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Araştırma Makalesi
Research Article

# Microstructural and mechanical characterization of MgO-reinforced Al-Cu metal matrix composites fabricated via powder metallurgy

## *Toz metalurji yöntemiyle üretilen MgO-ile takviyeli Al-Cu metal matriks kompozitlerinin mikroyapisal ve mekanik karakterizasyonu*

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**Abstract:** Metal matrix composites (MMCs) incorporating ceramic particulates exhibit enhanced mechanical properties, including increased tensile strength, wear resistance, and thermal stability, compared to their unreinforced counterparts. This research investigates how varying amounts of magnesium oxide (MgO) affect Al-Cu composites' microstructure, porosity, and hardness produced through powder metallurgy. MgO was added in weight percentages of 1%, 3%, and 5%, and the composites were assessed using several methods, such as Vickers microhardness testing, Archimedean density measurement, and scanning electron microscopy for microstructural analysis. The findings indicate that incorporating MgO leads to a slight increase in composite density, with the highest hardness measured at 1% MgO. This increase in hardness is associated with the presence of rigid ceramic reinforcements and intermetallic compounds that resist plastic deformation. Additionally, MgO particles promote grain refinement, likely due to their nucleating effect, which further enhances mechanical properties. This research provides valuable insights into the role of MgO as a reinforcement in Al-Cu composites, underscoring its potential applications in industries that demand materials with high strength and low density.

**Keywords:** Metal Matrix Composites, Magnesium Oxide, Aluminum-Copper, Powder Metallurgy, Vickers Hardness

**Özet:** Seramik parçacıkları ile takviye edilmiş metal matriks kompozitleri (MMCs), takviye edilmemiş matrislere kıyasla artırılmış dayanım, aşınma direnci ve termal stabilite gibi üstün özellikler sunar. Bu çalışma, toz metalurjisi ile üretilen Al-Cu kompozitlerinin mikroyapısı, yoğunluğu ve sertliği üzerindeki değişen magnezyum oksit (MgO) içeriğinin etkilerini incelemektedir. MgO, %1, %3 ve %5 ağırlık oranlarında eklenmiş ve kompozitler, Vickers mikrosertlik testi, Arşimet Prensibi ile yoğunluk ölçümü ve mikroyapısal analizler gibi çeşitli yöntemlerle karakterize edilmiştir. Sonuçlar, MgO eklenmesinin kompozit yoğunluğunda hafif bir artışa yol açtığını, en yüksek sertlik değerlerinin ise %1 MgO içeren kompozitte gözlendiğini göstermektedir. MgO parçacıklarının varlığı, sert seramik parçacıkları ve intermetalik fazların oluşumu yoluyla plastik deformasyonu sınırlayarak sertliği artırmaktadır. Ayrıca, MgO'nun eklenmesi, muhtemelen çekirdeklenme ajanı olarak rol oynayarak tane yapısını iyileştirmiş ve bu da mekanik özelliklerin daha da gelişmesine katkı sağlamıştır. Bu çalışma, MgO'nun Al-Cu kompozitlerinin özelliklerini iyileştirmedeki rolüne dair değerli bilgiler sunmakta ve yüksek dayanıklı, hafif malzemelere ihtiyaç duyan sanayilerdeki potansiyel uygulamaları vurgulamaktadır.

**Anahtar Kelimeler:** Metal Matris Kompozitleri, Magnezyum Oksit, Alüminyum- Bakır, Toz Metalurjisi, Vickers Sertliği

## 1. Introduction

Composites with metallic matrices and ceramic reinforcements generally exhibit superior service temperature capabilities, increased strength, enhanced creep and wear resistance, and greater thermal stability compared to unreinforced matrices (Foltz and Blackmon, 1998)1998. While particulate-reinforced composites may not offer the same level of performance enhancement as continuous fiber-reinforced composites, they provide isotropic properties and a more favorable property-to-cost ratio.

For discontinuous metal matrix composites (MMCs), achieving a uniform dispersion of the reinforcing phase is crucial (Huang et al., 2015). Defects such as reinforcement particle clustering can negatively affect mechanical properties. Particle agglomeration is influenced by differences in size, density, shape, flow characteristics, and electrical charge accumulation (Angelo et al., 2022). Compared to casting methods, Powder Metallurgy (PM) enables better reinforcement distribution across a wide range of reinforcement contents. In PM, blending the matrix and reinforcement powders is a critical step to en-

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sure even dispersion in the final composite. Post-processing techniques like powder extrusion further enhance reinforcement distribution. In the study (Ateş and Coşman, 2025) , carbon black (CB), derived from the pyrolysis of waste tires and SiC reinforced Al6061 alloy composite, was produced by PM. The research aimed to evaluate both the feasibility of using CB as a reinforcement and its compatibility with SiC. A notable increase in hardness was observed with higher reinforcement content.

Aluminum is one of the most widely used non-ferrous materials. Its low density and lightweight nature make aluminum metal matrix composites (Al-MMCs) highly suitable for applications in the automotive (Wu and Zhang, 2024), aerospace (Oyewo et al., 2024), sports gear (Chen, 2024), electronic packaging (Godbole et al., 2024), and the renewable energy industry (Kar et al., 2024). These composites are valued for their excellent strength-to-weight ratio, high thermal and electrical conductivity, availability, and cost-effectiveness. Adopting lightweight materials in vehicles and spacecraft contributes to reduced fuel consumption, helping to mitigate energy crises and lower pollution levels. Although aluminum matrix composites dominate the field, many emerging applications require matrices made of superalloys, titanium, copper, magnesium, or iron (Schwartz, 1984). Hybrid composites with Al6061 matrix, eggshell powder, SiC and Al2O3 reinforcement were produced. It was found that the hardness, ultimate tensile stress increased and the elongation decreased with the increase of eggshell powder by weight in the composite (Tok and Ateş, 2023) . Similar studies were conducted by Kocaman et al. (Kocaman and Ateş, 2023), Hardness tests revealed that coal slag powder can enhance the composite's hardness almost as effectively as SiC and Al2O3. Wang et al. (Wang et al., 2011) studied the effects of particle size and distribution on the mechanical properties of SiC reinforced Al–Cu alloy composites. It was shown that homogenous distribution of the SiC particles resulted in higher yield strength, ultimate tensile strength and elongation. Yu et al. (Yu et al., 2003) reported Al2O3 reinforced Al-Cu matrix composites. The Vickers hardness value of the oil-quenched sample has an average of 123, which is 50% higher than that of the furnace-cooled sample. Furthermore, A study by (kundu and Mondal, 2024) introduced a novel technique, Multistage Ball Milling (MSBM), for producing powder metallurgy-based Al-MMCs containing 5 wt% copper (Cu) and 0.5–1.5 vol% multi-walled carbon nanotubes (MWCNTs). MSBM incorporates two mixing stages at varying rotational speeds, combining the benefits of flake powder metallurgy while minimizing structural damage and CNT agglomeration. The mechanical, electrical, thermal, and microstructural properties of MSBM-processed composites were compared to those produced using a fixed-speed single-stage ball milling (SSBM) method. The Al-Cu-CNT composites produced using MSBM demonstrated superior electrical conductivity (+15.03%), thermal conductivity (+5.88%), and hardness (+9.68%) compared to SSBM-processed composites. Furthermore, the Al-Cu-CNT composites exhibited remarkable electrical and thermal conductivity improvements over pure sintered aluminum (+138.45% and +9.39%, respectively). Hassan et al (Hassan et al., 2008) investigated the mechanical properties of various powder metallurgy (P/M) aluminum alloys containing 0–5 wt% copper (in 1 wt% increments) and their corresponding metal matrix composites reinforced with 5 or 10 vol% silicon carbide (SiC) particles. The addition of Cu and/or SiC significantly improved hardness values.

However, certain applications require even greater thermal stability, hardness, strength, and wear resistance. To address these challenges, further improvements can be achieved by incorporating carbide- and oxide-forming materials such as $B_4C$ (Jain et al., 2016), ZrB2 (Kaku et al., 2018), TiC (Aktar Zahid Sohag et al., 2020), SiC (Kaya and Birgin, 2024), WC (Rodríguez-Cabriales et al., 2020)`, ZnO (Sadooghi and Hashemi, 2019), ZrO2 (Moustafa et al., 2024). Yu et al. (Yu et al., 2003) studied an Al-Cu alloy matrix composite reinforced with $Al_2O_3$ particles and found that the hardness of oil-quenched samples was approximately 50% higher than that of furnace-cooled coarse-grained samples. Another study was conducted by Erdemir et al. (Erdemir et al., 2015). In this study, functionally graded Al2024-SiC materials, with varying SiC content and graded layer configurations, were successfully produced using the powder metallurgy method combined with hot pressing. The study extensively examined how increasing SiC content and layer count affected microstructure and mechanical properties. The findings revealed that higher microhardness and intermetallic compound formation played a crucial role in improving composite performance. Additionally, another study explored the impact of TiC ratio and particle sizes on the microstructure, density, hardness, of Al/Cu matrix composites (Kaftelen et al., 2011). Two fabrication methods, PM and casting, were compared. In the PM process, an Al-Cu matrix alloy was reinforced with 10 wt% TiC powders of two distinct average sizes (13 μm and 93 μm) via mechanical milling. The composite reinforced with smaller TiC particles (0.6–3.5 μm) exhibited superior hardness compared to the one with larger TiC particles (0.8–5.6 μm).

This study investigates the fabrication and characterization of MgO reinforced Al-15Cu MMCs produced through PM. Although ceramic reinforcements such as SiC, $Al_2O_3$, and TiC have been widely studied in aluminum-based matrices, the use of MgO, particularly in Al-Cu systems, has received limited attention. This work addresses that gap by systematically examining the effects of varying MgO content on the microstructure, density, and hardness of the composites. It provides a more integrated analysis compared to previous studies, which often consider these properties separately. In addition, a simple and cost-effective ring milling process is introduced to refine coarse MgO particles and improve their dispersion within the matrix. By combining a relatively unexplored reinforcement material with a technically significant Al-Cu alloy system and a well-controlled PM approach, which includes magnetic stirring, cold pressing, and T6 heat treatment, this study offers a unique and valuable contribution to the development of high-performance and lightweight MMCs.

## 2. Materials and Methods

For the fabrication of MgO-reinforced Al-15Cu composites, aluminum (99.9% purity, ~44 µm), copper (99.9% purity, ~44 µm), and MgO (90% purity, 2-4 mm) were sourced from Nanografi and ZAG Chemistry. The coarse MgO particles (2-4 mm) were ground into finer particles using ring milling. After using siever, the remaining weight of the MgO powder on the sieve having 45 µm size was used in the experiment. A total of 15 g of the sample was weighed, and MgO was added at weight fractions of 1%, 3%, and 5%. These ratios are chosen based on previous study (Al-Twejri et al., 2023). The powders were then combined in a beaker and thoroughly mixed using a magnetic stirrer set at 700 rpm for 20 minutes. To ensure uniform distribution, the mixture was further stirred manually for an additional 5 minutes. Once homogeneity was achieved, the powder samples were cold-pressed into bulk samples using a steel die at 200 MPa. The press die and bulk samples are given in ▶**Figure 1**. To achieve maximum mechanical properties and microstructure distributions (Zhao et al., 2007), these bulk samples then underwent T6 heat treatment, which involved sintering at 500°C for two hours, followed by rapid quenching in water at room temperature. After quenching, to precipitate fine, hard particles, the samples were artificially aged at 180°C for 20 hours using an ETUV furnace before being allowed to cool in air (Çankaya, 2022). The entire process is illustrated in ▶**Figure 2**.

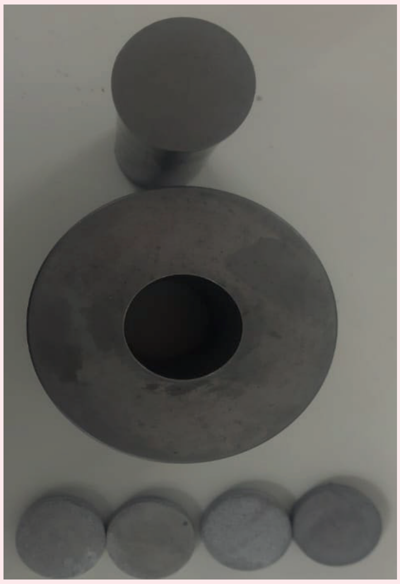

**Figure 1.** The press die having 3 cm diameter and bulk samples of Al-Cu composite

## 3. Results and Discussions

To produce MgO-filled Mg composites, MgO was added in weight fractions of 1%, 3%, and 5%. The densities of these composites were determined using the Archimedean principle, with distilled water as the immersion medium. ▶**Figure 3** illustrates the measured densities for each corresponding MgO weight percentage. The inclusion of MgO led to a slight increase in density. Interestingly, MgO has a higher density (3.58 g/cm$^3$) compared to pure Mg (2.7 g/cm$^3$), which explains the observed rise in density with increasing MgO content (Sadoun et al., 2020). Previous studies have reported similar findings, attributing this trend to the presence of reinforcing par-

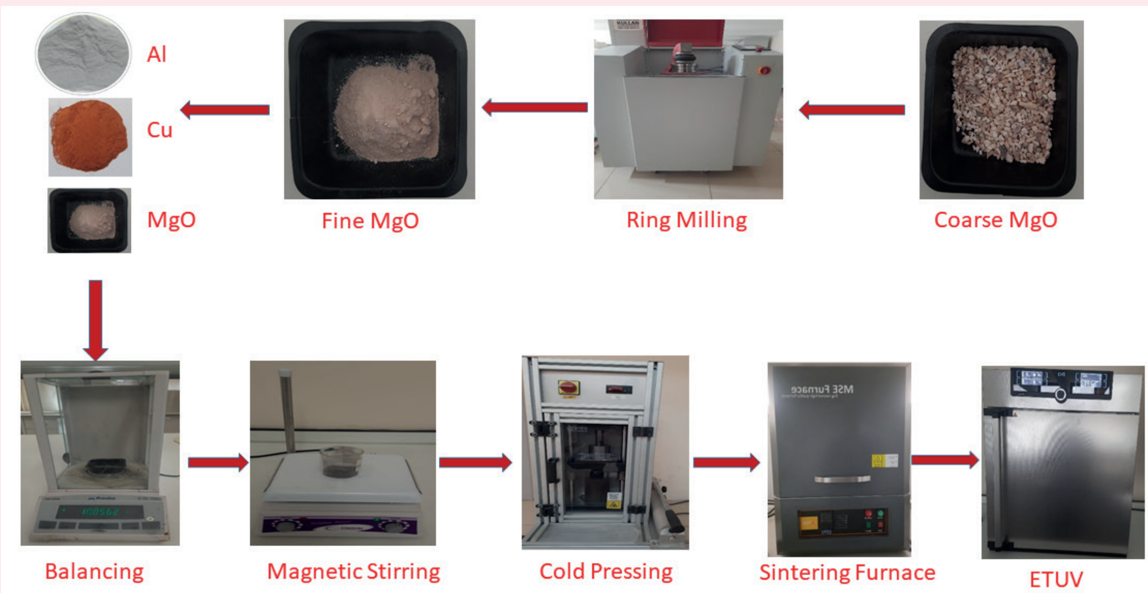


**Figure 2.** The procedure for producing MgO reinforced Al-Cu composites

ticles (Aslan, 2023a, 2023b, 2024; M. Aslan et al., 2023; Mikail Aslan et al., 2023). However, in the composite containing 5% MgO, a decrease in density was observed compared to those with lower MgO content. This reduction is likely due to the agglomeration of MgO nanoparticles, which diminishes the overall reinforcement efficiency and limits the practical use of higher MgO concentrations. This trend also aligns with the observed hardness values. Conversely, adding particles may contribute to a decrease in the measured density values. For example; in the study (Guo et al., 2020), incorporating $TiB_2$ particles into the copper matrix reduces its overall density. In Cu-5.8 vol.% $TiB_2$ composites, the density further decreases as the $TiB_2$ particle size increases. This trend is likely due to the poor wettability between the copper matrix and $TiB_2$ particles. Interestingly, during sintering, the copper matrix does not chemically react with the $TiB_2$ particles. Instead, exposure to high temperatures leads to recrystallization and grain growth in the metal powder material.

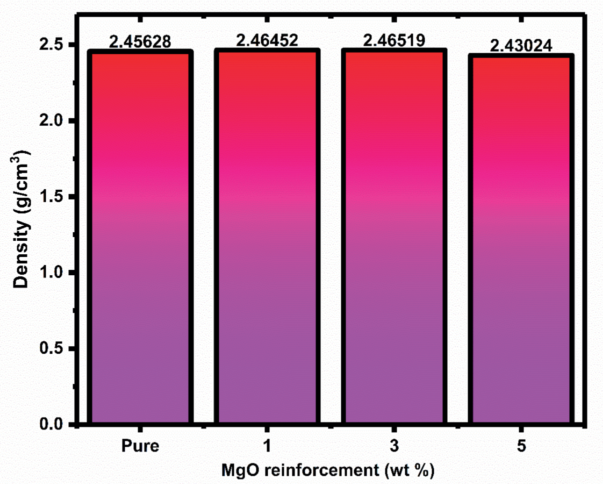


**Figure 3.** Density Analysis of Al-Cu Composites Reinforced with Varying MgO Percentages

The preparation of samples for Vickers hardness testing involved both sanding and polishing. Sanding was performed using sandpapers with mesh sizes of 450, 600, and 1000, followed by polishing with diamond suspensions of 6 μm and 3 μm to achieve a smooth surface finish. Hardness measurements were carried out using an AOB Vickers Microhardness tester, applying a 0.1 kgf load with a dwell time of 10 seconds. For each sample, ten measurements were taken, and the average value was calculated. As shown in ▶**Figure 4**, the highest hardness value was observed in the composite containing 1% MgO by weight. This improvement is attributed to the presence of MgO, which enhances hardness by restricting plastic deformation in the base alloy through the addition of hard ceramic particles, ferrous compounds, and intermetallic phases. Additionally, a reduction in porosity due to the formation of spinel aggregates further contributes to the improved microhardness properties of the composites. In the study related to nano MgO reinforced Al composites (Yar et al., 2009) , In spite of generally increasing trend of hardness vs. content of MgO, composites with 5 vol% content of MgO represent lower hardness than samples with 2.5 vol% MgO. This may be arisen from the presence of more porosity in composites with the higher content of MgO. However, in another study conducted by Beder et al. (Beder et al., 2024) the highest hardness value was obtained for the 5 wt% Al2O3 reinforcement samples for Al-Cu-Mg composites

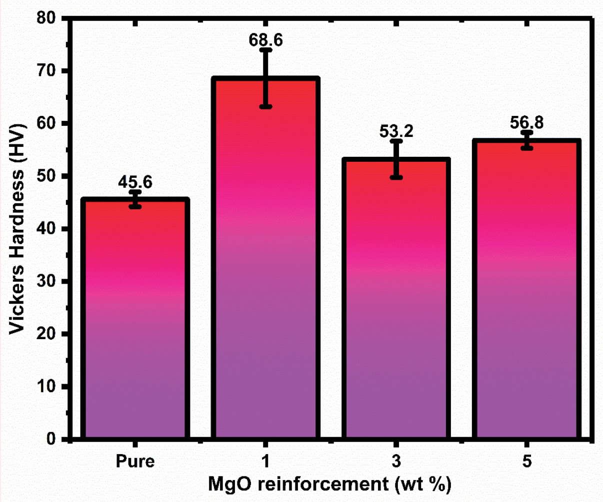


**Figure 4.** Hardness Analysis of Al-Cu Composites Reinforced with Varying MgO Percentages

The specimens were etched using the dipping method, with Keller's reagent serving as the etching agent. This reagent, commonly used for aluminum alloys and composites, consisted of 95 mL of water, 2.5 mL of $HNO_3$, 1.5 mL of HCl, and 1.0 mL of HF. The optical microscope images were obtained by using Nikon Eclipse model, as shown in ▶**Figure 5**. Unlike the pure Al-Cu composites, clear grain boundaries were observed in all other structures, providing significant evidence that the incorporation of MgO influences the grain size of Al-Cu composites. Notably, the sample containing 1% MgO exhibited relatively smaller grain sizes, which contributed to increased hardness values. This observation aligns well with the hardness test results. The refinement of the grain structure can be attributed to the presence of MgO, which likely acts as a nucleating agent, restricting grain growth during processing. This finer grain structure enhances the mechanical properties, including hardness, as smaller grains hinder dislocation movement, leading to greater resistance to deformation. Additionally, the improved dispersion of MgO particles within the matrix may further strengthen the composite, reinforcing the relationship between microstructural features and hardness. Some grain boundaries are very clear in the structures of the samples. MgO particle clusters can be seen in the sample having 1% MgO reinforcement.

## 4. Conclusion

This study shows that adding MgO to Al-Cu composites through powder metallurgy significantly improves their

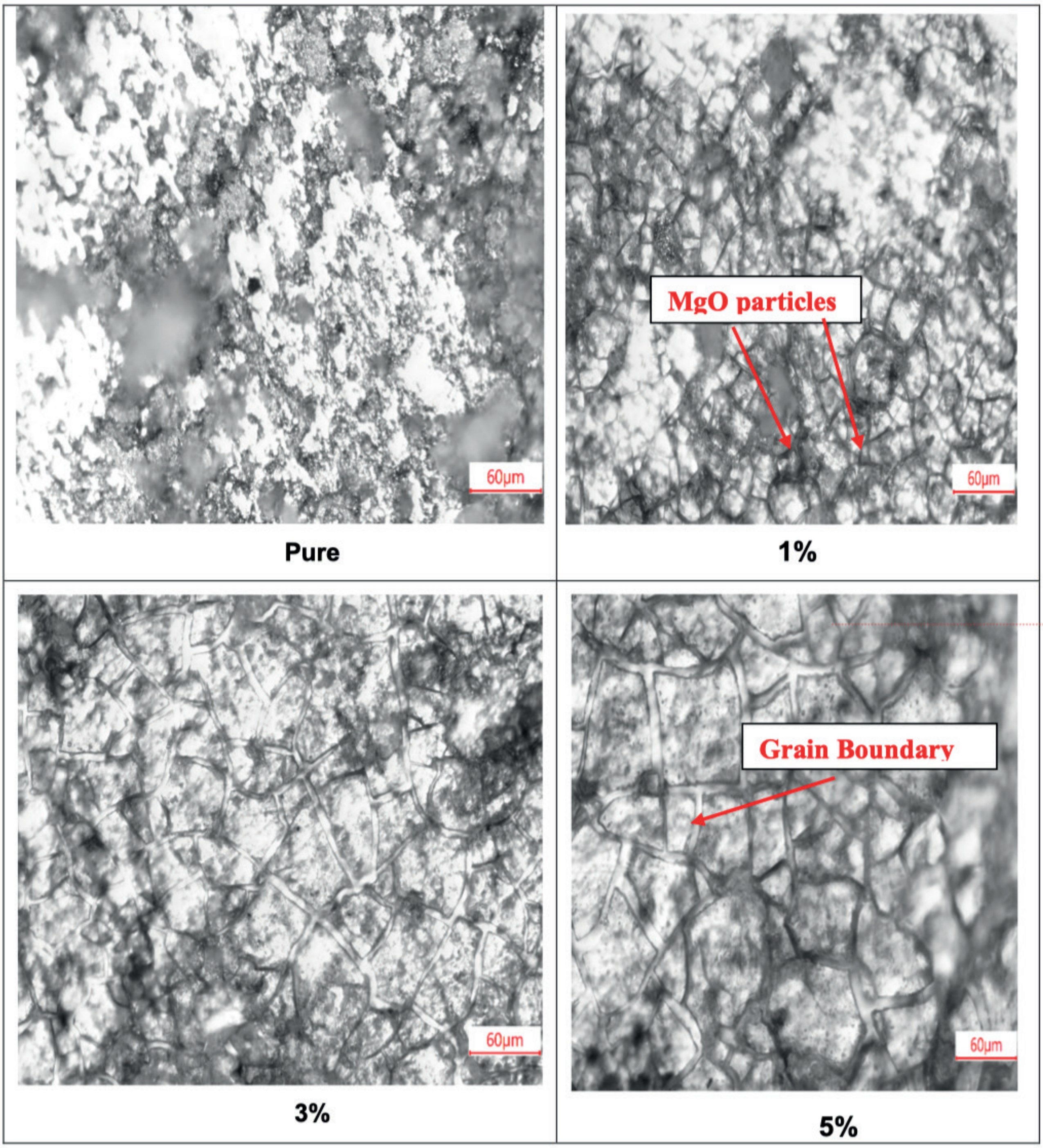


**Figure 5.** The microstructures of Al-Cu Composites Reinforced with Varying MgO Percentages

microstructural and mechanical properties. MgO was incorporated in different weight fractions of 1%, 3%, and 5%, which influenced both the density and microhardness of the composites. While there was a slight increase in density with MgO addition, an unexpected decrease in density occurred at the highest MgO level, likely due to particle agglomeration. On the other hand, the microhardness of the composites improved notably, with the 1% MgO composition achieving the highest hardness values (68.6 HV) while lowest hardness was seen at the pure form of the sample (45.6 HV). This enhancement in hardness can be linked to the strengthening effect of MgO, which minimizes plastic deformation and encourages the formation of spinel aggregates, thereby boosting the overall microhardness.

Microstructural analysis indicated that MgO affected grain size, with the 1% MgO composite showing finer grains. This refinement is probably because MgO acts as a nucleating agent, limiting grain growth during processing. The smaller grain structure led to increased hardness and better resistance to deformation. Furthermore, the even distribution of MgO particles within the Al-Cu matrix further improved the composite's overall performance, underscoring the significance of uniform reinforcement distribution in achieving superior material properties.

In summary, this study indicates that MgO-reinforced Al-Cu composites have significant potential for applications that require enhanced hardness and mechanical strength. The results also highlight the essential role of reinforcement distribution and particle size in optimizing the performance of metal matrix composites.

## Research Ethics

Not applicable.

## Author Contributions

Mikail Aslan was involved in the conceptualization, supervision, experimental design, carrying out measurements and writing original draft.

## Competing Interests

The authors states no conflict of interest.

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## Data Availability

Not applicable.

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