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**INVESTIGATION OF COPPER-ALUMINUM OXIDE METAL MATRIX COMPOSITES: EFFECT OF PARTICLE SIZE AND VOLUME FRACTION ON MECHANICAL PROPERTIES**

Tiba jamal ahmed

Ministry of Finance / Administrative and  
Financial Department Material Engineering  
xmam23672@gmail.com

**Abstract**

This research study the synthesis and characterization of copper-aluminum oxide (Cu-Al<sub>2</sub>O) metal matrix composites made through powder metallurgy. The aim of research is to study two variables: (1) Al<sub>2</sub>O<sub>3</sub> particle size (nano sized = < 50 nm; micro sized = 5-10 μm); and (2) volume fractions (2.5%, 5%, 7.5%, 10%), and on augmentation of mechanical properties. Bulk copper powders (>99.9% copper purity) and aluminum oxide particles, were mixed together, cold pressed at pressures at or above 100 MPa - 400 MPa, and sintered in hydrogen at 850°C. Microstructural characterization was completed by using scanning electron microscopy (SEM) and X-ray diffraction (XRD). Mechanical characterization including hardness (Vickers), compressive strength, and density was determined. Many of the results indicate that nano sized Al<sub>2</sub>O<sub>3</sub> produced superior mechanical properties than the micro sized Al<sub>2</sub>O<sub>3</sub>. Best composition was Cu-7.5 vol% nano sized Al<sub>2</sub>O<sub>3</sub> produced 145 HV hardness (178% increase) and 420 MPa in compressive strength and 89% conductivity compared to pure copper. Microstructural examination indicated that nano fortified samples had good particle distribution while the micro samples had particle clumping. The proposed mechanisms for the enhancement in mechanical properties were load transfer, grain refinement, and thermal mismatch strengthening. This paper demonstrates the possibilities of Cu-Al<sub>2</sub>O<sub>3</sub> designed composites as thermal and electrical management materials.

**Keywords:** Copper matrix composites, Aluminum oxide, Powder metallurgy, Mechanical properties, Particle size effect.

**Introduction**

Metal matrix composites (MMCs) have emerged as a new and exciting type of engineering material that enables the advantages and familiar properties of metals to be combined with the enhanced properties provided by reinforcements (1). Copper-based composites have received significant interest because of the great electrical and thermal conductivity, corrosion resistance, and ease of processing associated with copper (2). However, pure copper has limitations in mechanical strength, hardness, and wear resistance, which affects its ability to act in demanding environments such as electrical contacts, heat exchangers, and structural applications (3).

The addition of ceramic reinforcements to copper matrices can overcome the limitations above while still providing acceptable electrical and thermal properties (4). For example, aluminum oxide



(Al<sub>2</sub>O<sub>3</sub>) can be an attractive ceramic reinforcement because of its hardness (2000-3000 HV), good thermal stability, chemical inertness, and low cost (5). Other advantages are also present (6). In the Al<sub>2</sub>O<sub>3</sub>-copper system, there are advantages such as minimal interfacial reactions, good wetting under the right processing conditions, and the ability to control properties through processing parameters.(6)

As the interest in electronics, aerospace, and automotive industries has grown, both Cu-Al<sub>2</sub>O<sub>3</sub> composites have been developed for applications where high-strength, good conductivity, and thermal management are needed (7). Traditionally, copper-based alloys need to perform well mechanically, but must also achieve the right balance of mechanical properties and electrical conductivity. Some copper-based alloys exhibit a decrease in electrical conductivity when reasonable mechanical properties are achieved with alloying additions. Commercially available ceramic-reinforced copper composites can achieve better mechanical properties with little detrimental change to electrical performance when compared to pre-alloyed copper (8). Powder metallurgy (PM) has become the most applicable manufacturing process for Cu-Al<sub>2</sub>O<sub>3</sub> composites due to the enhanced uniformity of the reinforcement's distribution, easier compositional control, and simultaneous near-net-shape manufacture (9). The PM process avoids the complications present using liquid-state processes, such as the settling of the reinforcement, interfacial reactions at elevated temperatures, and the difficulty in producing homogeneous microstructures (10). The PM process allows the introduction of high volume fractions of reinforcement that are impractical to achieve using conventional casting methods.(11)

Mechanical properties of Cu-Al<sub>2</sub>O<sub>3</sub> composites are very much dependent on several microstructural parameters, with size and volume fraction of the reinforcement being cited as some of the most important (12). The size effect incorporates a number of mechanisms including the influence on the distribution of particles and interfacial area, as well as activating different strengthening mechanisms. Nano-sized reinforcements will generally allow for the best load transfer efficiency due to having a higher surface-to-volume ratio and ability to achieve more intimate contact with the matrix (13). However, the nano-sized particles present problems with agglomeration potential and processing.(14)

Volume fraction has a direct effect on the amount of properties enhancement, but it also influences other properties affectively, such as electrical conduit RFC, thermal expansion properties, and processing properties (15). Balancing mechanical property enhancement with the retention of the original properties of copper is an important aspect for practical applications (16). Several studies have reported different optimal volume fractions based on application requirements and/or processing conditions .(17)

Strengthening mechanisms for Cu-Al<sub>2</sub>O<sub>3</sub> composites occur via multiple processes acting in parallel. The first strengthening mechanism in action is load transfer strengthening, where processed loads transfer from the relatively soft copper matrix to the harder Al<sub>2</sub>O<sub>3</sub> particles. The effectiveness of the load transfer is dependent on the quality of interface bonding and the aspect ratio (18). As for grain refinement strengthening, it occurs because the Al<sub>2</sub>O<sub>3</sub> particles act as obstacles to grain growth, making matrix grain size finer, which for polycrystalline materials increases strength based on the Hall-Petch relationship (19). The third possible effect in strength arises from thermal mismatch strengthening, which arises from the difference in the thermal



expansion coefficients of copper and  $\text{Al}_2\text{O}_3$ . The thermal expansion difference produces internal stresses that lead to strengthening.(20)

The difference in the coefficient of thermal expansion (CTE) between copper ( $16.5 \times 10^{-6}/^\circ\text{C}$ ) and  $\text{Al}_2\text{O}_3$  ( $8.1 \times 10^{-6}/^\circ\text{C}$ ) leads to an inherent thermal stress during cooling from process temperatures (21). The thermal mismatch stresses may lead to possible dislocations generated in the copper, and their distribution could lead to work-hardening effects. However, too much thermal stress could lead to interface debonding or matrix cracking; this leads to a careful use of process parameters .(22)

The electrical conductivity of  $\text{Cu-Al}_2\text{O}_3$  composites is determined based on the volume fraction and distribution of the insulating  $\text{Al}_2\text{O}_3$ . Ceramic additions always adversely affect the electrical conductivity versus pure copper; however, an electrical conductivity reduction can be reduced by microstructural design (23). Understanding the trade-off between conductivity and strength is essential for applications where both properties will be critical.(24)

Regardless, the eventual properties of  $\text{Cu-Al}_2\text{O}_3$  composites areThe initial distribution of reinforcement particles and the characteristics of different powder mix methods are affected by compaction pressure that has an effect on green density that will influence sintering (25). The sintering temperature/atmosphere will have an effect on densification, grain growth, and reactions at the interface (26). Therefore, optimization of the respective variables must occur to reach the desired properties.(27)

As previously discussed, there are new methods developing in powder metallurgy to provide better control of microstructural characteristics of  $\text{Cu-Al}_2\text{O}_3$  composites. One highlighted method is using mechanical alloying to achieve an improved particle distribution and minimize agglomeration (28). Sintering methods have progressed to include spark plasma sintering (SPS) that have shown the ability to complete full densification at lower sintering temperatures while maintaining finely developed microstructures (29). Hot pressing and hot isostatic pressing are also viable sintering methods studied for improved mechanical properties and reduced porosity.(30)

A holistic approach is required for the analysis of  $\text{Cu-Al}_2\text{O}_3$  composites - such that full characterization of microstructural features and properties must continue employed. There are microscopy tools such as scanning electron microscopy (SEM) that can characterize reinforcement distribution, interfacial characteristics and failure mechanisms (31). There are x-ray diffraction (XRD) techniques that can be performed to characterized the present phases and importantly influence if the properties have changed at the interface from reaction of the sintering process with the new chemical composition. Mechanical testing should take into account more than one loading scenarios to ascertain the composite properties.(32)

Current research trends on  $\text{Cu-Al}_2\text{O}_3$  composites are looking primarily at a fundamental understanding of the process - properties - microstructure triad, so there is a significant interest in developing models that promote prediction for modelling the process and the method of  $\text{Cu-Al}_2\text{O}_3$  composites with known properties (33). The other discussion respective knowledge was the hybrid reinforcing system approach that was comprised of coupling  $\text{Al}_2\text{O}_3$  composite systems with other reinforcing phases for synergy.(34)

This study will prospectively provide an assessment of how  $\text{Al}_2\text{O}_3$  particle size and volume fraction will influence the mechanical properties of copper matrix composites produced utilizing powder metallurgy. The study seeks to prepare intelligently designed composite materials as a function of



systematic materials characterization, utilizing varieties of volume fractions with nano and micro-sized reinforcement composites to prepare recommendation structures for optimizing Cu-Al<sub>2</sub>O<sub>3</sub> composites for specified applications. A holistic characterization approach may initial provide a qualitative understanding of the strength mechanisms operational and through weight (degree) of influence of each operational mechanism on the composite properties of copper matrix composites.

### **Methodology**

#### **Raw Materials**

High-purity electrolytic copper powder (99.9% purity, <75 μm particle size) was obtained from Atlantic Equipment Engineers (USA) and used as the matrix material. Two types of aluminum oxide reinforcements were employed: nano-Al<sub>2</sub>O<sub>3</sub> powder (99.5% purity, <50 nm average particle size, specific surface area 40 m<sup>2</sup>/g) and micro-Al<sub>2</sub>O<sub>3</sub> powder (99.9% purity, 5-10 μm average particle size) both supplied by Sigma-Aldrich. The copper powder exhibited irregular morphology with good compressibility characteristics, while both Al<sub>2</sub>O<sub>3</sub> powders displayed angular particle geometry typical of mechanically processed ceramics.

#### **Powder Characterization**

Initial powder characterization was performed using scanning electron microscopy (SEM, JEOL JSM-7600F) to examine particle morphology and size distribution. X-ray diffraction analysis (XRD, Rigaku MiniFlex 600) was conducted to confirm phase purity and crystal structure. Particle size distribution was measured using laser diffraction analysis (Malvern Mastersizer 3000) for verification of supplier specifications.

#### **Composite Preparation**

Cu-Al<sub>2</sub>O<sub>3</sub> composites were prepared with Al<sub>2</sub>O<sub>3</sub> volume fractions of 2.5%, 5.0%, 7.5%, and 10.0% using both nano and micro-sized reinforcements. Powder mixing was performed in a planetary ball mill (Fritsch Pulverisette 6) using hardened steel balls with a ball-to-powder ratio of 5:1. Mixing was conducted for 4 hours at 200 rpm in an argon atmosphere to prevent oxidation. Stearic acid (0.5 wt%) was added as a process control agent to reduce cold welding and improve powder flow characteristics.

The powder mixing sequence involved initial blending of copper and Al<sub>2</sub>O<sub>3</sub> powders for 2 hours, followed by addition of stearic acid and continued mixing for an additional 2 hours. Periodic interruptions every 30 minutes prevented excessive temperature rise and ensured homogeneous mixing. After mixing, powders were dried in a vacuum oven at 80°C for 12 hours to remove residual moisture and organic solvents.

#### **Powder Compaction**

Mixed powders were compacted in a 25 mm diameter cylindrical steel die using a hydraulic press (Carver Model 3851). Compaction pressures of 100, 200, 300, and 400 MPa were applied to investigate the effect of green density on final properties. A controlled pressing sequence was employed with initial pressure application at 50 MPa for 30 seconds, followed by gradual increase to the target pressure over 2 minutes, and final pressure holding for 5 minutes to ensure uniform density distribution.



Die wall lubrication was achieved using zinc stearate to minimize friction effects and prevent galling. After compaction, green compacts were carefully ejected and their dimensions and weights recorded to calculate green density. Green strength was evaluated through handleability tests to ensure adequate integrity for sintering operations.

### **Sintering Process**

Sintering was performed in a tube furnace (Lindberg/Blue M HTF55342C) under controlled atmosphere conditions. The heating profile consisted of heating to 300°C at 5°C/min in argon atmosphere to remove organic additives, followed by atmosphere change to dry hydrogen and continued heating to 850°C at 3°C/min. The sintering temperature was maintained for 2 hours to ensure complete densification.

The hydrogen atmosphere served dual purposes of providing reducing conditions to prevent copper oxidation and facilitating the removal of any surface oxides present on the copper powder. Hydrogen flow rate was maintained at 2 L/min throughout the sintering cycle. Cooling was performed in hydrogen atmosphere at a controlled rate of 2°C/min to 400°C, followed by furnace cooling to room temperature in argon atmosphere.

### **Density Measurements**

Sintered density was measured using the Archimedes principle with distilled water as the immersion medium. Samples were first weighed in air, then submerged in water using a density determination kit attached to an analytical balance (Mettler Toledo XS205). Theoretical density calculations were based on the rule of mixtures considering the densities of copper (8.96 g/cm<sup>3</sup>) and Al<sub>2</sub>O<sub>3</sub> (3.98 g/cm<sup>3</sup>).

### **Microstructural Characterization**

Metallographic specimens were prepared following standard procedures involving mounting in conductive bakelite, grinding with SiC papers (220-1200 grit), and polishing with diamond paste (6, 3, 1 μm) followed by final polishing with 0.05 μm alumina suspension. Etching was performed using a solution of 5 g FeCl<sub>3</sub> + 10 ml HCl + 100 ml H<sub>2</sub>O for 10-15 seconds to reveal the copper matrix structure.

Scanning electron microscopy (SEM) analysis was conducted using a JEOL JSM-7600F field emission SEM operated at 15 kV accelerating voltage. Backscattered electron (BSE) imaging was employed to enhance contrast between the copper matrix and Al<sub>2</sub>O<sub>3</sub> reinforcement. Energy dispersive X-ray spectroscopy (EDS) mapping was performed to verify compositional distribution and identify any interfacial reaction products.

### **X-ray Diffraction Analysis**

Phase identification was performed using X-ray diffraction with Cu K $\alpha$  radiation ( $\lambda = 1.5406 \text{ \AA}$ ) at 40 kV and 30 mA. Scanning parameters included 2 $\theta$  range of 20-80°, step size of 0.02°, and counting time of 2 seconds per step. Peak identification was accomplished using ICDD PDF-4+ database. Rietveld refinement was employed to quantify phase fractions and determine lattice parameters.



### Mechanical Property Evaluation

Vickers hardness testing was performed using a Buehler Micromet 5114 microhardness tester with 1 kg load and 15-second dwell time. At least 10 measurements were taken per sample and averaged to ensure statistical reliability. Hardness measurements were distributed across the sample cross-section to evaluate property homogeneity.

Compressive strength testing was conducted using cylindrical specimens (10 mm diameter  $\times$  15 mm height) on an Instron 5982 universal testing machine at a strain rate of  $10^{-3} \text{ s}^{-1}$ . Strain was measured using a calibrated extensometer to ensure accurate determination of elastic modulus and yield strength. Ultimate compressive strength was determined as the maximum stress sustained before sample failure.

### Electrical Conductivity Measurements

Electrical conductivity was measured using the eddy current method with a Sigmascope SMP10 conductivity meter. Measurements were taken at multiple locations on polished sample surfaces and expressed as percentage of International Annealed Copper Standard (%IACS). Temperature compensation was applied to normalize all measurements to 20°C standard conditions.

### Results

The experimental results demonstrate significant effects of both  $\text{Al}_2\text{O}_3$  particle size and volume fraction on the properties of copper matrix composites. Tables 1-4 present comprehensive property data for all compositions investigated.

**Table 1: Density and Porosity Results**

Composition	Particle Size	Compaction Pressure (MPa)	Green Density ( $\text{g/cm}^3$ )	Sintered Density ( $\text{g/cm}^3$ )	Relative Density (%)	Porosity (%)
Pure Cu	-	200	7.52	8.89	99.2	0.8
Cu-2.5% $\text{Al}_2\text{O}_3$	Nano	200	7.41	8.76	98.8	1.2
Cu-5% $\text{Al}_2\text{O}_3$	Nano	200	7.28	8.61	98.5	1.5
Cu-7.5% $\text{Al}_2\text{O}_3$	Nano	200	7.15	8.45	98.1	1.9
Cu-10% $\text{Al}_2\text{O}_3$	Nano	200	7.02	8.28	97.6	2.4
Cu-2.5% $\text{Al}_2\text{O}_3$	Micro	200	7.45	8.72	98.4	1.6
Cu-5% $\text{Al}_2\text{O}_3$	Micro	200	7.32	8.55	97.9	2.1
Cu-7.5% $\text{Al}_2\text{O}_3$	Micro	200	7.19	8.37	97.3	2.7
Cu-10% $\text{Al}_2\text{O}_3$	Micro	200	7.06	8.19	96.7	3.3

**Table 2: Hardness Results at Different Compaction Pressures**

Composition	Particle Size	100 MPa (HV)	200 MPa (HV)	300 MPa (HV)	400 MPa (HV)
Pure Cu	-	52 $\pm$ 3	58 $\pm$ 2	61 $\pm$ 2	63 $\pm$ 2
Cu-2.5% $\text{Al}_2\text{O}_3$	Nano	74 $\pm$ 4	82 $\pm$ 3	86 $\pm$ 3	89 $\pm$ 3
Cu-5% $\text{Al}_2\text{O}_3$	Nano	95 $\pm$ 5	108 $\pm$ 4	115 $\pm$ 4	119 $\pm$ 4
Cu-7.5% $\text{Al}_2\text{O}_3$	Nano	118 $\pm$ 6	135 $\pm$ 5	145 $\pm$ 5	151 $\pm$ 5
Cu-10% $\text{Al}_2\text{O}_3$	Nano	142 $\pm$ 7	158 $\pm$ 6	168 $\pm$ 6	174 $\pm$ 6
Cu-2.5% $\text{Al}_2\text{O}_3$	Micro	68 $\pm$ 4	75 $\pm$ 3	79 $\pm$ 3	82 $\pm$ 3
Cu-5% $\text{Al}_2\text{O}_3$	Micro	85 $\pm$ 4	96 $\pm$ 4	102 $\pm$ 4	106 $\pm$ 4
Cu-7.5% $\text{Al}_2\text{O}_3$	Micro	103 $\pm$ 5	118 $\pm$ 5	126 $\pm$ 5	131 $\pm$ 5
Cu-10% $\text{Al}_2\text{O}_3$	Micro	122 $\pm$ 6	138 $\pm$ 6	147 $\pm$ 6	153 $\pm$ 6

**Table 3: Compressive Strength and Electrical Conductivity**

Composition	Particle Size	Compressive Strength (MPa)	Electrical Conductivity (%IACS)
Pure Cu	-	245 ± 8	100.0 ± 1.2
Cu-2.5%Al <sub>2</sub> O <sub>3</sub>	Nano	298 ± 12	96.2 ± 1.5
Cu-5%Al <sub>2</sub> O <sub>3</sub>	Nano	356 ± 15	92.8 ± 1.8
Cu-7.5%Al <sub>2</sub> O <sub>3</sub>	Nano	420 ± 18	89.1 ± 2.1
Cu-10%Al <sub>2</sub> O <sub>3</sub>	Nano	485 ± 22	85.3 ± 2.4
Cu-2.5%Al <sub>2</sub> O <sub>3</sub>	Micro	278 ± 10	95.1 ± 1.4
Cu-5%Al <sub>2</sub> O <sub>3</sub>	Micro	325 ± 13	91.2 ± 1.7
Cu-7.5%Al <sub>2</sub> O <sub>3</sub>	Micro	372 ± 16	87.4 ± 2.0
Cu-10%Al <sub>2</sub> O <sub>3</sub>	Micro	418 ± 19	83.6 ± 2.3

**Table 4: Statistical Analysis of Property Enhancement**

Property	Maximum Enhancement (%)	Optimal Composition	Standard Deviation Range
Hardness	178 (nano), 155 (micro)	Cu-7.5%Al <sub>2</sub> O <sub>3</sub>	±3.2 to ±6.8
Compressive Strength	71 (nano), 52 (micro)	Cu-7.5%Al <sub>2</sub> O <sub>3</sub>	±8.2 to ±22.1
Density Retention	97.6 (nano), 96.7 (micro)	Cu-10%Al <sub>2</sub> O <sub>3</sub>	±0.15 to ±0.35
Conductivity Retention	89.1 (nano), 87.4 (micro)	Cu-7.5%Al <sub>2</sub> O <sub>3</sub>	±1.2 to ±2.4

The results clearly demonstrate that nano-sized Al<sub>2</sub>O<sub>3</sub> reinforcement consistently outperforms micro-sized particles across all measured properties. The optimal composition appears to be Cu-7.5%Al<sub>2</sub>O<sub>3</sub> with nano-sized reinforcement, providing the best balance between mechanical property enhancement and retention of electrical conductivity. Higher Al<sub>2</sub>O<sub>3</sub> contents (10%) show continued mechanical property improvements but with diminishing returns and increased porosity. The compaction pressure effect is most pronounced at lower Al<sub>2</sub>O<sub>3</sub> contents, suggesting that higher reinforcement levels dominate the strengthening mechanisms regardless of initial green density.

### Discussion

The experimental results demonstrate a number of significant fundamental properties of Cu-Al<sub>2</sub>O<sub>3</sub> composite behavior which at least partly clarify the mechanisms of property development. The improved outcomes of nano Al<sub>2</sub>O<sub>3</sub> with respect to micro Al<sub>2</sub>O<sub>3</sub> are a result of many variables acting simultaneously to promote mechanical properties while minimizing adverse effects on electrical conductivity.

### Microstructure and Reinforcement distribution

The SEM images of the sintered composites indicated an observable difference in distributions of the added reinforcement in nano and micro Al<sub>2</sub>O<sub>3</sub>. Nano particle-reinforced composites display more uniform distributions of the particles and significantly less clustering than the micro-reinforced particulate which cluster noticeably more with an increase in volume fraction. The experimental findings within this study match the predictions made from the theory on particle packing and material mixing during powder processing.(35)

The main advantage factor for the improved distribution of nano-reinforced particles can be attributed to the increased particle number density for a given volume fraction; the statistical spacing between particles favors more uniform distribution. There surface energy of the nano-particles also leads to greater interactions to the particle-matrix density during sintering which



contributes to better interfacial bonding. However, the same high surface energy that promotes interfacial bonding will also promote greater agglomeration, and it is important to manage processing parameters to remain within a processing range of dispersion.(36)

Al<sub>2</sub>O<sub>3</sub> particles have an effect on the behaviour of grain growth in Copper as a result of the Zener pinning mechanism. Nano-particles have a better effect on pinning grain boundaries since they exhibit a considerable number density which keeps inter-particle distances smaller in size. Thus, if one considers these explanations, as well as the potential increases to near-theoretical densities and contributions of relatively large, secondary structuring, the distribution of finer matrix grain sizes in nano-reinforced composites certainly promotes strengthening according to Hall-Petch theory. The grain refinement effect is quantified by estimating the average sizes of the grains using the linear intercept method and shows that the nano-reinforced composites' grains are 35% smaller compared to the micro-reinforced composites .(37)

### Strengthening Mechanisms

The enhancement of mechanical properties in Cu-Al<sub>2</sub>O<sub>3</sub> composites occurs by a group of different strengthening mechanisms acting concurrently with the contribution of each mechanism depending on the reinforcement design and the fraction of volume of the reinforcing ceramic .

The first is load transfer strengthening which occurs when applied loads apply stresses to the copper matrix that are transferred to the harder Al<sub>2</sub>O<sub>3</sub> particles through interfacial shear stresses. The amount of load transferred will depend on the amount of load transferred will depend on the quality of interfacial bonding between the copper matrix and the Al<sub>2</sub>O<sub>3</sub>, and the aspect ratio of the reinforcing particles possible higher for elongated particles such as fibers .(38)

Samples reinforced with nano-sized particles demonstrate higher load transfer strength to the load transferred because nano-sized particles have a larger surface-to-volume ratio and area of interfacial area to transfer stress per unit volume of reinforcement. This is why there are consistently higher mechanically properties for nano-reinforced composites. The modified rule of mixtures correctly predicts the observed strength increase using factors to account for load transfer efficiency and using the correct parameters for interface efficiency.(39)

A second strengthening mechanism is thermal mismatch strengthening as a result of the difference in coefficients of thermal expansion for copper ( $= 16.5 \times 10^{-6}/^{\circ}\text{C}$ ) and Al<sub>2</sub>O<sub>3</sub>( $= 8.1 \times 10^{-6}/^{\circ}\text{C}$ ). When cooling to room temperature from the sintering temperature, thermal stresses are developed in particle-matrix interfaces during cooling which can produce dislocations in the copper matrix that can lead to work hardening. The amount of thermal mismatch strengthening is a function of volume fraction of reinforcement and the effects history of thermal processing (40The thermal stress component is computed with the following equation:  $\Delta\sigma = 6GM_f(\Delta T)(\Delta\alpha)/(2-3f)$ , (with  $G$  = matrix shear modulus,  $M_f$  = volume fraction of reinforcement,  $\Delta T$  = temperature change,  $\Delta\alpha$  = difference in thermal expansion coefficients, and  $f$  = a geometric factor). Thermal mismatch accounts for about 15-25% of the overall improvement in strength (41.)

### Effect of Volume Fraction

The relationship between Al<sub>2</sub>O<sub>3</sub> volume fraction and mechanical properties is best described as nonlinear with the potential for diminishing return at higher levels of reinforcement. The behavior is likely due to competing influences of the increasing effectiveness of reinforcement but



simultaneously decreasing matrix continuity, and potential increases in porosity. The balance point at 7.5% volume fraction is where maximum potential improvement can be obtained while still having sufficient density and electrical conductivity.(42)

At low volume fractions (2.5-5%), strengthening is primarily by load transfer and grain refinement effects, which results in an almost linear relation between volume fraction and mechanical properties. When the volume fraction of reinforcement exceeds 7.5%, clustering of the particles occurs. This clustering changes the reinforcement effectiveness of the particle distribution and creates stress concentration sites that may initiate failure. Larger volume contents of reinforcement will also make it more difficult to achieve full densification during sintering.(43)

With regards to electrical conductivity reduction with increased Al<sub>2</sub>O<sub>3</sub> fraction, the results can be explained by the percolation theory for conductors and large particle composites. Al<sub>2</sub>O<sub>3</sub> is an electrical insulator and breaks the pathways of current flow in the copper matrix. The amount of conductivity reduction is less severe for nano-reinforced composites than for micro-reinforced composites, because the distributed nano-particles led to a more continuous phase of copper material, while micro-reinforced composites had clustered micro-particles that disrupted continuity of copper pathways (44). Impacts of Variables on Properties

The compaction stress affects green density and sintered attributes to a greater extent when the composites are at low Al<sub>2</sub>O<sub>3</sub> levels. The effects of compaction stress advance with higher compaction stresses which improves the efficiency of packing of the particles and restrictions in initial porosity help to densify in sintering. At greater amounts of reinforcement the effects of the compaction stress reduced because there is interference between the particles which inhibit further densification.(45)

The sintering behavior of Cu-Al<sub>2</sub>O<sub>3</sub> composites is different than pure copper due to the additional non-deformable particles that do not allow copper particles to reposition and bond. Therefore, the final density from sintering was slightly less than pure copper densities, and this was slightly exaggerated when larger un-deformed reinforcements created greater disruption in continuity of the copper matrix.(46)

The sintering temperature of 850°C was utilized to achieve sufficient thermal energy to initiate densification in copper at lower temperature, with reduced possibility of excessive grain growth or the occurrence of interfaces that may form via any interfacial reactions during sintering. Higher temperature would increase opportunity for densification but would also enhance the chance of grain grow, which would negate the contribution of grain refinement improvement in strength. Lower temperatures would lead to incomplete densification of the composites material, therefore limiting properties of the composites.(47)

### **Applications**

The properties exhibited in optimized Cu-Al<sub>2</sub>O<sub>3</sub> composite materials lend themselves to good potential application environments such as electrical and thermal management systems which require enhanced mechanical performance without severely limiting electrical properties. The Cu-7.5%Al<sub>2</sub>O<sub>3</sub> nano-reinforced composite, developed with a hardness of 145 HV and 89% retained electrical conductivity represents an excellent compromise for electrical contacts, heat sinks, and structural electrical components.(48)



The tribology characteristics of the increased hardness will suggest improved wear resistance compared to pure copper, and consequently the possibility of prolonging the service life in sliding contact applications. Nonetheless the increase in hardness may also result in increased brittleness, and component design will require consideration of the loading conditions and possible stress concentration.(49)

The thermal management applications will benefit from increased mechanical properties as well as modified thermal expansion behaviour.  $Al_2O_3$  has a lower coefficient of thermal expansion than pure copper, which may improve thermal stability during cycling applications, while retaining an appropriate level of thermal conductivity for thermal dissipation .(50)

### Conclusions

This extensive investigation was conducted utilizing Cu- $Al_2O_3$  metal matrix composites and has provided useful insight into the effects the reinforcement characteristics, processing parameters, and final properties have on these composites. The results presented in this dissertation show that all nano-reinforced composites significantly outperformed their micro-sized counterparts demonstrating superior mechanical properties and better preservation of electrical conductivity. The most remarkable performance can be attributed to Cu-7.5vol% $Al_2O_3$  with nano reinforced particles, which showed a 178% increase in hardness and a 71% increase in compressive strength while retaining 89% of the electrical conductivity of pure copper.

It can be concluded that all the strengthening mechanisms contribute synergistically and collectively enhance the overall properties of the composites. Load transfer, grain refinement, and thermal mismatch all benefit the composites in their own manner. The microstructural analysis has shown that to achieve the best overall properties future designs should include uniform distribution of reinforcement, as nano-particles have better dispersion properties than micro-sized particles.

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