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Impact of Mechanical Ball Grinding Duration on Graphite-Copper Composite's Characteristics and Microstructure

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Abstract

In this study, copper and graphite powders were utilized as base materials to fabricate a graphite-copper composite using the powder metallurgy sintering process. Mechanical ball milling coupled with ultrasonic dispersion was applied to ensure uniform mixing and distribution of the powders. The impact of varying milling durations (2 to 48 hours) on the microstructure and mechanical properties of the composites was analyzed using Optical Microscopy, Scanning Electron Microscopy (SEM), and Vickers hardness testing. Results indicated that increasing the ball milling duration up to 18 hours enhanced particle distribution uniformity, increased relative density (85.1%), and improved hardness (58.6 HV). Further increase in milling time beyond 18 hours led to property degradation or stabilization, likely due to over-fragmentation and agglomeration of particles.

Keywords: *Metal Matrix Composite, Mechanical Properties, Mechanical Ball Grinding, Micro structures*

1. Introduction

The development of metal matrix composites (MMCs) with superior thermal, electrical, and mechanical properties has drawn significant attention in modern engineering applications. These composites are particularly valued in industries that demand materials with high performance under extreme conditions, such as aerospace, automotive, defense, and electronics. MMCs can be tailored to exhibit a unique combination of strength, wear resistance, conductivity, and thermal stability, making them ideal for components exposed to high stress and thermal cycling[1].

Among the various MMC systems, graphite-copper (Gr-Cu) composites stand out due to their excellent blend of complementary properties. Graphite is known for its self-lubricating characteristics, low density, and thermal resistance, while copper is prized for its exceptional thermal and electrical conductivities. When combined, these materials produce a composite that is highly suited for a variety of applications including electrical contacts, brushes, current-carrying components, heat sinks, and sliding elements like bearings. The synergistic effect of combining graphite and copper results in materials that can efficiently dissipate heat, reduce friction, and conduct electricity while maintaining mechanical strength and dimensional stability[2].

The fabrication of graphite-copper composites through powder metallurgy is a preferred method due to its capability to produce near-net shape components with precise control over composition and microstructure. Within this process, mechanical ball milling plays a critical role. It is a high-energy technique used to blend powders and promote fine particle dispersion. The repeated collision of balls within the mill facilitates the fracture and cold welding of powder particles, leading to refined grain sizes and enhanced material homogeneity. Additionally, it helps to break down agglomerates and increases the surface area for sintering, improving the densification and interfacial bonding of the composite during the sintering phase[3].

One of the most influential parameters in the ball milling process is the duration of milling. Milling time determines the extent of particle refinement, the uniformity of the mixture, and the interaction between constituent phases. Short milling times may lead to poor mixing and insufficient bonding, while excessive durations may cause particle agglomeration, over-fragmentation, or even contamination from the milling media. Hence, optimizing the milling duration is crucial for achieving the desired balance between mechanical integrity and functional properties in the final composite[4].

This study systematically investigates the impact of varying mechanical ball milling durations on the characteristics and microstructure of graphite-copper composites. By employing a range of milling times from 2 hours to 48 hours, and combining this with ultrasonic dispersion, the research aims to evaluate the changes in particle distribution, hardness, relative density, and microstructural uniformity. The resulting composites are analyzed using techniques such as Optical Microscopy, Scanning Electron Microscopy (SEM), and Vickers hardness testing to determine the relationship between processing parameters and material performance. Through this approach, the study not only sheds light on the optimal milling time for achieving enhanced properties but also provides deeper insight into the underlying mechanisms that govern the structural evolution of Cu-Gr composites during mechanical processing[5—7]].

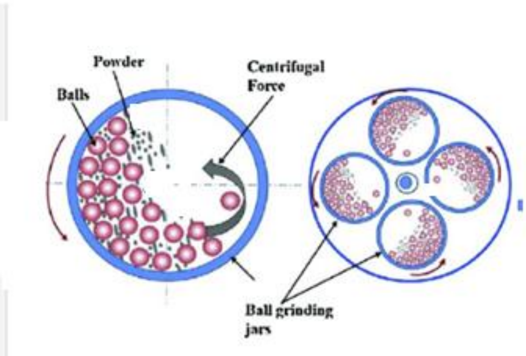
2. Materials and Methods

2.1 Materials

In this study, high-purity elemental powders were selected to fabricate graphite-copper composites using the powder metallurgy route. Copper powder with a purity greater than 99% and an average particle size of approximately 45 micrometers was used as the base metal matrix. The copper powder was chosen for its excellent thermal and electrical conductivity, as well as its good sinterability and compatibility with graphite. Graphite powder, serving as the reinforcement phase, had a purity exceeding 98% and an average particle size of around 20 micrometers. Graphite was selected due to its unique properties such as low density, high thermal stability, and inherent lubricity, which contribute to enhanced tribological performance in the resulting composite. Both powders were free from contaminants and were stored in sealed containers to avoid moisture absorption and oxidation prior to processing. The selection of these specific powders, with high purity and controlled particle sizes, was crucial in achieving uniform mixing during ball milling and ensuring the development of a homogenous and high-performance composite structure[8-11].

2.2 Ball Milling Procedure

The copper and graphite powders were accurately weighed in a fixed ratio of 90:10 by weight, ensuring consistency in composition across all samples. These powder mixtures were then subjected to mechanical ball milling for varying durations—specifically 2, 6, 12, 18, 24, 36, and 48 hours—to study the influence of milling time on composite characteristics. A planetary ball mill was employed for this purpose, which is known for its high energy impact and effective particle size reduction. The ball-to-powder weight ratio was maintained at 10:1, a standard proportion to ensure efficient milling without causing excessive wear or contamination. Ethanol was used as the milling medium to prevent oxidation and to aid in the uniform dispersion of graphite particles within the copper matrix. Additionally, prior to the compaction process, the milled powders underwent ultrasonic dispersion for 30 minutes. This step was crucial in breaking down any agglomerates that may have formed during milling and ensuring an even distribution of particles, thereby enhancing the homogeneity of the final composite structure[11-12].



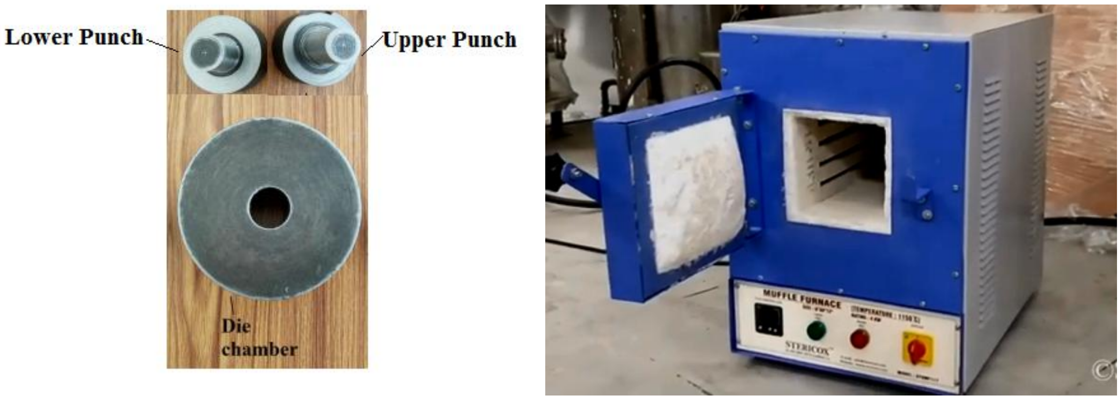
(a)

(b)

Figure1 (a)High-energy ball milling process (b) Ball mill

2.3 Compaction and Sintering

After milling and ultrasonic dispersion, the blended copper-graphite powders were dried and then compacted in compaction die using a uniaxial hydraulic press. The compaction process was carried out at a pressure of 600 MPa to ensure adequate green density and structural integrity of the compacted pellets. This high-pressure compaction helped in reducing porosity and achieving a uniform packing of particles, which is essential for effective sintering. Once compacted, the green samples were placed in a controlled atmosphere furnace to undergo the sintering process. Sintering was performed in muffle furnace at 850°C for a duration of 2 hours in an inert gas environment to prevent oxidation of the copper matrix. The elevated temperature facilitated solid-state diffusion, allowing the powder particles to bond together and densify. This stage was crucial for enhancing the mechanical strength, improving interfacial adhesion between copper and graphite, and reducing residual porosity. The controlled sintering conditions ensured that the final composite structure exhibited a stable microstructure with improved physical and mechanical properties suitable for functional applications[11-15].



(a) (b)

Figure2 (a) Compaction die (b) Muffle Furnace

3. Results and Discussion

3.1 Microstructural Analysis

The microstructure of the sintered graphite-copper composites changed significantly with varying milling durations. Up to 18 hours, the composite exhibited improved particle refinement, distribution, and interfacial bonding. Optical and SEM analysis showed a gradual transition from segregated to homogeneously mixed phases as milling time increased, with 18 hours yielding the most uniform and well-dispersed microstructure. This optimal duration allowed for sufficient cold welding and fracture of particles, enhancing packing density and sintering efficiency.

Beyond 18 hours, however, signs of degradation became evident. Extended milling led to excessive particle fragmentation and the re-agglomeration of fine graphite, resulting in microstructural inhomogeneities and the formation of localized pores. These effects hindered proper compaction and bonding, ultimately reducing the mechanical integrity of the composite. Thus, while moderate milling times enhance microstructural characteristics, excessive durations can have adverse effects on composite quality.

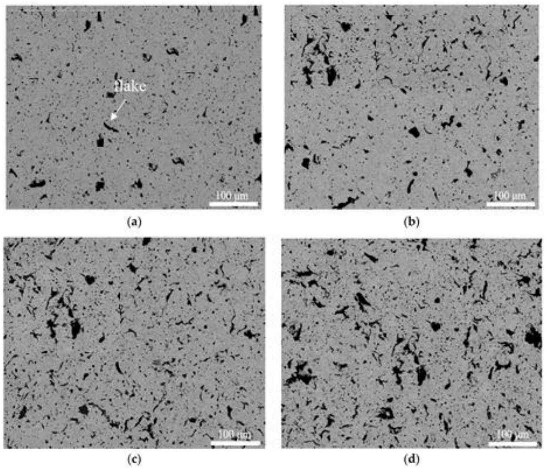


Figure 1-Microstructure

The copper-graphite metal matrix composite exhibits significant changes in its microstructural properties with varying milling times. At 2 hours of milling, the particle distribution is poor with minimal fragmentation and no agglomeration. As milling time increases to 6 hours, the distribution improves to a moderate level with mild fragmentation, still avoiding agglomeration. A notable enhancement occurs at 12 hours, where the particle distribution becomes good, fragmentation is moderate, and agglomeration is minimal. At 18 hours, optimal conditions are observed with excellent particle distribution, controlled fragmentation, and no agglomeration. However, extending milling beyond this point begins to deteriorate the quality. By 24 hours, slight degradation in distribution occurs, with high fragmentation and the onset of agglomeration. At 36 and 48 hours, the composite shows clear signs of degradation, with severe fragmentation and increasingly notable to high levels of agglomeration, indicating a threshold beyond which extended milling negatively affects the material's structural integrity.

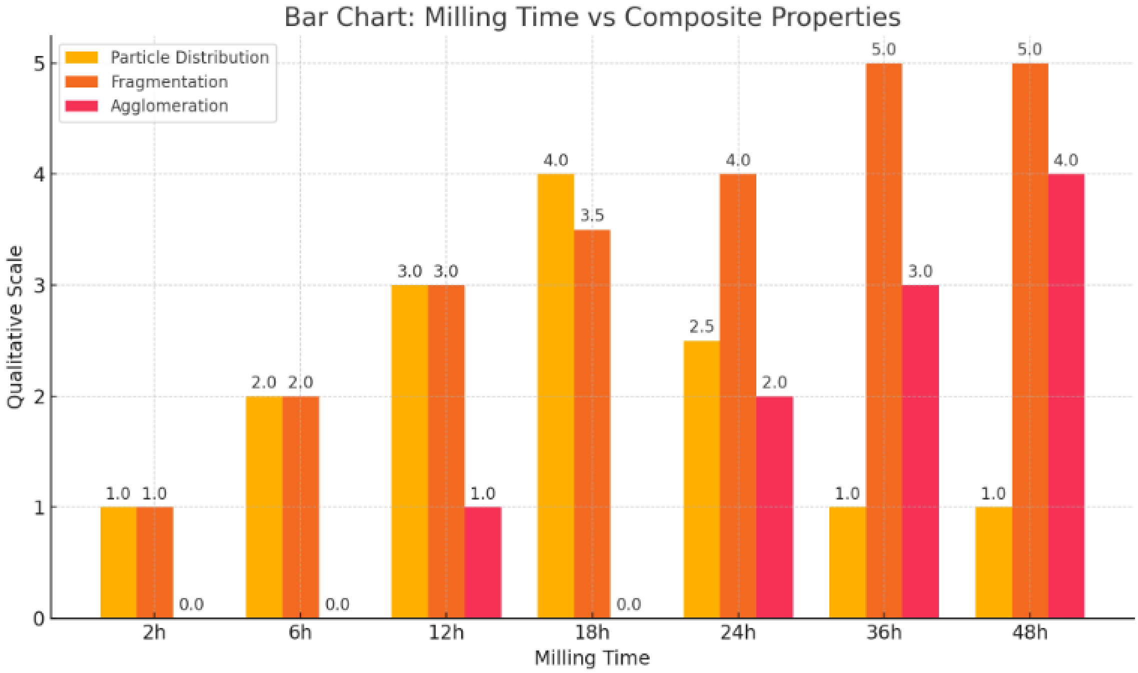


Figure 2: Variation in particle distribution, fragmentation, and agglomeration with milling time

3.2 Hardness and Density

The graph in Figure 3 illustrates the variation in Vickers hardness of the graphite-copper composites as a function of milling time. As shown, the hardness increases steadily with longer milling durations, reaching a peak value of 58.6 HV at 18 hours. This improvement is attributed to enhanced dispersion of graphite particles within the copper matrix and improved interfacial bonding due to prolonged mechanical agitation. The increased contact between particles leads to better densification during sintering, which directly influences the hardness. However, beyond 18 hours, a noticeable decline in hardness is observed. This reduction can be attributed to excessive fragmentation of particles and potential agglomeration during extended milling, which negatively affects uniformity and packing efficiency, ultimately reducing the composite's hardness.

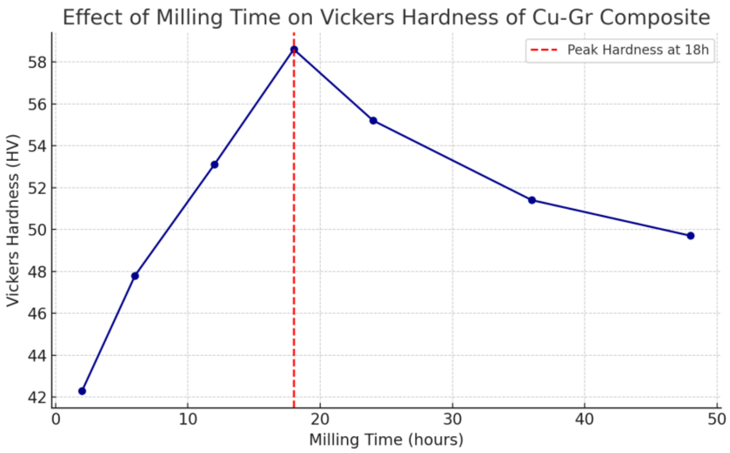


Figure 3. Vickers Hardness vs Milling Time

Figure4 presents the relationship between relative density and milling time for the graphite-copper composites. Similar to the trend observed in hardness, the relative density increases with longer milling durations and reaches a maximum value of 85.1% at 18 hours. This peak signifies the optimal balance between particle size reduction and uniform mixing, which promotes effective packing during compaction and enhanced bonding during sintering. Beyond 18 hours, a slight but consistent decline in relative density is noted. This drop may result from the formation of fine particulates and agglomerates due to over-milling, which hinders efficient particle rearrangement and creates microvoids during sintering. These observations confirm that 18 hours is the optimal milling time for maximizing both hardness and density in the fabricated composites.

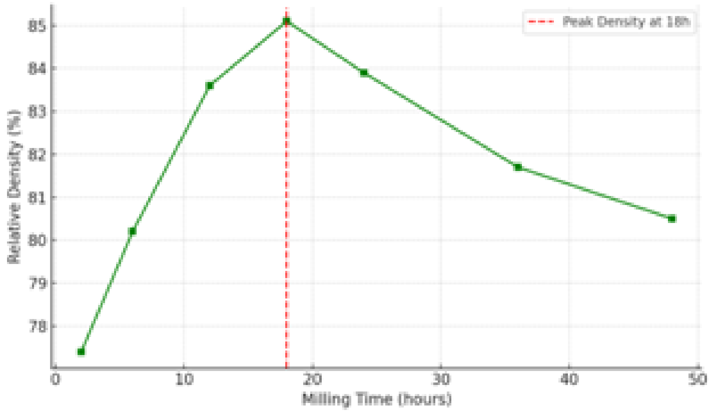


Figure 4. Relative Density vs Milling Time

Table 1. Hardness and Density Values

Milling Time (h)	Hardness (HV)	Relative Density (%)
2	32.1	71.5
6	41.3	76.0
12	49.6	81.2
18	58.6	85.1
24	54.3	82.7
36	47.8	78.0
48	45.1	76.5

4. Conclusion

This study highlights the critical role of ball milling duration in tailoring the microstructure and properties of graphite-copper composites. An optimal duration of 18 hours provided the best balance between particle refinement, bonding, and material densification. Prolonged milling beyond this point led to microstructural degradation due to over-fragmentation and agglomeration. Therefore, for powder metallurgy-based Cu-Gr composites, precise control of milling parameters is essential to achieve desired performance.

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