

Original Research

**GREEN ENGINEERING APPROACH TO Sn-0.7Cu/xGNS COMPOSITES
PRODUCED BY POWDER METALLURGY: MICROSTRUCTURAL AND
MECHANICAL PROPERTIES FOR SUSTAINABLE ELECTRONICS**

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Abstract

The increasing demand for environmentally friendly electronic materials has encouraged the development of lead-free solder alloys and sustainable production technologies. Despite numerous alternatives, the eutectic Sn-0.7Cu alloy has been recognized as a promising candidate for lead-free solder applications due to its low cost, acceptable mechanical properties, and compliance with RoHS and WEEE regulations. This study investigates the effect of graphene nanoparticles, in the form of graphene nanosheets (GNS), on the microstructural and mechanical properties of Sn-0.7Cu matrix composites produced via powder metallurgy. GNS was incorporated into the matrix in small weight fractions (0, 0.02, 0.04, 0.06, 0.08, and 0.10 wt.%) to promote microstructural refinement and enhance the mechanical properties of the composites. Optical microscopy was used to characterize the microstructure of the sintered samples, while microhardness was measured using the Vickers method. The results indicate that increasing the graphene content significantly refines the grains, reducing the average grain size by approximately 54 % and increasing the microhardness by about 16 % compared to the base alloy.

Keywords: lead-free solder, graphene nanoparticles, powder metallurgy, composites.

INTRODUCTION

The electronics industry faces growing demands to develop materials that combine high performance with environmental sustainability. The replacement of toxic Sn-Pb solders with lead-free alternatives has been strongly encouraged by environmental regulations such as the RoHS and WEEE Directive [1]. Among lead-free systems, eutectic Sn-0.7Cu solder is widely used due to its ecological acceptability, relatively low cost, excellent wettability, and satisfactory soldering performance. However, its mechanical properties are lower than those of eutectic Sn-Pb and Sn-Ag-Cu solders, potentially affecting the reliability of soldered joints

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[2]. The incorporation of reinforcement phases through composite technology provides an effective strategy for improving the performance of Sn–Cu solder.

Over the past decade, nanocomposite solders obtained by incorporating nanoparticles into conventional solders have been extensively investigated to improve the performance of solder joints under various service conditions [3]. Numerous studies have employed various types of nanoparticles to modify lead-free solders. However, to date, relatively few studies have focused on the incorporation of carbon-based nanomaterials, particularly graphene, which has attracted significant interest in advanced materials research due to its outstanding properties. [4]. Graphene, in the form of graphene nanosheets (GNS), is a two-dimensional carbon nanomaterial with exceptional mechanical strength, high thermal and electrical conductivity, and a large specific surface area, making it an ideal reinforcement phase for enhancing the properties of metal matrix composites [5].

Among the various techniques available for adding reinforcements to a solder matrix, powder metallurgy (PM) is the most frequently used. From a sustainability perspective, this technique offers an efficient processing route that minimizes material waste, enables near-net-shape production, and provides precise control over composition. Compared to conventional casting, PM can reduce energy consumption and lower environmental impact [6].

The main focus of this research is to investigate the effect of small amounts of GNS on the microstructure and microhardness of the Sn-0.7Cu based composites. The composites were synthesized using the PM technique, and the results were compared with those of the base alloy.

MATERIALS AND METHODS

Materials used in this study included atomized tin (Sn) and copper (Cu) powders, with particle sizes up to 75 μm , and GNS with an average diameter of 5–10 μm and a thickness of 3–5 nm. Six different compositions, Sn-0.7Cu/xGNS ($x = 0, 0.02, 0.04, 0.06, 0.08, \text{ and } 0.10 \text{ wt.}\%$) were synthesized. For each composition, the corresponding powders were first mixed in a “Turbula T2F” three-axis mixer at 50 rpm for 30 hours to produce the Sn-0.7Cu matrix powder. The matrix powder and GNS were then mechanically alloyed in a high-energy planetary ball mill “FRITSCH Planetary Ball Mill P-7” at 100 rpm for 3 hours to ensure a uniform distribution of GNS within the matrix. The resulting powder mixture was cold compacted using a “Mohr-Federhaff-Losenhausen” hydraulic press under a uniaxial pressure of 300 MPa. Compacted samples were then sintered in a furnace at 185 °C for 3 hours in an argon atmosphere to obtain the final specimens.

The microstructural analysis of the sintered samples was performed using a “Reichert MeF2” optical microscope at a magnification of 1000x. After standard metallographic preparation by grinding and wet polishing, the samples were etched with a solution of (2 mL HCl + 98 mL of 95 % methanol).

The microhardness of the samples was measured in accordance with the ASTM E384 standard [7] using a PMT-3 Vickers microhardness tester. To ensure reliable results, the sample surfaces were carefully ground and polished. A pressing force of 0.05 N and a load

duration of 15 seconds were applied. Each measurement was repeated six times, and the average value was calculated.

RESULTS AND DISCUSSION

Figure 1 shows the optical microphotographs of the investigated sintered samples with different GNS contents. The microstructure of the Sn-0.7Cu base alloy is shown in Figure 1a, while Figures 1(b–f) illustrate the microstructures of the samples containing GNS. It can be observed that the addition of reinforcement particles significantly reduces the grain size, as confirmed by measurements of the average grain size using ImageJ software (Figure 2). The average grain size continuously decreased from 27.19 μm to 12.64 μm with increasing GNS content. The Sn-0.7Cu/0.10GNS composite exhibited the finest microstructure, with approximately 54 % lower grain size than the Sn-0.7Cu base alloy.

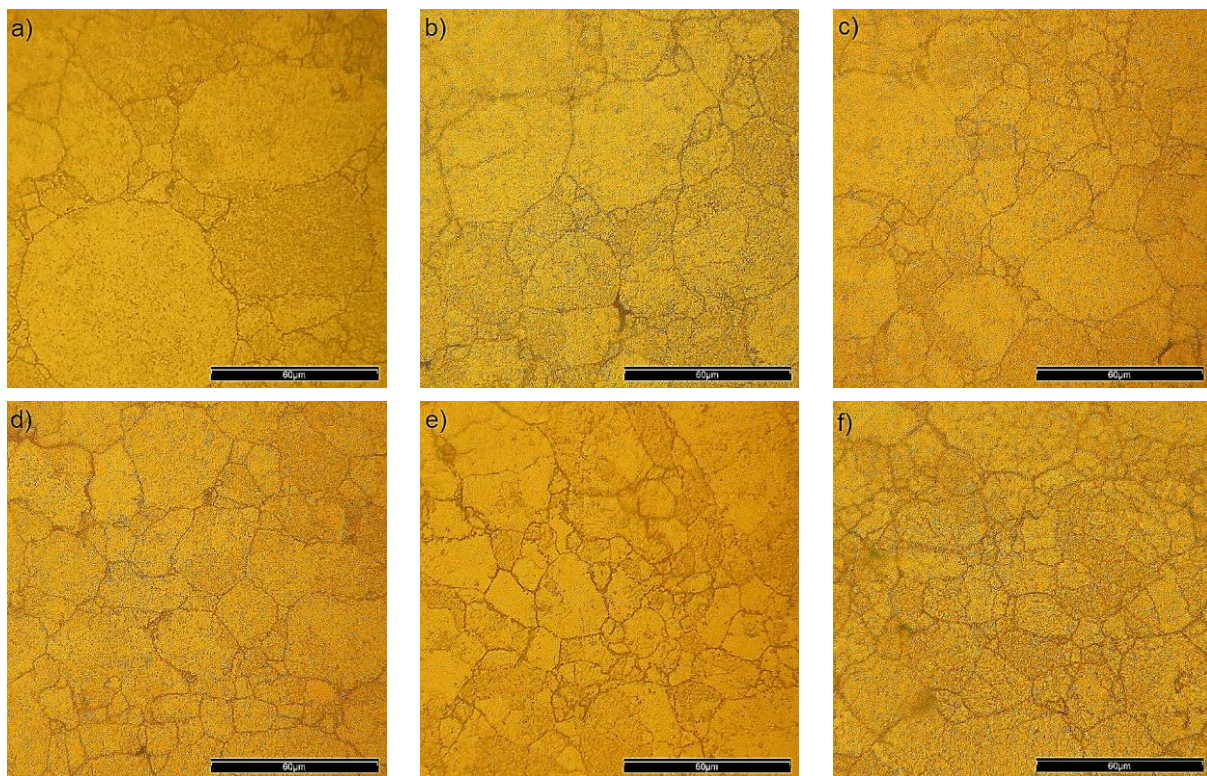


Figure 1 Optical microphotographs of the sintered Sn-0.7Cu/xGNS samples: a) Sn-0.7Cu; b) Sn-0.7Cu/0.02GNS; c) Sn-0.7Cu/0.04GNS; d) Sn-0.7Cu/0.06GNS; e) Sn-0.7Cu/0.08GNS; f) Sn-0.7Cu/0.10GNS

Microstructural analysis indicated that the addition of GNS affected the grain morphology of the composites. Optical micrographs showed that the grains are polygonal with well-defined boundaries. The microstructure is heterogeneous, showing variations in grain size, which may be attributed to the non-uniform distribution of GNS during the powder metallurgy process. Porosity is minimal, indicating good consolidation of the powder during the sintering process. At this magnification, GNS particles are not visible. GNS reinforced samples exhibited significant grain refinement and a more homogeneous microstructure

compared to the base alloy. The observed grain refinement can be attributed to the role of GNS as a barrier to grain growth during sintering. The presence of GNS at the grain boundaries may inhibit atomic diffusion, reducing grain boundary mobility and resulting in a finer microstructure. Similar findings were also reported by Yang *et al.* in their study [8].

Figure 3 illustrates the effect of different contents of GNS on the microhardness of the sintered Sn-0.7Cu/xGNS samples. The results indicate a linear trend of increasing microhardness with increasing GNS content. The Sn-0.7Cu base alloy exhibits a microhardness of 18.72 HV_{0.05}, while composite Sn-0.7Cu/0.10GNS has a microhardness of 21.65 HV_{0.05} (15.65 % higher than the Sn-0.7Cu base alloy). This enhancement can be attributed to the grain refinement induced by GNS, as well as the restriction of dislocation movement at the grain boundaries, where GNS particles act as barriers during deformation. These findings are consistent with the observations by Yin *et al.* [9], confirming that even small additions of GNS significantly improve the mechanical properties of the composites.

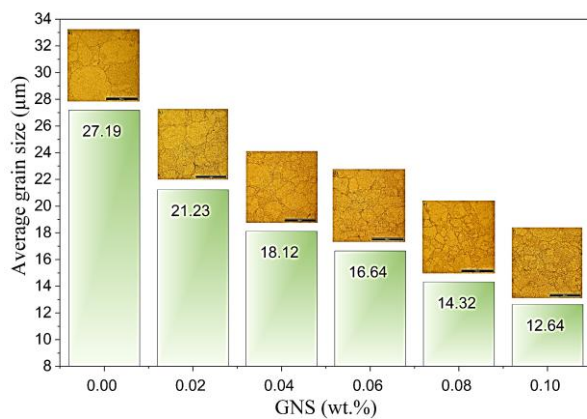


Figure 2 Effect of GNS content on the average grain size

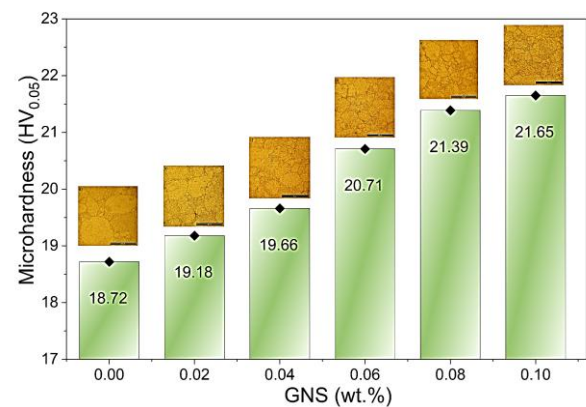


Figure 3 Effect of GNS content on the microhardness

CONCLUSION

In this study, Sn-0.7Cu based composites reinforced with GNS (0, 0.02, 0.04, 0.06, 0.08, and 0.10 wt.%) were successfully fabricated using the powder metallurgy technique. From a green engineering perspective, the PM process applied in this study offers several environmental advantages compared to conventional casting processes. Unlike traditional solder production, which requires complete melting of the alloy at temperatures typically above 250 °C, the PM process involves sintering at a significantly lower temperature of 185 °C. This reduced processing temperature directly lowers energy consumption during manufacturing and consequently decreases CO₂ emissions. Additionally, PM enables near-net-shape fabrication, which minimizes material waste and reduces oxidation losses commonly occurring during repeated melting operations. Material utilization efficiency in PM processing is typically above 95 %, contributing to improved resource efficiency.

Overall, the incorporation of very small amounts of GNS (≤ 0.10 wt.%) results in a significant increase in microhardness ($\approx 16\%$) and considerable grain refinement ($\approx 54\%$), enhancing the long-term reliability of solder joints. These improvements can extend the service life of electronic components and reduce e-waste. The combination of lower energy

demands, high material efficiency, and improved functional properties demonstrates that the developed Sn-0.7Cu/xGNS composites offer a sustainable solution for lead-free electronics applications.

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