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Alumina Particulate Blending and Sintering Temperature Effect on Powder Metallurgy Processed Copper Metal Matrix Composites

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Copper with higher electrical conductivity, reinforced with high-performance ceramic particulates, is suitable for use in industrial electrical contacts, connectors, and thermal management systems due to its tailorable mechanical properties, which improve its wear resistance accordingly. The stronger effect of particle mixing and sintering temperature variation is tailoring the mechanical properties, allowing the copper matrix to be met for the desired applications. The influence of sintering temperature and alumina particulate ratio on the microstructure, compressive strength, ultimate tensile strength, flexural strength, and micro hardness of copper–alumina composites were systematically studied. Copper matrices were reinforced with 5, 10, 15, and 20 vol.% alumina powder and sintered at three different temperatures: 750 °C, 800 °C, and 850 °C. The composite containing 15 vol.% alumina sintered at 750 °C exhibited the highest compressive strength. The maximum ultimate tensile strength was observed in the composite with 20 vol. % alumina sintered at 850 °C. The greatest flexural strength was achieved with 5 vol.% alumina at 850 °C, while the highest micro hardness was recorded in the composite containing 15 vol.% alumina sintered at 800 °C.

Keywords: *Metal Powder, Copper, Particulate reinforcement, Sintering, Hardness, Strength.*

1. Introduction

Copper has been widely utilized by several researchers for centuries because of its exceptional thermal and electrical conductivity, corrosion resistance and ductility. These properties make it necessary in electrical wiring, heat exchangers, plumbing, and industrial machinery[1]. Copper alone might not provide the necessary mechanical strength, wear resistance, or thermal stability required in cutting-edge engineering applications. Incorporation of ceramic particles in to the copper, leads to the fabrication of composites precisely copper matrix composites (Cu-MCs)[2]. These materials are used in high-performance applications, including: electrical contacts and connectors, Heat sinks and thermal management systems to enhance thermal stability[3]. Bearings and bushings to obtain better frictional properties, aerospace and automotive components require lightweight and also with high strength[4]. In order to enhance the mechanical properties of copper matrix reinforcing ceramic particles such as alumina (Al_2O_3), silicon carbide (SiC), and zirconia (ZrO_2) are preferred[5]. These reinforcements of particles significantly improve the hardness, strength, and wear resistance whereas maintaining the desirable thermal and electrical conductivity to some extent.

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Alumina (Al_2O_3) is one of the most commonly used ceramic reinforcement particle in copper-based composites, and it is preferred because of its high hardness, thermal stability, and electrical insulation properties[6]. Enhancement of mechanical properties incorporating alumina is added into the copper, suitable for sliding wear applications in electrical sliding contacts and also improves the oxidation resistance and increasing lifespan of the composites in harsh environments[7].

Fabrication of Copper-alumina composites improves the mechanical strength and thermal stability making them ideal for the modern applications; in electrical sliding contacts, short-circuiting devices, miniature circuit breakers (MCBs) and large circuit breakers (LCBs)[8]. Alumina's intrinsic hardness, reaching up to the level of 2200 HV[9], imparts an exceptional wear resistance for the fabricated composites, effectively reduced the material degradation during high-stress events like electrical arcing. Therefore, the inclusion of alumina particles in metal matrices is a strategic approach which enhances the performance and reliability of fabricated components exposed to harsh operating conditions and severe short-circuit scenarios.

The fabrication of copper-alumina ($Cu-Al_2O_3$) composites adopting powder metallurgy (PM) owing to its ability of attaining a uniform dispersion of alumina particles in the copper matrix while maintaining the desired mechanical, thermal, and electrical properties[5]. Several researchers focused on improving Cu-based composites via powder metallurgy because of its uniform dispersion and better interfacial bonding. Other conventional fabrication techniques, such as casting or melting-based processes, are not suitable for Cu-Al_2O_3 composite production due to the vast difference in processing temperatures between copper (~1085°C) and alumina (~2072°C), which leads to poor wettability, agglomeration of alumina particles, and uneven distribution within the matrix[10].Powder metallurgy route provides a numerous advantage over other processing techniques, including precise control over the composites microstructure, dispersion of particles in uniform manner, net shape fabrication and enhancement of mechanical and thermal properties[11]. In the powder metallurgy process, fine copper and alumina powders are mixed using ball milling or mechanical alloying techniques to ensure homogeneous dispersion of the ceramic reinforcement. The powder mixture is then subjected to cold compaction under high pressure to form a green compact. This compact is subsequently sintered at different temperatures in a vacuum or controlled atmosphere to enhance the densification while preventing oxidation[12].

Reported a powder-metallurgy based approach by creating a three-dimensional continuous graphene network architecture in a copper matrix by welding graphene-like nanosheets produced on the surface of copper powders under thermal stress. This research report shows enhancement of wear resisting quality by the result of electrical arc[12] fabricated Copper (Cu)/Graphene Nanostructure Sheet (GNS) composites adopting powder metallurgy technique enhanced the compressive strength by over 10% compared to pure Cu and also reported retention of higher electrical conductivity. Enhancement of relative density of fine-grained Copper-Tungsten composite with an increase in sintering temperature[13]. The wear properties of the copper-tungsten composite were shown to be superior to those of other ceramic-reinforced composites. However, the reduction in electrical conductivity is a concern for its use in miniature electrical contacts, where high electrical conductivity is essential for proper functioning.

Rezayat et al.[5] fabricated Cu–Al_2O_3 composites via high-energy milling and reported an improvement in hardness with limited tensile analysis. Cu-based MMCs emphasizing that maximum research investigated either mechanical or tribological properties alone with considering the individual effect of sintering temperature or reinforcement. Likewise,Rajkovic et al. 2014 studied Cu–Al_2O_3 composites with low alumina content but did not investigated flexural or compressive behavior[14]. In Cu/alumina reinforcements lacked in systematic study on considering the sintering temperature effects. Comprehensive evaluation of multiple mechanical properties (compressive, tensile, flexural strength, and hardness) as a function of both alumina content and sintering temperature remains scarce. Most previous works were optimized either reinforcement content or processing temperature independently without exploring their combined effect on microstructure and mechanical performance. Limited studies were investigated with the combined effect of alumina content and sintering temperature on mechanical properties. The experiments were designed via parametric approach through varying two key factors: alumina particle (5–20 vol.%) and sintering temperature (750 °C, 800 °C, 850 °C). A full factorial design was implicitly followed and ensuring that all combinations of these factors were examined for evaluating the combined influence of reinforcement ratio and sintering temperature on multiple mechanical properties of the composites. The present study reports this gap by systematic investigation on fabricating Cu–Al_2O_3 composites with varying the reinforcements percentage of alumina particle (5–20 vol.%) via powder metallurgy and sintering at different temperatures (750 °C, 800 °C, and 850 °C) by unique investigation with the combined effect of alumina ratio and sintering temperature on compressive, tensile, flexural strengths, and microhardness, to provide the optimal processing parameters for high-performance of Cu–Al_2O_3 composites in electrical and structural applications.

2. Materials

Copper powder (size 15 μm) procured from a Vishnupriya Chemicals Private Limited in Hyderabad at a purity level of 99.1%. The copper powder remains highly pure and is suitable for various applications in industries where quality and consistency are paramount. Alumina powder (size 10 μm) composed primarily of aluminum oxide (Al_2O_3) is a versatile material with wide ranging industrial applications. It was procured from Vishnupriya chemicals private limited Hyderabad with the density of 3.95 g/cc.

3. Fabrication Methods

3.1. Green compaction

Fabrication Composites were fabricated by mixing copper powder with different volume fractions of alumina powder (5%, 10%, 15% and 20%) as shown in Table 1. The centrifugal rotating blender used to blend the powders for 12 hours at 300 rpm. The mixed powders were compacted into cylindrical pellets using an electrically operated uniaxial cold compaction machine. The compaction process was carried out under an applied pressure of 400 MPa to ensure the required density and mechanical properties. Stainless steel dies were fabricated to the required dimensions for testing the mechanical properties of the composites prior to the compaction process. To prevent adhesion of the compacted pellets to the die walls, graphite was used as a lubricant, ensuring a smooth release of the specimens and preventing damage to their surfaces.

Specimens were prepared to evaluate the mechanical properties of compression, tensile, flexural, hardness, and wear tests as per the ASTM standards. According to ASTM E09 for the compression test the specimens were prepared at a diameter of 20 mm and length of 40 mm maintaining a length-to-diameter ratio of 2. For the flexural test samples were prepared with dimensions of 31.5 mm × 12.7 mm × 6.3 mm and ensuring compatibility with standard flexural testing procedures (ASTM E290). The wear test samples were prepared in line with ASTM G99 at a diameter of 10 mm and a length of 20 mm. Finally, for the hardness test, specimens were prepared with the dimensions of 12.5diametermm and a thickness of 37.5 mm according to ASTM E18 for precise hardness measurements.

3.2. Sintering

The compacted specimens were sintered using a tubular furnace under an argon atmosphere. The sintering temperature for each test specimen was varied across three levels: 750°C, 800°C, and 850°C While a heating rate of 5°C per minute and maintained a constant holding time of 1 hour. Initially, the tube was evacuated to achieve a vacuum level of 10^{-3} mbar. Following this, argon gas was purged through the tube to create an inert environment and prevent the formation of oxides on the specimen surfaces during the heating, sintering, and holding stages. This controlled atmosphere was critical to maintaining the integrity of the material properties.

After the sintering process, the specimens were allowed to cool naturally at room temperature within the tubular furnace. By ensuring this process it gradually cools and reduces the thermal stress or cracking.

Table 1. Fabricated specimens of Cu-Al_2O_3 MMCs with designation

Sample ID	Sintering Temperature	Designation as per volume %
CA1	750°C	95%Cu,5%Al_2O_3
CA2	750°C	90%Cu,10%Al_2O_3
CA3	750°C	85%Cu ,15% Al_2O_3
CA4	750°C	80%Cu,20%Al_2O_3
CA5	800°C	95%Cu,5%Al_2O_3
CA6	800°C	90%Cu,10%Al_2O_3
CA7	800°C	85%Cu,15% Al_2O_3
CA8	800°C	80%Cu,20%Al_2O_3
CA9	850°C	95%Cu,5%Al_2O_3
CA10	850°C	90%Cu,10%Al_2O_3
CA11	850°C	85%Cu,15% Al_2O_3
CA12	850°C	80%Cu,20%Al_2O_3

3.3. Compression test

The compression test was conducted on the prepared copper-alumina (Cu-Al_2O_3) composites by varying volume percentages of alumina (e.g., 5%,10%, 15% and 20%) and the fabricated samples are sintered at different temperatures (e.g., 750°C, 800°C, 850°C) in a controlled atmosphere to attain the optimal densification as shown in Table 1. Compression testing was executed in a universal testing machine (UTM) as per standards of ASTM E09 to determine the ultimate compressive strength. The load was applied to the prepared samples at a constant strain rate of 10^{-4} S^{-1} until specimen failure, and the results were analyzed to evaluate the effect of alumina content and sintering temperature on the compressive behavior of the fabricated copper alumina composites. The prepared typical compressive strength sample is shown in the Figure 1 (a).

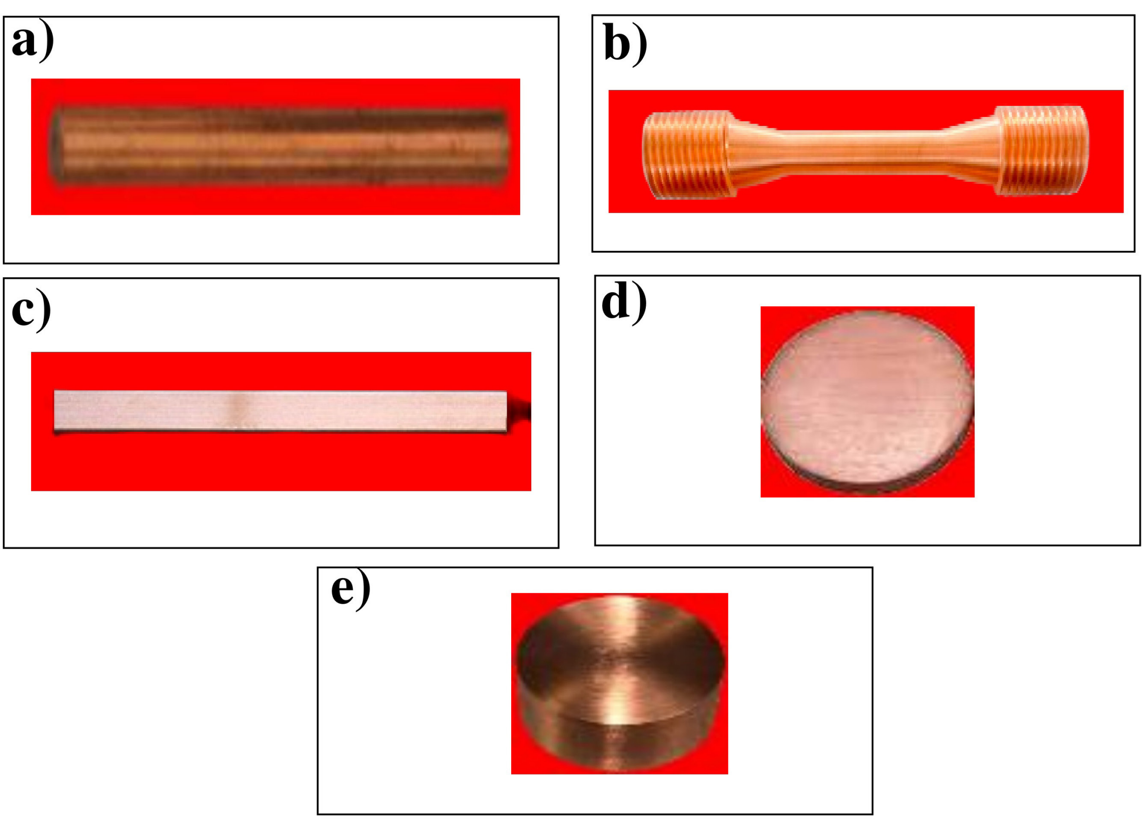

Figure 1. Test specimens for a) Compression, b) Ultimate Tensile, c) Ultimate Flexural, d) Micro hardness and e) SEM analysis.

3.4. Tensile test

The tensile test was carried out for the fabricated copper-alumina (Cu-Al_2O_3) composites fabricated using the powder metallurgy (PM) method, with varying alumina volume fractions (5%, 10%, 15% and 20%). The compacts were sintered at various temperatures as shown in Table 1 (e.g., 750°C, 800°C, 850°C) under a controlled atmosphere to improve their micro structural characteristics. Tensile testing was performed on a universal testing machine (UTM) following ASTM E09 standards to measure yield strength, ultimate tensile strength, and elongation. The test specimens were prepared according to standards with the dimensions of a specific gauge length as 25 mm, and diameter of 10 mm. The results were studied to assess the effect of alumina content and sintering temperature on the tensile properties of the prepared copper alumina composites. The samples subjected to conduct tensile test is shown in the Figure 1 (b).

3.5. Flexural test

The flexural test was conducted in Universal Testing Machine as per ASTM E290 for the prepared specimens with dimensions of 10 mm in width, 3 mm in thickness, and a length of 160 mm. The prepared flexural test sample is shown in Figure 1 (c).

3.6. Hardness test

Vickers micro hardness testing method applied with a small pointed indenter of pyramid shape to the material surface under a controlled load. The hardness test was performed using a HV Vickers micro hardness testing machine with an applied load of 3 kg for a dwell time of 10–15 seconds to ensure stable readings. The prepared specimen for hardness test is shown in Figure 1 (d).

3.7. Scanning electron microscope

SEM analysis was performed for the copper alumina composites and studied the microstructure characteristics of metallographically polished samples influenced by reinforcement of alumina particle and different sintering conditions. Ferric chloride solution 5g FeCl3 and 50 ml HCl in 100 ml distilled water was employed as an etchant to selectively attack the grain boundaries. Micrographs were taken at an accelerating voltage of 20 kV. The SEM images were analyzed to observe the morphology of reinforcement particles, their distribution, and integrity with the matrix. Electron dispersive X-ray analysis was performed to investigate the compositional details of the sections. The prepared specimen Scanning Electron Microscope is shown in Figure 1 (e).

4. Results and Discussion

4.1. Scanning electron microscopy

Figures 2 (a-l) are providing detailed information about the distribution of reinforcement (Al_2O_3 particles), and the quality of the interface between particles and matrix. In the SEM images, lighter areas (white regions) correspond to the copper matrix[15] while darker areas (black regions) represent the Al_2O_3 reinforced particles. The main finding discussed is that with an increase in particulate content, in some places the clustering or aggregation of Al_2O_3 particles were seen, specifically at 20%, in Figure 2 (a-l).

Particle clustering can significantly affect the mechanical properties and uniformity of the composite material. The SEM micrographs are instrumental in illustrating how the sintering temperature affects the degree of sintering and interface between matrix and particles. distribution and clustering of reinforcement particles in the copper matrix.

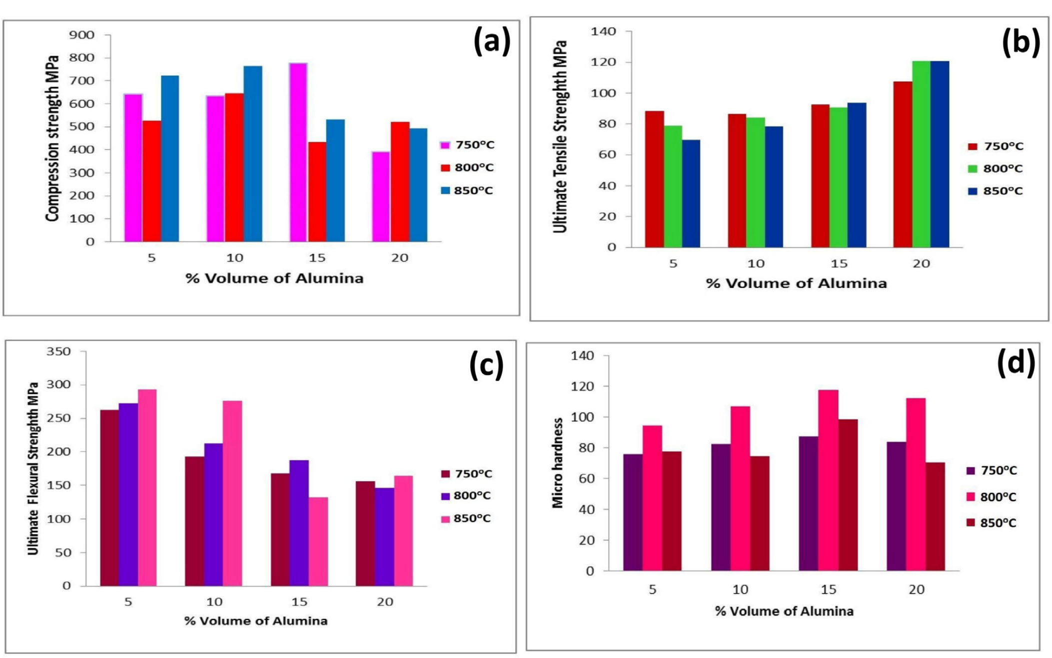

Figure 2. Scanning Electron Microscopy for various percentage of Alumina at different Sintering Temperature.

As the sintering temperature increases, the copper matrix becomes stronger due to significant diffusion of matrix material and also dispersed particles affect heat distribution around the matrix material[16]. SEM images of sintering temperature at 750 °C, at varied dispersion of alumina particles at 5% to 20%, as shown in Figure 2 (a-d), show that sintering had taken place; however, some interface voids and fissures are visible in the matrix material and also between the matrix and particles. At sintering temperature increased to 800 °C, as shown in Figure 2 (e-h), the degree of sintering was said to be good, leading to the disappearance of some defects, and the integrity between the particle and matrix material was good[17]. In addition, the matrix material becomes stronger, as evidenced by mechanical properties presented in the preceding section. Further, with an increase of sintering temperature to 850 °C, there was a tendency of grain growth that may be attributed, and also some defects like interface voids and surface fissures were evidenced in Figure 2 (i-l), leading to a decline in matrix strength.

4.2. Compression strength for Cu–Al_2O_3 composites at different sintering temperature

The compression strength of the fabricated copper-alumina composites exhibits significant variations at different percentages of alumina and sintering temperatures[18] of (750,800, 850°C), as shown in the Figure 3 (a). The compression strength of Cu–Al_2O_3 composites is strongly influenced by both alumina content and sintering temperature, as these factors determine densification, particle bonding, and microstructural integrity.

The reinforcement particles are well-dispersed at moderate alumina (10-15 vol.%), results in effective load transfer and an increase in strength. The copper alumina combinations with 15% of alumina, shows the highest value (777.24 MPa) at the sintering temperature of 750^{0}C, because of the reinforcement particle distribution, interfacial bonding and adequate densification attained the fine densification and mechanical performance in compression tests. The reinforcement particles enhance the transfer of loads and the mechanical strength. This temperature allows the particular composition provided the optimal bonding and structural integrity which increase the compressive strength values of the matrix materials[19].

But when the concentration of alumina increases to 20%, the value drops to 392.4MPa, owing to the agglomeration of the particles, interfacial voids rise leading to the increase of porosity and the low interfacial adhesion, which hinder densification and reduction of mechanical strength. Excessive ceramic reinforcement disrupts the metal matrix continuity leading to stress concentration and premature failure, causes a drastic drop in mechanical performance[20]. The highest value of 646.21MPa attained at 800^{o}C, shows an interaction between the composition and temperature has an significant effect on the mechanical properties of the composites. This increased temperature is probably more efficient in sintering and densification thus leading to a higher load bearing factor but in the 15 percent alumina composite case, there is a significant reduction (432.61 Mpa) which means that incremental addition of ceramic reinforcement occurs at this temperature and might in turn impede the diffusion bonding[21].

Similarly, at 850°C, the 10% alumina composite again achieves the highest value (764.16 MPa), demonstrating that a moderate alumina content facilitates enhanced densification and mechanical stability at elevated temperatures.

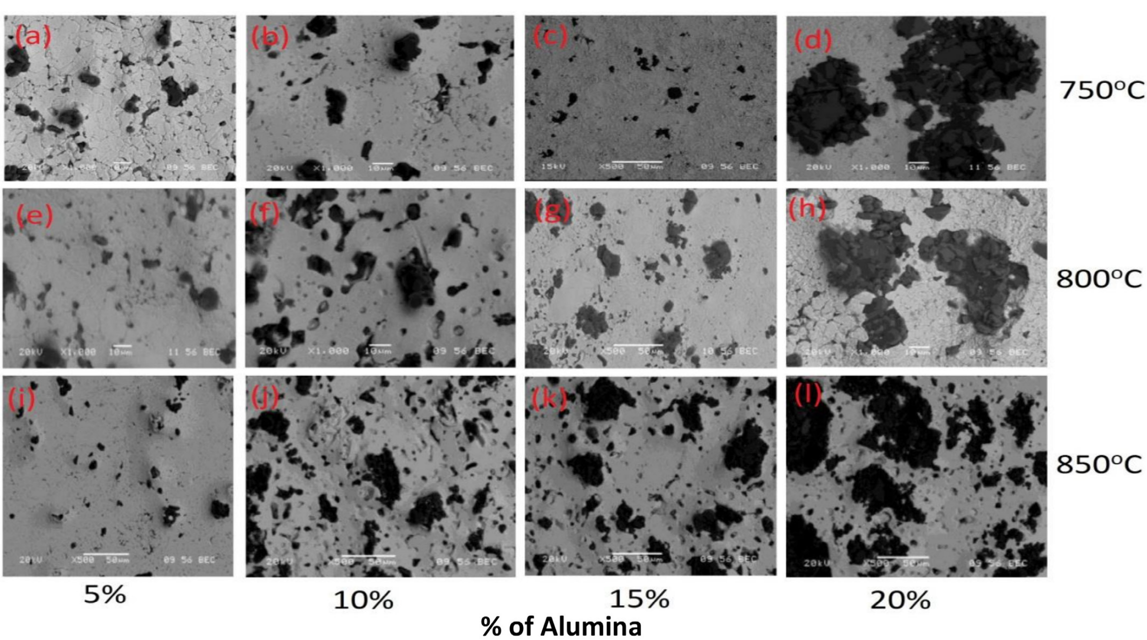

Figure 3. a) Compression Strength, b) Ultimate Tensile Strength, c) Ultimate Flexural Strength and d) Micro hardness for Cu–Al_2O_3 composites at different sintering temperature.

Here, the further increase in temperature potentially enhances grain growth and reduces porosity, contributing to the material's overall strength under compression. These variations highlight that an optimal balance of alumina content and sintering temperature is crucial for achieving superior mechanical properties, where excessive alumina can lead to weak interfacial bonding, while inadequate sintering temperatures may result in incomplete densification[22]. The compression test results underscore the complex relationship between composition and sintering temperature in Cu-Al_2O_3 composites. While the 15% Al_2O_3 composite excels at lower temperatures by showing a higher mechanical strength, the 10% Al_2O_3 composition proves superior at higher temperatures, specifically 850°C.

At the temperature of 750 °C, an initial reduction in porosity favors better strength at 15 vol.% alumina and at 800 °C, improved densification enhances bonding; however, excessive addition of reinforcement hinders the copper particle diffusion. At 850 °C, grain growth weakens the matrix, results in reduction of compressive strength despite higher densification. Similar observations were stated by Rajkovic et al. (2014) and Rezayat et al. (2023), that excessive addition of ceramic content and high sintering temperatures leads to particle aggregation, weak bonding and thereby lowering the matrix strength.

4.3. Ultimate tensile strength for Cu–Al_2O_3 composites at different sintering temperature

The tensile strength of Cu–Al_2O_3 composites depends on grain structure, and porosity, all of which are affected by alumina content and sintering temperature. The ultimate tensile strength (UTS) of copper-alumina composites was investigated through a series of experiments varying the alumina composition and sintering temperatures, as detailed in Figure 3 (b) The study focused on specimens containing alumina at volume fractions of 5%, 10%, 15%, and 20%. The results revealed notable trends where increasing the percentage of alumina generally led to an enhancement in tensile stress[23]. Specifically, the highest tensile strengths observed for the 15% of alumina reinforcement with the measured value of 120.7 MPa. These values corresponded to specimens with 15% alumina content sintered at temperatures of 750°C, 800°C, and 850°C, respectively. The measured value has the significant influence of both alumina content and sintering temperature on the mechanical properties of the composites. The increase in tensile strength with higher alumina content can be attributed to several factors. Alumina, being a ceramic material with high hardness and strength, acts as a reinforcing phase within the copper matrix. This reinforcement effectively strengthens the composite, enhancing its ability to resist tensile forces and deformation under load. Moreover, the variation in sintering temperature also plays a critical role. Sintering affects the consolidation and bonding between the copper and alumina particles, influencing the microstructure and mechanical properties of the composite. Sintering temperatures of 800^{0}C typically promote better bonding and densification, leading to improved mechanical performance[24].

The study has demonstrated the significant impact of alumina content and sintering temperature on the tensile strength of these composites. Optimizing alumina content involves finding the ideal balance where the reinforcement effect maximizes without compromising the ductility of the copper matrix excessively and achieved through precise control of processing techniques, including particle size distribution, mixing methods, and sintering conditions[25]. At 15 vol.% alumina, tensile strength is highest because the particles act as barriers to dislocation motion while still maintaining good ductility. However, at 20 vol.%, particle clustering and poor interfacial bonding generate stress concentration sites, leading to premature failure under tensile loading. Sintering temperature also plays a critical role. At 750–800 °C, adequate diffusion of copper particles promotes strong bonding and uniform particle dispersion, which enhances tensile strength. At 850 °C, excessive grain growth and void formation reduce ductility, resulting in lower tensile strength despite better densification. SEM images from this study confirm that clustering and voids increase at higher reinforcement levels and sintering temperatures. Similar findings were reported in the literature [Rezayat et al., 2023], noting that the balance between densification and grain coarsening is crucial for optimizing tensile properties.

4.4. Ultimate flexural strength for Cu –Al_2O_3 composites at different sintering temperature

Flexural strength in Cu–Al_2O_3 composites are highly sensitive to matrix continuity, particle dispersion and interfacial bonding which are directly influenced by alumina content and sintering temperature. These composites typically consist of copper as the matrix material and alumina (Al_2O_3) as the reinforcement phase[26]. According to the findings presented in Figure 3 (c), the maximum flexural strength of 292.67 MPa was obtained for specimen composition of 20% alumina at the sintering temperature of 850°C. The temperatures increasing from 800°C and 850°C, the flexural strength were increased from 272.1 MPa to 292.67 MPa, for the sample composition of 5% alumina displayed in the Figure 3 (c).The plot reports that the incorporation of alumina, particularly at the 5% concentration level, significantly improves the flexural strength of the Cu –Al_2O_3composite specimens across different sintering temperatures of 750°C, 800^{o}C and 850°C underscores the impact of sintering temperature on the mechanical properties of the composites. Higher temperature results an increase of strength due to the improvement in densification and grain growth[14]. From the experimental result that the optimal combination of maximum flexural strength in using 5% alumina content, with the highest strengths achieved at higher sintering temperatures within the range tested (750°C, 800^{o}C and 850°C). The results are crucial for understanding the mechanical behavior of the material under varying conditions and for optimizing its performance in practical applications requiring high flexural strength. Copper alumina composites exhibit flexural strengths ranges from 147 MPa to 293 MPa depending on the specific composition and processing parameters. This range shows that the robustness of the materials in applications subjected to bending loads, structural components in aerospace and automotive industries. Reinforcement particle at 20% and increase of sintering lead to a cumulative effect of replacing aggregation of particles resulting in voids in an interface as well grain growth of an increase of sintering temperature of 800 °C and after.

At low alumina content (5 vol.%), the copper matrix remains continuous, providing better ductility and resistance to bending stresses. As alumina content increases to 15–20 vol.%, particle clustering and weak interfaces, reducing flexural strength under bending loads. Sintering temperature impacts bonding and densification. At 750–800 °C, particle–matrix adhesion improves due to sufficient diffusion, enhancing load transfer. However, at 850 °C, excessive grain growth and discontinuity in copper network due to particle aggregation weaken the matrix, as seen in SEM images (Figure 2) leading to a reduction in flexural strength at higher alumina levels. Excessive reinforcement shows porosity and interfacial defects, which lower the bending strength.

The trend of the flexural strength is not the same as that of compressive and tensile strength behaviour due to the difference in the stress location and failure mode of flexural bending and the uniaxial loading. The tensile and compressive stresses occur concurrently in flexural loading in the cross-section of the specimen - tensile stresses are stronger on the lower surface where cracks form more readily in the brittle or particle-rich areas. With reduced alumina (e.g. 5 vol.%), the copper matrix is continuous which means that good ductility and even distribution of stress under bending is ensured resulting in greater flexural strength. But at higher levels of alumina content (greater than 10-15 vol.%) interfacial bonding and particle agglomerations are formed, forming micro voids and locations of stress concentration. These flaws enhance the premature crack initiation under tensile loading in the flexural test, which results in the strength reduction despite the increase in compressive and tensile tests through reinforcement by loads. In addition, the presence of higher alumina fractions lowers the continuity of the matrices leading to brittle fracture behavior and low plastic deformation behavior at bending conditions. Thus, moderate alumina reinforcement enhances compressive and tensile strength by enhancing the dislocation by transferring more loads and resisting dislocation, but excessive alumina reinforcement reduces flexural performance by agglomerating, debonding interfaces and concentrating loads and strains at the tension side of the bending load.

4.5. Micro hardness of Cu –Al_2O_3 composites at different sintering temperatures

The measured values on the fabricated copper alumina composites by varying the reinforcement percentage of alumina (5%, 10 and 20%) and conducting hardness tests at different sintering temperatures (750°C, 800°C and 850°C) are shown in the Figure 3 (d). The microhardness obtained for the fabricated Cu–Al_2O_3 composites depends upon particle dispersion, interfacial bonding and grain size are influenced by both the reinforcement particle and sintering temperature. From the experimental results, the hardness values were consistently higher when the alumina particle at 15% across the sintering temperatures (750°C, 800°C and 850°C). This trend proposes an effect of alumina concentration on the mechanical properties specifically hardness of the composite material[27]. The specific outcome that the 15% of alumina composition shows the higher hardness values at all tested sintering temperatures suggests an optimal balance between alumina content and sintering conditions. This composition is likely characterized by means of uniform dispersion of alumina particles and effective bonding in the Cu –Al_2O_3composites.

At 750°C, the hardness increases gradually with alumina content, reaching a peak at 15% alumina (87.46 HV) by reason of an effective dispersion and bonding and a slight drop at 20% alumina (84.24 HV) proposes an increasing of porosity. At 800°C, the hardness is maximized at 15% alumina (117.81 HV) shows an optimal densification and uniform ceramic distribution. However, at 850°C, the values of hardness decrease across all the compositions at 20% alumina (70.48 HV) because of the excessive grain growth, porosity, and weak bonding at interface region. From the obtained results, it states an moderate alumina content and optimized sintering enhance hardness and excessive ceramic addition or high sintering temperatures may cause structural defects that degrade mechanical properties[14].

At 15 vol.% alumina, hardness attained maximum value because of the well-dispersed alumina particles which act as a strong barrier to dislocation motion and maintaining a good bonding with the Cu–Al_2O_3composites. At 20 vol.%, particle clustering reduce effective load transfer, leading to lower hardness values. Sintering temperature also plays a major role. At 800 °C, improved densification and diffusion bonding enhance particle–matrix interaction, resulting in the highest hardness (117.81 HV). However, at 850 °C, excessive grain growth and interfacial voids, visible in SEM micrographs, reduce hardness despite better overall densification. Similar observations were found that optimum reinforcement dispersion and controlled sintering lead to improved hardness, while excessive ceramic content or high temperatures cause defects that lower mechanical properties[27].

5. Conclusion

1. The compression strength of the fabricated copper-alumina composites is significantly influenced by alumina content and sintering temperature, with optimal strength observed at moderate alumina content (10-15%) and controlled sintering conditions. The highest strength (777.24 MPa) is observed at 750°C with 15% alumina, while excessive alumina content (20%) leads to a decline due to porosity and weak interfacial bonding.
2. The tensile strength of copper-alumina composites increases with 15% alumina content, reaching the highest value (126.7 MPa at 800°C), indicating optimal reinforcement and densification. A decline at higher alumina content (20%) suggests agglomeration and reduced ductility, affecting mechanical integrity
3. The hardness of copper-alumina composites increases with higher alumina content, reaching a peak at 15% alumina sintered at 800°C (117.81 HV), indicating optimal particle dispersion and densification. A decline at 850°C, especially for 20% alumina (70.48 HV), suggests grain coarsening, porosity formation, and weak interfacial bonding.
4. The flexural strength of copper-alumina composites was highest at 5% alumina, with a peak value of 292.67 MPa at 850°C, enhancing the ductility and matrix continuity. As alumina content increases,

flexural strength decreases, especially at 15% alumina (132.12 MPa at 850°C), due to increased brittleness, weak interfacial bonding, and formation of porosity.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.