel 7 N, hinnates mõlema sulami kulumiskiirust, hõõrdetegurit (COF) ja kõvadust. CuCrZr näitas suurepärast kulumiskindlust, stabiilset kõvadust ja ühtlast hõõrdekäitumist kõigil temperatuuridel, mis on tingitud selle sademete kõvenemise mehhanismist ja termilisest stabiilsusest. Seevastu CuZn39Pb3 ilmutas plii määrdeomaduste kadumise ja maatriksi lagunemise tõttu kõrgematel temperatuuridel märkimisväärset pehmenemist, suuremat kulumiskiirust ja ebaühtlast COF-käitumist. SEM-analüüsid näitasid, et CuCrZr puhul esines vähem tõsiseid pinnakahjustusi võrreldes CuZn39Pb3-ga, mille pinnal oli märgata kihistumist ja prahi teket. Uuringu tulemused rõhutavad CuCrZr sobivust kõrgete temperatuuridega ja märkimisväärsete triboloogiliste koormustega rakendusteks, mida toetavad ka arvutatud kontaktpinged. Kui CuCrZr näitab suurepärast termilist stabiilsust ja kulumiskindlust, siis CuZn39Pb3 on plii olemasolu tõttu paremini töödeldav ning seetõttu eelistatav rakendustes, kus eelistatakse valmistamise lihtsust.