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Technical Faculty in Bor

PROCEEDINGS

32nd International Conference

Ecological Truth & Environmental Research

24-26 June 2026

Editor
Prof. Dr Ana Radojević

EcoTER'26

Hotel Sunce, Sokobanja, Serbia

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PREFACE

The 32nd International Conference *Ecological Truth & Environmental Research – EcoTER'26* has been dedicated for more than three decades to presenting the latest scientific achievements, research findings, and innovative approaches in the fields of ecology, environmental protection, and sustainable development. In 2026, the conference was held in Sokobanja, Serbia, at Hotel Sunce, from 24 to 26 June.

The primary aim of the conference is to bring together leading experts, researchers, professionals, and young scientists from diverse fields in order to foster the exchange of knowledge, strengthen scientific collaboration, and promote innovative solutions to contemporary environmental challenges. By connecting science, education, industry, and society, EcoTER'26 seeks to inspire the transformation of attitudes and practices in everyday life, as well as within economic and industrial systems, contributing to a more sustainable future.

The 32nd International Conference *Ecological Truth & Environmental Research – EcoTER'26* is organized by the University of Belgrade, the Technical Faculty in Bor, with the co-organization of the University of Banja Luka, the Faculty of Technology; the University of Montenegro, the Faculty of Technology – Podgorica; the University of Zagreb, the Faculty of Metallurgy – Sisak; the University of Pristina, the Faculty of Technical Sciences – Kosovska Mitrovica; and the Association of Young Researchers – Bor (Serbia).

The Proceedings of EcoTER'26 include 98 scientific papers authored by researchers, academics, and industry representatives from universities, research institutions, and organizations across the following countries: Bosnia and Herzegovina, Bulgaria, the Czech Republic, Finland, Italy, Montenegro, North Macedonia, Pakistan, Romania, Slovenia, the Netherlands, the United Kingdom, the United States of America, Uzbekistan, and Serbia. It is our great honour and pleasure to welcome all participants and contributors and to express our sincere appreciation for their valuable scientific contributions.

Within this year's conference programme, the 7th Student Section – EcoTERS'26 was also organized. We highly value the contribution of students and their mentors, whose enthusiasm, creativity, and dedication represent an important foundation for the advancement of scientific knowledge. We encourage young researchers to continue exploring, questioning, and expanding the boundaries of knowledge, recognizing that education and scientific discovery are lifelong processes.

The support of our donors, together with their commitment, trust, and willingness to cooperate, has significantly contributed to the successful organization of the conference. The Organizing Committee expresses its deepest gratitude to the Platinum donors of the conference – Serbia Zijin Mining DOO Bor and Serbia Zijin Copper DOO Bor; the Gold donors – HBIS SERBIA, the Serbian Chamber of Engineers, and Elixir Prahovo; and the Silver donor – Rudex Explosives.

We extend our sincere appreciation to all authors who contributed to these Proceedings. Special recognition is given to the members of the Scientific, Organizing, and Honorary Committees, reviewers, invited speakers, session chairs, and all participants whose dedication and support have contributed to the success and continuity of EcoTER.

Our sincere gratitude goes to everyone who has contributed to the organization and delivery of this conference. Your efforts and collaboration continue to strengthen the mission of EcoTER and its role in promoting scientific excellence, environmental responsibility, and sustainable development.



Prof. Dr Ana Radojević

President of the Organizing Committee

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Original Research

ENVIRONMENTAL ASPECTS AND EXPERIMENTAL INVESTIGATION OF SAC/GNS COMPOSITE LEAD-FREE SOLDER

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Abstract

Ternary alloys of the Sn–Ag–Cu (SAC) system represent one of the most widely used lead-free solder materials due to their favorable mechanical properties and compliance with environmental regulations aimed at eliminating toxic lead from electronic components. Among these alloys, SAC338 (Sn–3.3Ag–0.8Cu) is recognized as one of the most promising alternatives to conventional Sn–Pb solders. Despite their ecological advantages, SAC alloys still exhibit challenges associated with the growth of intermetallic compounds and microstructural instability. The aim of this study was to investigate the influence of graphene nanosheet (GNS) additions on the microstructural properties of SAC composite. SAC composite containing up to 0.09 wt.% GNS were produced using powder metallurgy procedures. The results showed that the addition of GNS contributed to a more homogeneous microstructure and refinement of intermetallic phases such as Cu_6Sn_5 and Ag_3Sn. The addition of GNS improves the wettability of the composite solder by reducing the wetting angle, which enables better spreading of the molten solder and improves the quality of solder joints. From an environmental perspective, these improvements contribute to enhanced durability and longer service life of electronic components, leading to reduced material consumption, lower maintenance frequency, and decreased generation of electronic waste.

Keywords: SAC338, GNS, intermetallic phases, wettability.

INTRODUCTION

The rapid development of the electronics industry has resulted in increased consumption of electronic devices and a significant rise in electronic waste worldwide. Traditional Sn–Pb solder alloys, widely used for decades in electronic packaging, contain toxic lead that poses serious risks to human health and the environment. Due to the harmful effects of lead contamination, international environmental regulations such as the Restriction of Hazardous

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Substances (RoHS) Directive encouraged the replacement of lead-containing solders with environmentally acceptable alternatives [1–3].

Among the available lead-free materials, SAC alloys are considered the most promising candidates because of their favorable combination of mechanical strength, wettability, thermal stability, and soldering reliability. SAC338 alloy is especially important due to its eutectic composition and excellent performance in electronic packaging applications. Nevertheless, SAC alloys still exhibit several technological and ecological challenges. The formation of thick intermetallic compounds at the solder-substrate interface can reduce joint reliability and shorten service life. In addition, the relatively high silver content increases both production costs and environmental impact associated with mining and raw material extraction. Therefore, current research focuses on improving SAC alloys through reinforcement additions that can enhance performance while contributing to sustainability [4–6].

Nanomaterials such as GNS, carbon nanotubes, and ceramic particles have attracted considerable attention because they can refine the solder microstructure and suppress excessive intermetallic growth. These modifications may improve thermal stability and mechanical reliability, ultimately extending the operational lifetime of electronic devices and reducing electronic waste generation [7,8].

The aim of this paper was to investigate the effect of GNS content on the microstructural properties and wettability of SAC338–based composite materials. The obtained experimental results are expected to contribute to the further development of advanced composite solder materials with optimized properties for sustainable and environmentally responsible electronics manufacturing.

MATERIALS AND METHODS

SAC338 alloy and SAC338/GNS composite materials were produced using powder metallurgy techniques (PM). Environmentally, PM processing reduces material losses and energy consumption while allowing the production of advanced composite materials with enhanced functional properties. These factors support cleaner production technologies and more sustainable manufacturing practices in the electronics industry. Elemental powders of tin, silver, and copper were mechanically alloyed together with different concentrations of GNS (up to 0.09 wt.%) in the “Turbula T2F” mixer. Mechanical alloying was carried out for 5 h. The obtained powder mixture is then compacted under pressure of 150 MPa and subsequently sintered in the “Elektron ELP-08” furnace under an argon atmosphere at 190 °C for 2 h. The obtained samples were soldered onto copper substrates using flame soldering procedures.

Microstructural characterization was performed using scanning electron microscopy (SEM) “Tescan Vega 3LMU” coupled with energy dispersive spectroscopy (EDS) “Oxford Instruments X–act”. The investigations focused on the morphology of the solder matrix, distribution of GNS, and formation of intermetallic compounds at the solder-substrate interface. In order to determine the contact angle, the cross-sectional area of the solder joint was analyzed using micrographs and ImageJ software.

RESULTS AND DISCUSSION

Figure 1 shows the microstructures of the investigated samples after melting and solidification of the sintered specimens on a copper substrate, while Figure 2 presents the EDS analysis of the SAC/0.03GNS solder.

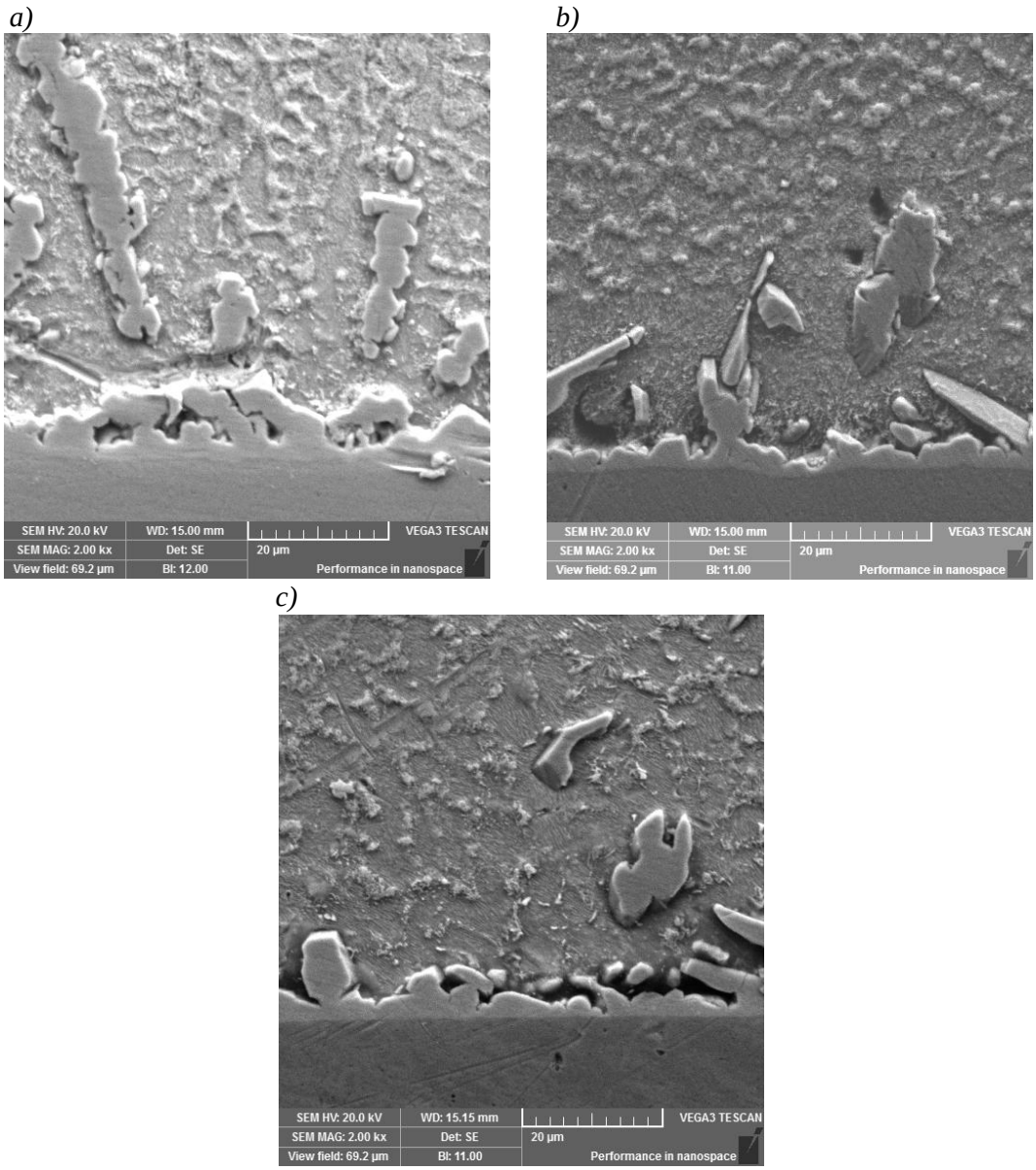
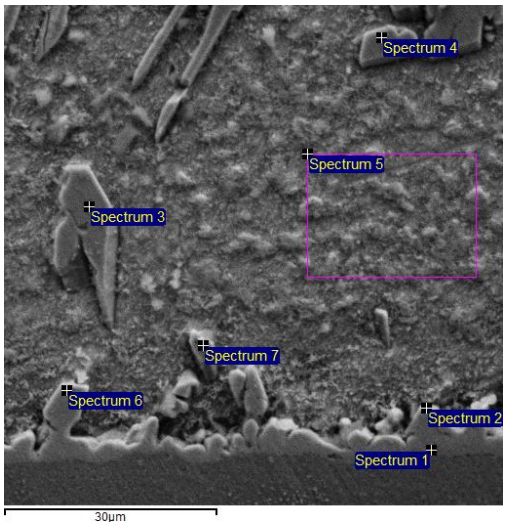


Figure 1 *SEM micrographs of the solders: a) SAC alloy; b) SAC/0.03GNS composite; c) SAC/0.09GNS composite*

All SEM micrographs of the solders reveal a relatively homogeneous matrix with clearly defined Sn–rich structures and needle-like Ag_3Sn phases forming a network within the β–Sn matrix. The primary Sn–rich dendritic phase represents the main solder structure, whereas the interdendritic regions consist of the β–Sn and Ag_3Sn eutectic mixture (Spectrum 5 in Figure 2).



Spectrum	*Cu*	*Ag*	*Sn*
Spectrum 1	*54.12*		*45.88*
Spectrum 3	*52.63*		*47.37*
Spectrum 5		*12.09*	*87.91*

Figure 2 *EDS analysis of the SAC/0.03GNS composite solder*

With increasing GNS content, a higher degree of phase homogeneity was observed. The addition of GNS contributed to microstructural refinement and reduced phase segregation. Copper precipitated in the form of the Cu_6Sn_5 intermetallic phase (Spectrum 3 in Figure 2), whose content was higher near the copper substrate and gradually decreased with increasing distance from the interface. Furthermore, increasing GNS content resulted in a significant reduction in both the size and fraction of Cu_6Sn_5 particles [9,10].

At the interface between the solder and the copper substrate, the formation of an intermetallic compound (IMC) layer was observed (Spectrum 1 in Figure 2). During the melting process, copper atoms from the substrate diffused into the solder and reacted with tin, resulting in the growth of the intermetallic layer toward the solder interior. The thickness of the IMC layer plays an important role in determining the mechanical and electrical properties of the joint [11,12]. It was observed that increasing the GNS content in the solder reduced the thickness of the intermetallic layer.

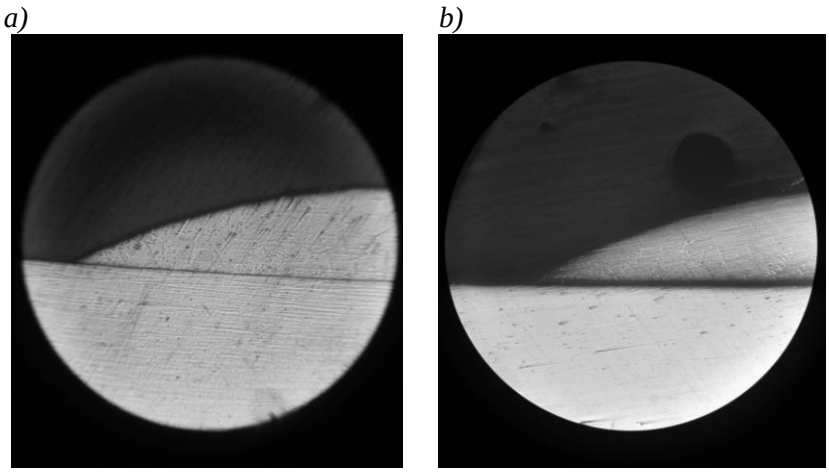


Figure 3 *Contact angles of (a) SAC338/0.03GNS; (b) SAC338/0.09GNS*

Contact angle analysis was performed for the SAC and SAC/GNS composite solders (Figure 3). The incorporation of GNS resulted in a reduction of the contact angle (from 85^o

for SAC to 35^{o} for SAC/0.09GNS) of the composite solders, indicating improved wetting behavior and enhanced spreading ability during the soldering process. Improved wettability promotes the formation of higher–quality and more reliable solder joints with fewer defects, such as pores and incomplete bonding [13]. From an environmental perspective, enhanced joint reliability contributes to longer service life of electronic components, reduced material losses during manufacturing and repair processes, and lower generation of electronic waste. Consequently, the addition of GNS supports the development of more sustainable and environmentally friendly lead-free solder materials for electronic applications.

CONCLUSION

The addition of reinforcement GNS improves the microstructural stability and reliability of SAC alloys by refining the microstructure and suppressing excessive intermetallic compound growth. These improvements extend the service life of electronic components and contribute to reducing electronic waste generation.

Powder metallurgy processing offers additional ecological advantages through lower material losses and improved manufacturing efficiency. Consequently, SAC composite reinforced with GNS constitute a promising direction for sustainable electronic materials and environmentally responsible electronic packaging technologies.

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