Enhancing Wear Resistance of Brass Composites Using Fly Ash Reinforcement: A Specific Weight Loss Study

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ABSTRACT

Metal Matrix Composites (MMCs) with a brass matrix reinforced by coal-derived fly ash present a promising alternative to conventional brass. The addition of fly ash improves the material properties; however, its effect on the wear resistance of brass-based MMCs remains insufficiently studied. This study investigates the specific weight loss behavior of brass composites with varying fly ash content. In this study, MMCs were fabricated using the stir casting method in a gas furnace with varying fly ash contents of 5%, 10%, 15%, and 20% by weight. Brass was used as the matrix material. Hardness tests of the resulting composites were performed using the Rockwell-B hardness test method. Wear testing was conducted utilizing the pin-on-disk method, applying a load of 1000 grams. Tests were carried out at sliding distances of 600, 800, and 1000 m. The results showed that the addition of fly ash significantly affected both hardness and wear resistance. The MMCs with 5% fly ash exhibited the highest hardness value of 78 HRB and the lowest specific weight loss of 0.055 mg/m, indicating better wear resistance compared to the MMC without fly ash. Increasing the fly ash content beyond 5% led to a gradual decrease in hardness and an increase in weight loss.

Keywords-brass; fly ash; MMC; specific weight losses; wear

I. INTRODUCTION

Brass is a copper-based alloy primarily composed of copper and zinc, with the copper content typically ranging from 60% to 70%, and the remainder consisting of zinc and small amounts of other metals. This alloy offers several advantages, including excellent corrosion resistance, good ductility, and ease of fabrication. Additionally, brass can be easily shaped, machined, and polished into a variety of forms and finishes, making it suitable for a wide range of industrial and decorative applications. The uses of brass include pipe and plumbing fittings, machine components (gears, bearings, and valves), electrical equipment (connectors, terminals, and switches), and household items (door handles, knobs, hinges, and other decorative items) [1, 2]. The widespread use of brass is due to its unique combination of properties, such as corrosion resistance, ductility, and attractive aesthetics, as well as ease of forming and machining [3, 4].

Friction is one of the causes of wear in metal components. The energy lost by friction is converted into heat. Friction in industrial machines can cost about 1500 billion per year [5]. These losses are in the form of component replacement costs, cessation of the production process during repairs, and loss of energy due to friction.

Wear is a process where the material on the surface of an object experiences reduction or partial loss as a result of friction or pressure that occurs during contact with another surface. This takes place through the mechanical interaction between two surfaces in contact with each other, a phenomenon that is common in various situations, such as when two objects rub together or an object moves against a force [6]. The addition of fly ash to brass produces a material known as MMC, which has different mechanical properties from the brass. These changes directly affect the wear resistance characteristics of the MMC. The wear rate of the latter can be used as a basis for its application to appropriate components. In addition, reducing the wear rate will extend the service life of the component. To this end, this study discusses in more depth the effect of the amount of fly ash on the wear rate of a brass MMC.

Abrasive wear occurs due to contact on the surface of an object with an object that has a higher level of hardness. The contact between two surfaces creates scratches, resulting in the removal of material from the other surface [7]. Abrasive wear is classified into two types: two-body and three-body abrasion. Two-body abrasion occurs due to the erosion of the surface of an object by an object with higher hardness. Three-body abrasion occurs due to the presence of residual wear/debris particles that have hardened and participate in the process of loss of material on the surface of the object [8, 9]. Lubricants coat the surface of the components and can reduce the coefficient of friction between surfaces, while bushings and bearings use balls or cylinders that move more easily to reduce friction. Bushings use solid materials that have low friction and the ability to self-lubricate [10, 11]. Bushings have advantages compared to bearings. Bearings require lubricants, especially for the ball or cylinder parts. However, the use of lubricant on bearings can cause dirt to be retained in the form of dust or fine metal grit on the surface of the ball. The presence of dirt can increase the friction between the metal surfaces because dirt can function as an abrasive medium.

The materials used to make bushings, bearings, or other components with a high risk of wear are metals or other materials with a low coefficient of friction and high hardness. The hardness of the material affects the maximum force that the bushing can withstand. Polymer or polymer composite bushings have a low coefficient of friction but cannot be used in components that experience high forces. Metal materials are used for components that experience high loads. One material that is widely used as a bushing is brass. Brass has a hardness that is suitable for bushing materials and has been widely employed for this purpose [12, 13].

The addition of fly ash to a brass matrix increaseσ its hardness and toughness [14, 15]. An increase in the mechanical properties, particularly hardness, directly correlates with improved wear resistance. This is because harder materials require more energy to deform and erode, thereby reducing the material loss rate. Conversely, softer materials deform more easily under load, creating a larger contact area and increasing friction, which accelerates the wear rate. The wear rate is typically quantified as the specific weight loss, that is, the weight loss per unit distance traveled. Therefore, data on specific weight loss can be used to predict the service life of a component.

This study investigates the specific weight loss of fly ash-reinforced brass MMC, focusing on the composition that exhibits the highest hardness. It also examines the effect of fly ash content on the MMC's wear rate. The experimental procedure involved a series of hardness tests, followed by wear tests using the pin-on-disk method.

II. EXPERIMENTAL PART

A. *Materials*

Beta-type brass was obtained from the "Sakti" engineering shop. The composition was Cu 48.73%, Zn 46%, Al 0.80%, Si 0.39%, P 0.10%, Fe 0.71%, and other impurities below 0.1%. Fly ash from burning coal was obtained from PLTU Paiton, East Java Province, Indonesia. The coal for the Paiton PLTU was produced from coal mines on the island of Kalimantan, Indonesia. The composition of the fly ash was Fe 30.80%, Ca 27.40%, Si 21.60%, Al 9.80%, Mg 3.00%, K 1.79%, Ti 1.24%, Mo 2.00%, and other elements below 0.05%.

B. *Production of MMC*

The MMC was fabricated in a gas-burning furnace without protective gas and using a stir casting process. A brass rod with a diameter of 25 mm was sectioned into 50 mm lengths. This preparatory step was undertaken to optimize the brass melting process. Following the complete melting of the brass, fly ash was introduced in precise mass proportions according to the predetermined compositions (i.e., 5, 10, 15, or 20% of the total mass). The molten metal mixture was then uniformly stirred at a rotational speed of 400 rpm. Subsequently to the stirring process, the liquid alloy was poured into a mild steel mold featuring a cavity with dimensions of 30 × 30 mm and a length of 300 mm. The specimens for the wear tests were 4 mm in diameter and 15 mm long, as illustrated in Figure 1.

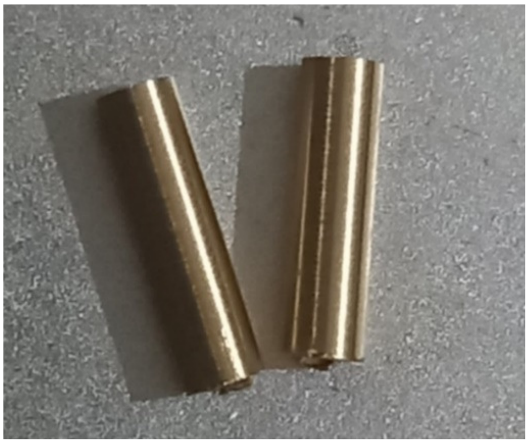

Fig. 1. MMC specimen for pin-on-disc tests.

C. Hardness Tests

Before testing, the surface of the MMC was rubbed with 1000 mesh sandpaper and then cleaned using acetone. The hardness of the MMC tested was conducted using the Rockwell-B (Tinius Olsen FH-0300002) hardness test method with a dwelling time of 20 s.

D. Wear Tests

Wear testing was carried out with a pin-on-disk machine with a load of 1200 gr and test track distances of 600, 800, and 1000 m. Each MMC was conducted in triplicate. The wear tests were conducted on brass and MMC with the highest hardness. Data were analyzed using one-way ANOVA.

The pin-on-disk method is an ideal and widely deployed technique for measuring the specific weight loss in metals. This method provides a controlled and repeatable simulation of sliding wear conditions, mirroring those found in real-world applications like bearings and gears. In this study, wear tests were conducted on a hardened VNC 150 steel disk.

The specific weight loss was determined by weighing the test specimens before and after each wear test using an analytical balance with a precision of 0.1 mg. To ensure reliability, three separate measurements were performed for each specimen, and a total of three specimens were tested for each experimental variable (fly ash content and applied load). The collected data for hardness and weight loss were then subjected to statistical analysis, including the calculation of the mean, standard deviation, and normality tests.

The wear rate can be determined by [16-18]:

$$SWL = \frac{\Delta W}{F \cdot L} \tag{1}$$

III. RESULTS AND DISCUSSION

The results of the hardness tests performed on the brass and fly ash MMCs using the Rockwell-B method are shown in Figure 3. The hardness of the MMC without fly ash was 71.8 HRB and increased to 77.6 HRB when 5 wt. % fly ash was added. However, increasing the fly ash content resulted in higher hardness compared to brass, but with a decreasing trend with higher fly ash content. Specifically, the hardness was 76.5 and 73.2 HRB for the MMCs with 10% and 15% fly ash, respectively, and then reduced to 70 HRB for 20% fly ash content. The highest hardness was observed for the MMC with a fly ash of 5%. The hardness of MMC with 10 and 15 % fly ash is still higher than that of brass, but 20 % fly ash resulted in a lower hardness than that of the pristine brass. The observed data reveal a nonlinear relationship between the fly ash content and the hardness of the MCC. The initial incorporation of fly ash at 5% significantly enhanced the hardness, indicating the effectiveness of fly ash as a reinforcement material. This improvement can be attributed to several factors. Fly ash particles, being hard and brittle ceramic inclusions, act as barriers to dislocation movement within the softer metallic matrix, thereby increasing the material's resistance to plastic deformation [19, 20].

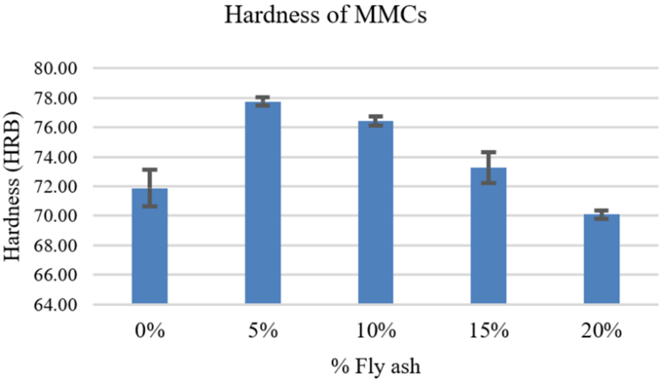

Fig. 2. Hardness of MMC brass matrix with varying fly ash content.

The decrease in the hardness of the MMC is expected due to the clustering of the fly ash particles. The reduction in hardness at higher fly ash percentages (10%, 15%, and especially 20%) can be explained by several mechanisms. At higher reinforcement loading, there is an increased probability of particle agglomeration [21]. Agglomerated particles can lead to the formation of voids and porosity within the composite, which act as stress concentration points and weaken the material, thereby reducing its hardness. Poor wettability of the fly ash particles by the molten metal at high concentrations can also lead to inadequate bonding and matrix segregation, further compromising the composite's integrity. Additionally, beyond an optimal volume fraction, the metallic matrix may not be able to effectively encase and transfer the load to all the reinforcement particles, leading to a decrease in the overall mechanical properties. The drastic drop at 20% suggests that the detrimental effects of excessive fly ash, such as increased porosity and poor distribution, outweigh any reinforcing benefits. The microstructures of the MMCs are shown in Figures 3 and 4. The microstructure of the MMC with 10% fly ash (Figure 4) has smaller grains compared to brass (Figure 3). The fly ash in the MMC is still dissolved in the matrix, indicating that the fly ash has not yet separated from the brass matrix.

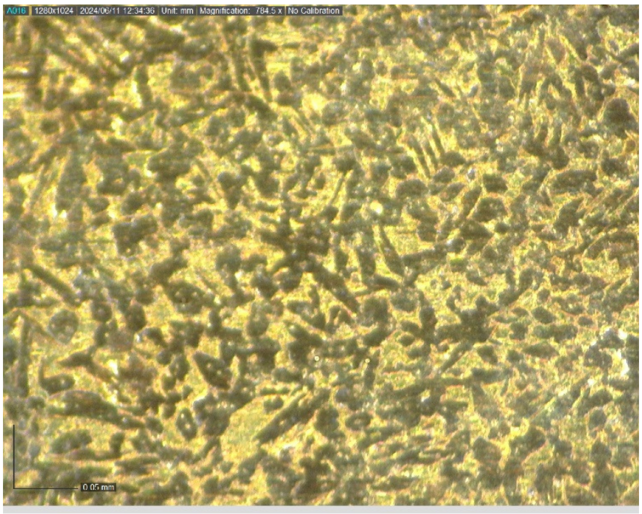

Fig. 3. Microstructure of brass.

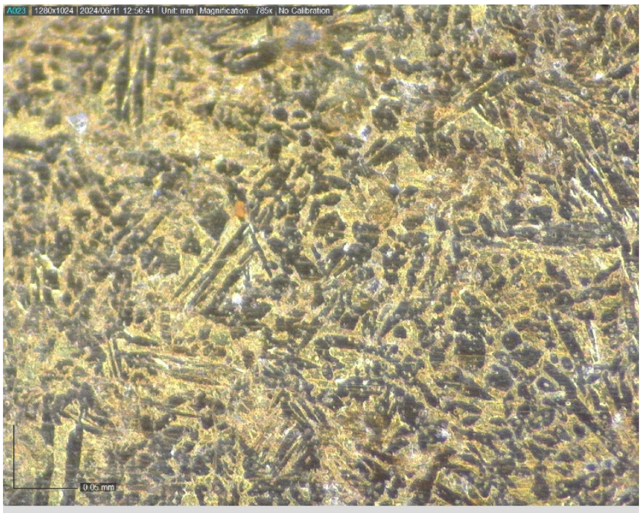

Fig. 4. Microstructure of MMC with 10% fly ash.

Wear testing was performed on MMCs with a fly ash content of 0% and 5%. This was done to determine which MMC had the highest hardness, because the lowest wear rate occurs in metals with the highest hardness [22-24].

The primary data acquired from the pin-on-disc test were the mass reduction of the test specimen. From this measured mass reduction, the specific wear rate, a quantitative parameter for material wear, was calculated using (1). The specific wear rate values for the MMC specimens are depicted in Figure 5.

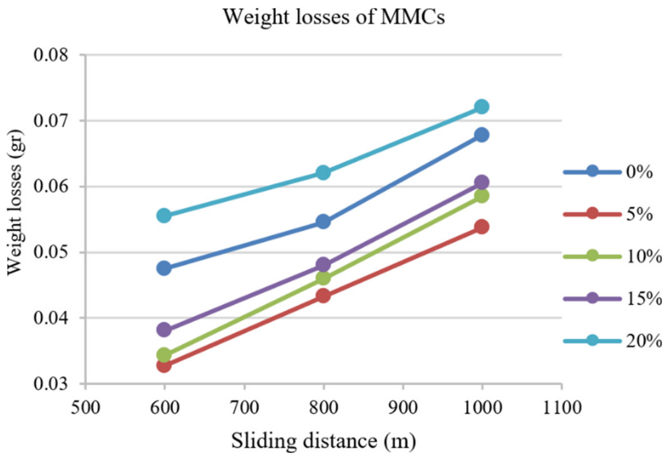

Fig. 5. Weight losses of MMCs.

The MMC without fly ash exhibited a specific weight loss of 0.69 mg/m. When 5% by weight fly ash was added, a significant reduction in specific weight loss was observed, decreasing to its lowest value of 0.55 mg/m. This 20.3% reduction compared to the base material highlights the reinforcing benefits of fly ash, likely due to the increased hardness or the formation of a protective tribo-layer [1]. However, as the fly ash content increased, the specific weight loss began to increase again. At 10% fly ash, the weight loss slightly increased to 0.59 mg/m, and this upward trend continued with values reaching 0.62 mg/m at 15% fly ash. The highest weight loss was recorded at 20% fly ash, where it climbed to 0.81 mg/m. This marks a 17.4% increase over the base material and a notable 47.3% increase from the optimal 5% fly ash addition.

Figure 5 reveals that the highest specific weight loss occurs in brass without fly ash, while the specific weight loss in MMC with 5% fly ash has the lowest specific weight loss rate. When compared to the hardness of MMC, the wear rate is inversely proportional to the hardness of the MMC [25]. Brass without fly ash exhibited the lowest hardness and the highest specific weight loss.

The specific weight loss was calculated using (1) for the 800 m sliding distance test. The results of the specific weight loss are outlined in Figure 6.

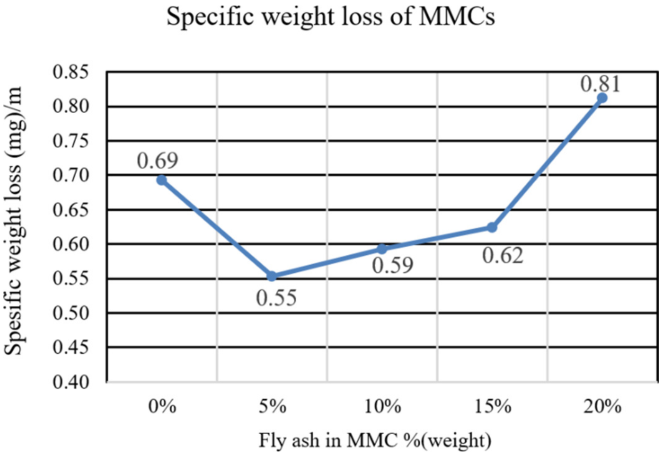

Fig. 6. Specific weight loss of MMCs at 800 m sliding wear test.

The data of specific weight loss were analyzed using one-way ANOVA according to the following steps:

- First, the null hypothesis, H_0, was formulated: The fly ash content variable (A) and the distance variable (B), either individually or together, do not have a significant effect on the weight loss variable (Y).
- The alternative hypothesis, H_1, was: The fly ash content variable (A) and the distance variable (B), either individually or together, have a significant effect on the weight loss variable (Y).

According to the ANOVA analysis, a p-value of 0.001 (less than 0.05) was obtained, indicating that H_0 is rejected and H_1 is accepted. Therefore, it can be concluded that the fly ash content has a significant effect on the weight loss.

The specific weight loss of MMC with 5% fly ash is lower than brass; this happened in tests with sliding distances of 600, 800, and 1000 m. The specific weight loss with a sliding distance of 600 m was higher than that with sliding distances of 800 and 1000 m, which was caused by the roughness on the surface of the specimen [26]. On a rough surface, the friction area between two objects is smaller, so the force acting on the surface is higher. One of the factors that influences wear is the working force. Increasing the force on the sample increased the wear. This is what caused the wear loss rate in the 600 m pin-on-disk test to be higher than that in the test process with a track of 800 and 1000 m.

The surface morphology of the MMCs after wear testing with a pin-on-disk tool can be seen in Figures 7 and 8. The wear that occurred on the metal (0% fly ash) and MMC with 5% fly ash was abrasive wear. On brass, the wear appears deeper than that on the MMC with 5% fly ash (Figure 8), which can be attributed to the higher hardness of the MMC compared to brass. In abrasive wear, longitudinal scratches are expected on the surface [6, 19, 27]. Longitudinal scratches were observed on the brass, as illustrated in Figure 7.

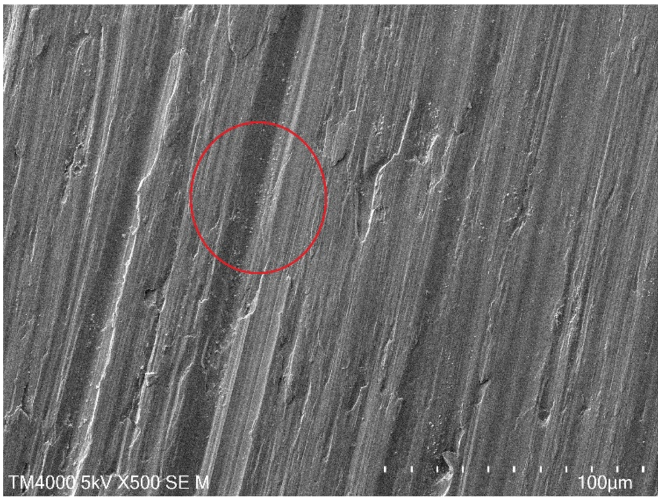

Fig. 7. MMC morphology after wear testing, fly ash 0%.

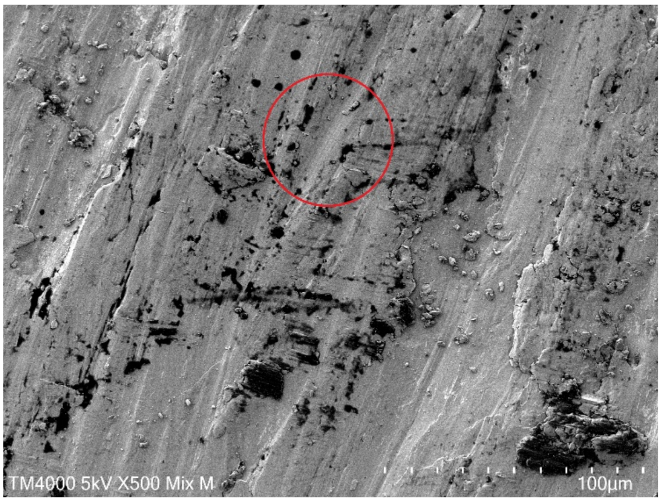

Fig. 8. MMC morphology after wear testing, fly ash 5%.

In addition to the surface morphology, abrasive wear can also be seen from the debris resulting from the wear. Figure 9 demonstrates that the debris from the pin-on-disc test had a flake shape, which is indicative of abrasive wear [19, 28].

The specific weight losses at a sliding distance of 1000 m on brass were 0.69 mg/m, whereas on MMC, they were 0.55 mg/m, a 20% decrease in the specific weight losses. This reduction signifies that the wear on MMC components made from brass and 5% fly ash will be lower, thereby increasing the service life of these components. The use of brass MCCs with 5% fly ash will not only reduce component prices but also reduce product prices. It can also increase the service life of the components, which will greatly reduce the use of metals (copper and zinc). The wear rate of the MMC is linked to its hardness. Hard metals/materials are more resistant to wear and tear since more energy and friction time are required to remove the atoms from the surface [29-31].

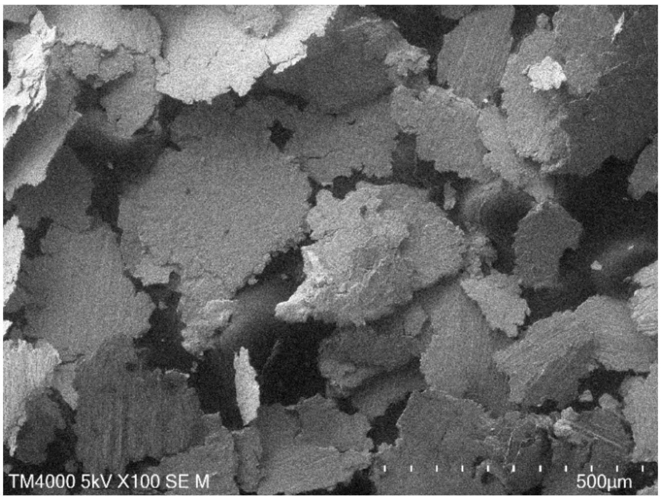

Fig. 9. Debris of MMC from the pin-on-disc test.

The results indicate that the addition of fly ash increases the hardness of the MMC, with a peak value observed at a 5% fly ash content. Further addition of fly ash decreased the hardness. However, even the addition of 15% fly ash resulted in MCC with higher hardness than that of the pristine brass. This confirms a direct relationship between the hardness of the MMC and its wear rate: a higher hardness corresponds to a lower wear rate. This significant reduction in the wear rate can extend the service life of a component and allow it to perform effectively under higher loads.

IV. CONCLUSION

Brass-based composites with varying fly ash reinforcement were successfully fabricated and characterized for their wear properties. The brass Metal Matrix Composite (MMC) with 0% fly ash showed a specific weight loss of 0.69 mg/m. Incorporating 5% fly ash, the specific weight loss decreased to 0.55 mg/m, with 10% fly ash, the weight loss was 0.59 mg/m, with 15% fly ash, the weight loss was 0.62 mg/m, and with 20% fly ash, the weight loss was 0.81 mg/m. The brass MMC with 5% fly ash exhibited approximately 20% lower specific weight loss than the pristine brass without fly ash, which can be attributed to the increased hardness of the MMC upon the addition of 5% fly ash.

The results of this study contribute significantly to material science by identifying that a brass MMC with 5% fly ash content is the optimal composition for enhancing the hardness and wear resistance of brass composites. These findings demonstrate that industrial waste, such as fly ash, can be effectively utilized to produce high-performance MMC materials, which are applicable in applications like bearing components.

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