https://doi.org/10.2298/SOS230415027A

## UDK: 692.533.1; 676.017.2

# Mechanical and Electrical Properties of Graphene Nanosheet Reinforced Copper Matrix Composites Materials Produced by Powder Metallurgy Method

# Ahmed Basheer Mohammed Albartouli<sup>1</sup>, Arif Uzun<sup>2\*)</sup>

<sup>1</sup>Department of Materials Science and Engineering, Institute of Science, Kastamonu University, Kastamonu, Turkey

<sup>2</sup>Department of Mechanical Engineering, Kastamonu University, Kastamonu, Turkey

#### Abstract:

This study investigated the mechanical and electrical properties of copper matrix composite materials reinforced with graphene nanosheets. The composite materials were produced using the powder metallurgy method, with several weight percentages graphene nanosheets (0, 0.5, 1 and 1.5) added to the copper matrix powders. The mixed powders were compacted unidirectionally in a steel mold at different pressures (500, 600 and 700 MPa) and sintered in an argon atmosphere at different temperatures (850, 900 and 950°C). Furthermore, the sintered samples were subjected to microstructure analysis, hardness and electrical conductivity measurements. The results showed that the microstructure exhibited porosity and agglomeration with increasing amounts of graphene nanosheets, resulting in a decrease in relative density up to 87.4%. The highest electrical conductivity was 76.59 IACS (0% GNS-500 MPa-950°C), while the lowest was 43.49 IACS (1.5% GNS-500 MPa-850°C). The addition of graphene nanosheets resulted in a relative increase in hardness of up to 1%. **Keywords:** GNS-Cu composite; Powder metallurgy; Electrical conductivity.

#### **1. Introduction**

The combination of copper's exceptional electrical and thermal qualities, along with its durability and corrosion resistance, make it a versatile and widely used material in electrical equipment and electronics industry [1, 2]. Their strength and hardness at room temperature are generally lower compared to other structural materials. This lower strength and hardness can result in higher wear rates and limit their applications in certain structural materials [3]. While reinforcements like carbon fibers, ceramic fibers, and ceramic particles can enhance the mechanical properties of copper matrix composites (Cu-MMCs), they can have a detrimental impact on the electrical and thermal properties of copper [4-7]. Carbon nanotubes (CNTs) have been preferred as reinforcements in Cu-MMCs to overcome the drawbacks associated with other reinforcements and to maintain or improve the electrical and thermal properties of copper [8]. CNTs are indeed a unique and innovative material that can enhance the strength, electrical conductivity, and thermal conductivity of Cu-MMCs. However, the challenges associated with producing CNTs and achieving homogeneous dispersion within the composite have led researchers to explore alternative reinforcing materials.

<sup>\*)</sup> **Corresponding author:** auzun@kastamonu.edu.tr

Recently, graphene which have similar physical properties to carbon nanotubes, have become potential for Cu matrix composites [4]. Graphene offers several advantages over traditional additives like oxides and graphite particles when it comes to improving the mechanical performance of composites while preserving or enhancing electrical and thermal conductivity [9,10]. Several methods have been employed to disperse graphene within a copper matrix to achieve a uniform distribution and strong bonding between the two materials. Some of the commonly used methods are mechanical ball milling/mixing, electrical adsorption, chemical/electrochemical processes and in situ chemical vapor deposition (CVD) processes. Each of these methods has its advantages and limitations, and the choice of method depends on the specific requirements of the graphene-copper composite. Researchers continue to explore and refine these techniques to achieve better dispersion and stronger bonding between graphene and copper. Dutkiewicz et al. [11] conducted a study where they aimed to create copper matrix composites reinforced with graphene. They employed a method involving ball milling to combine powders, followed by uniaxial hot pressing under vacuum conditions. The graphene ratio in the composite prepared using two different sizes of flaky graphene was 1% and 2% by weight. According to the findings of the researchers, the finer graphene particles were more effective in reinforcing the copper matrix, leading to enhanced mechanical properties (hardness) and improved electrical conductivity (lower resistance) in the composite material Li et al. [12] focused on developing a copper/graphene composite with enhanced electrical conductivity. The researchers employed a specific set of techniques involving the production of graphene-coated copper powders through ball milling, followed by spark plasma sintering (SPS) to fabricate the composite material. Cao et al. [13] transformed copper particles into flake form to create graphene-copper composites. They noticed a considerable improvement in the composite's tensile and yield strengths, as well as excellent ductility and electrical conductivity. The composite containing 1.6% graphene compared to pure copper showed a 70% increase in yield strength, but no significant change in total elongation. In a different work, the researchers created a composite material by stacking single-layer graphene made using the chemical vapor deposition (CVD) process on copper foil called Cu-Graphene-Cu. The electrical conductivity reached an IACS value of 117% with a very low graphene content of 0.008% by volume in the composite material. This result for copper-graphene composites is one of the highest electrical conductivity values ever recorded in the literature [14]. Luo et al. [15] strengthened the interface bonding between the reinforcement and matrix by coating copper on the reinforcement surfaces, and successfully produced lamellar composite structures using a combination of flake powder metallurgy and vacuum hot pressing. Shi et al. [16] demonstrated that doping the transition metal elements in the interface can strengthen the bond between graphene and copper matrix, and thereby enhance the bond strength of the graphene/Cu interface. Chen et al. [17] conducted a study where copper matrix composites with varying graphene content were created using a molecular level mixing technique and a spark plasma sintering process. The results of the study revealed that the volume proportion of graphene had a significant influence on its distribution within the composite matrix. Chu ve Jia [18] investigated the effects of incorporating graphene nanoplates (GNPs) into a copper matrix using ball milling and hot pressing techniques. The addition of GNPs had a significant impact on the mechanical properties of the composite material. By introducing 8% by volume of GNPs into the copper matrix, the yield strength of the composite material increased by 300 MPa compared to pure copper. This implies that the composite material became stronger and more resistant to deformation. Additionally, the Young's modulus of the composite material increased by 37% to 114 GPa. The study highlights the significance of achieving a balance between reinforcing effects and avoiding agglomeration-induced defects to optimize the mechanical performance of graphene-reinforced composite materials. Khobragade et al. [19] produced graphenereinforced Cu-based nanocomposite (Cu-Gr) structures with 96% relative density and 84% electrical conductivity using the high pressure forming method (~8 GPa). Li et al. [20]

examined the mechanical and tribological characteristics of copper matrix composite materials with graphene nanosheet (GNS) and graphite reinforcement made by hot pressing. The researchers obtained the highest microhardness values in GNS reinforced composites. However, hardness values decreased after 7.5% GNS ratio. The composites' flexural strength values decreased when the reinforcing ratio was raised. For the same reinforcement ratios, the flexural strength of GNS reinforced composites is higher than that of graphite reinforced composites.

This study's objectives are to create copper matrix composites reinforced with GNS via powder metallurgy and to investigate the effect of fabrication parameters on mechanical, microstructural and electrical properties. For this purpose, the effects of graphene content, applied compression pressure and sintering temperatures were determined in detail.

#### 2. Materials and Experimental Procedures

In experimental studies, Cu powder (99.7% pure - average 44  $\mu$ m in size) as matrix material from Nanokar company and graphene nanosheets (GNS) (99.9% purity - 3 nm size) as reinforcement element from Nanography company were obtained. Images of the powders taken using a scanning electron microscope (SEM) are shown in Fig. 1.



Fig. 1. SEM image of powders used in experimental studies.



Fig. 2. Schematic view of the production process of Cu-GNS composites.

First, the experimental studies started with mixture of initial powders. For this process, 0%, 0.5%, 1%, and 1.5% GNSs by weight were mixed with copper powders separately. As shown schematically in Fig. 2, the GNSs were placed in a container containing 40 ml alcohol to ensure a homogeneous distribution before mixing. Then this mixture was placed in an ultrasonic bath filled with distilled water and mixed for 30 minutes at room temperature. Subsequently, Cu powders were added to the solution consisting of alcohol and graphene and mixed in a stainless steel vessel (250 ml) with a ball mixer at a stirring speed of 400 rpm for 120 minutes. Stainless steel balls with a diameter of 10 mm were added into the mixture powder so that the ball/powder ratio by weight was 10:1. After the mixing process, the mixture was placed in the furnace and dried at 80°C for 180 minutes. The mixed powders were compressed uni-directionally in a steel mold under 500, 600 and 700 MPa pressure with a hydraulic press. After compression, 27 mm diameter cylindrical samples were produced. The samples produced were subjected to the sintering process in an argon atmosphere at 850, 900 and 950°C in a tube furnace.

The traditional metallographic procedure was used for micro and macro-structural analysis of the composite samples produced. According to this procedure, the sample surfaces were sanded with SiC abrasives and polished with diamond solution. Thus, samples were made ready for macro and microstructural analysis. Scanning electron microscope (SEM) containing energy dispersive spectrometry (EDS) (FEI /Quanta FEG 250 model) and optical microscope (Nikon/MA100 model) were used in the microstructure studies.

The densities  $(\rho_s)$  of the produced samples were calculated by using the formula given in Eq. 1 with the ratio of the weight of the samples in air  $(m_h)$  to the volume (v) due to the dimensional size.

$$\rho_s = \frac{m_h}{v} \tag{1}$$

The theoretical densities ( $\rho_t$ ) of the composite samples were calculated according to the mixing rule. Relative density ( $\rho^*$ ) values were obtained by proportioning the experimental density to the theoretical density (Eq. 2).

$$\rho *= \frac{\rho_s}{\rho_t} \times 100\% \tag{2}$$

Microhardness measurements of the produced composite samples were made in Schimadzu (HMV-G) microhardness device by applying 0.025, 0.05, 0.1, 0.3 and 0.5 N loads. Holding time in load is 10 s. Microhardness values were evaluated by taking the average of at least five measurements for each samples.

Electrical conductivity measurements Olympus Nortec 500 D type digital eddy current metal conductivity meter was measured. Measurements were made at the Turkish Standards Institute Nondestructive Testing Laboratories. For each sample, at least five measurements were made to obtain an average value.

### 3. Results and Discussion

The morphology of Cu powders after ball milling is shown in Fig. 3. Initially, the Cu powder had a spherical shape with an average diameter of 44  $\mu$ m (Fig. 1). However, this morphology underwent significant changes during the mixing process. Figure 3a illustrates that the Cu powders transformed into a flaky structure as a result of ball milling. Throughout the ball milling process, the powder particles underwent cold welding, crushing, and rewelding procedures. Furthermore, the cold welding and crushing processes can dominate each stage of ball milling. This is mainly attributed to the deformation properties and kinetics

of the powder precursors [21]. Varol and Çanakçı [22] have reported that composites produced using Cu powders with pulsed morphology exhibit improved functional properties. In Fig. 3b, it can be observed that fracture occurs in the coarse flakes formed by Cu powders after ball milling.



Fig. 3. Morphology of Cu powders after ball milling a) 250x magnification b) 1000x magnification.



Fig. 4. Optical microscope images of GNS-reinforced Cu matrix composites.

Optical microscope images of GNS-reinforced Cu matrix composites pressed at different pressures and sintered at different temperatures are presented in Fig. 4. The graphene-free samples showed no significant porosity in their structure, whereas noticeable structural defects were observed in the graphene-added samples. The increase in GNS ratio substantially raised the number of GNS particles at the particle boundaries and within the Cu matrix powders. Consequently, agglomeration and porosity occurred, particularly at the grain boundaries (Fig. 5). The presence of GNSs in the particle boundaries during the pressing process caused a significant alteration in the microstructure of the samples. For further investigation, EDS line scan analyses were conducted on the grain boundaries of Cu-1.5 GNS samples, and the detailed results are presented in Fig. 6. The EDS analysis convincingly

demonstrated the presence of graphene at the grain boundaries of Cu-1.5 GNS composites. The observed agglomeration of GNSs acted as virtual pores, impeding complete densification. Similar findings were reported by Salvo et al. [21]. The formation of pores due to agglomeration had adverse effects on the physical and mechanical properties of the produced composites [22].



Fig. 5. SEM image of Cu-GNS composites densified at 600 MPa and 900°C.



Fig. 6. EDS line scan analysis of Cu-1.5 GNS composites densified at 600 MPa and 900°C.

Fig. 7 displays the relative density of Cu-GNS composites as determined by the Archimedes technique. It was observed that the relative density values of the samples decreased depending on the increase in graphene content. On the other hand, increasing the compression pressure led to higher relative density values. Particularly, the effect of compression pressure was more significant at a low sintering temperature (850°C). At this temperature, the sample without GNS, pressed at 700 MPa compression pressure, achieved the highest relative density (94.9%). The lowest relative density value, calculated as 87.4%,

was obtained in the sample containing 1.5% GNS, pressed at 500 MPa compression pressure. A 7.5% change in relative density occurred with the decrease in pressing pressure and the increase in GNS content.



Fig. 7. Relative densities of Cu-GNS composites.



Fig. 8. XRD models of pure Cu and Cu-1.5 GNS composites compressed at 700 MPa pressure and sintered at different temperatures (850, 900 and 950°C).

For samples sintered at high temperatures, the effect of compression pressure on relative density change is relatively small. In samples sintered at 950°C, the highest relative density (94.6%) was obtained in the sample without GNS, pressed at 600 MPa compression pressure. The relative density values for samples sintered at the same temperature and pressed at 700 MPa and 500 MPa compression pressures were determined as 93.7% and 93.3%, respectively. It is evident that the compression pressure for samples without GNS at this temperature creates a maximum difference of 1.3% in relative density change. For samples sintered at 950°C, the lowest relative density was observed in the sample containing 1.5% GNS pressed at 500 MPa compression pressure, resulting in a relative density of 90.5%. The

change in pressing pressure and the increase in GNS content accounted for a 4% difference in relative density change. The increase in GNS content led to a decrease in relative density values. This observation is supported by the presence of pores in Cu-1.5 GNS composites (Fig. 5). On the other hand, Wei et al. [23] reported that increasing the graphene percentage from 1% to 5% resulted in the highest relative density values (96.68%).

XRD models (Fig. 8) of pure Cu and Cu-1.5 GNS composites, compressed at 700 MPa pressure and sintered at different temperatures (850, 900, and 950°C), are shown in Figure 8, respectively. The XRD models of pure Cu and Cu-1.5 GNS composites exhibit diffraction peaks at 43.2, 50.3, and 74.1, corresponding to the reflections of Cu (111), (200), and (220), respectively [24]. No significant difference was observed between the XRD patterns depending on the sintering temperature. Intriguingly, there are no graphene-induced diffraction peaks in the Cu-1.5 GNS samples. This may be caused by (a) the distribution of a low amount of graphene in the Cu matrix, which cannot be detected within the limits of XRD detection; (b) masking of graphene-associated peaks by highly intense diffraction peaks associated with Cu; or (c) stacking of graphene sheets during milling and the occurrence of well-dispersed monolayer GNS distortions in the Cu matrix [21, 23]. According to Wejrzanowski et al. [25], bulk graphene-copper composites exhibited a similar XRD pattern behavior.

The deformation and fracture caused by the application of a load are considered indicators of material hardness. Microhardness is a test method used to measure the hardness of materials and determine their mechanical properties. Among the various methods, Vickers hardness is widely used to describe mechanical properties. In this study, six different loads (F = 0.245, 0.490, 0.980, 1.960, 2.940, and 4.900 N) were applied to investigate the mechanical properties of pure Cu and Cu-xGNS (x: 0.5, 1, and 1.5) composites at room temperature. Eq. 3 is employed to calculate the relationship between the load (F)/area of the indentation (A) and Vickers microhardness:

$$H_v = 1854,4 \left(\frac{F}{d^2}\right)(GPa)$$
 (3)

Here Hv is the Vickers microhardness, F is the applied load (N) and d is the diagonal length ( $\mu$ m) of the indentation.

-		Pressing pressure (MPa)		
Sample	Sintering temperature	500	600	700
	(°C)	Average hardness in the plateau region		
		(GPa)		
Cu- 0 %- GNS	850	0.341	0.302	0.339
	900	0.335	0.301	0.331
	950	0.322	0.341	0.338
Cu- 0.5 %- GNS	850	0.464	0.329	0.378
	900	0.357	0.383	0.367
	950	0.346	0.348	0.389
Cu- 1 %- GNS	850	0.507	0.439	0.435
	900	0.370	0.380	0.467
	950	0.475	0.467	0.516
Cu- 1.5 %- GNS	850	0.408	0.361	0.375
	900	0.347	0.385	0.434
	950	0.408	0.371	0.302

Tab. I Average hardness values obtained in the plateau region.



Fig. 9. Microhardness changes depending on the applied load.

Material behavior can manifest as the indentation size effect (ISE) or reverse indentation size effect (RISE) in microhardness characterization [26, 27]. While the RISE behavior shows an increase in hardness with the applied test load, the ISE behavior indicates a decrease in hardness as the applied load increases. Fig. 9 illustrates the changes in microhardness values corresponding to the applied loads. Considering the variations in microhardness values among the samples, the significance of the production parameters (pressing pressure, sintering temperature, and the addition of graphene into the copper matrix) becomes evident. Indentation size effect (ISE) was observed in all samples. It is evident that the hardness gradually decreases as the applied load increases, reaching a minimum at 4.900 N in this study, in contrast to the findings of Salvo et al.'s study [21].

As shown in Fig. 9, it is seen that the loading curves take the form of an approximate plateau after a certain load value (1.960 N). The average hardness values measured for this plateau are given in Table I. The load-independent hardness values of Cu-1 GNS composite samples are relatively higher compared to the hardness values obtained in pure Cu and Cu-0.5 GNS composite samples. This situation clearly reveals the effect of the added GNS particles.

The improvement in hardness can be attributed to the strengthening effect of GNSs. However, as the content of reinforcements reaches 1.5 % wt, a reduction in Vickers microhardness of the composites became evident. This decrease indicated that the degradation of the strengthening effect. It suggests that beyond a certain reinforcement ratio the addition of more GNSs no longer contributes to an improvement in the hardness of the composites [28].

Fig. 10 shows the electrical conductivity of Cu-GNS composite samples as a function of production parameters. The electrical conductivity values are presented as a percentage of IACS (International Annealed Copper Standard). According to this standard, the conductivity of annealed pure copper at 20°C was determined as  $58 \times 10^6$  S.m<sup>-1</sup>, which is considered 100% IACS. The results showed that the addition of GNS in the copper matrix reduced the electrical conductivity of the composites compared to the reference sample without GNS. It should be noted that graphene's electrical conductivity is much lower than that of copper and therefore reduces its electrical conductivity [23, 29-31].



Fig. 10. Electrical conductivity of Cu-GNS composites.

The highest electrical conductivity (76.59 IACS) was obtained in a reference sample without GNS, pressed at a compression pressure of 500 MPa and sintered at a temperature of 950°C. On the other hand, the lowest electrical conductivity (43.49 IACS) was obtained in composite samples containing 1.5% GNS, pressed at a compression pressure of 500 MPa and sintered at 850°C. The electrical conductivity tends to increase with an increase in compression pressure, while the effect of sintering temperature on conductivity exhibits a complex correlation.

The electrical conductivity of the composite decreased with the addition of graphene into the Cu matrix. Low interaction between free electrons and nuclei is a characteristic of metals. Cu has strong electrical conductivity because free electrons may travel around easily [32, 33]. On the other hand, the addition of graphene strengthens the links that exist between the nucleus and the free electrons. Additionally, graphene causes a reduction in grain size and an increase in dislocation density. These factors, including increased grain boundaries and the formation of more barriers, contribute to a decrease in electrical conductivity [34].

Taha and Moustafa [35] reported that conductivity increases with increasing sintering temperature. The samples produced by the powder metallurgy may contain micro-pores in the structure even after the sintering process. It is also thought that the aggregated GNSs in the structure have a negative effect on conductivity. Varol and Çanakçı [22] emphasized that the proportional increase in multilayer graphene particles causes aggregation and weakens

conductivity by causing electron scattering in these regions. It is recommended that the IAC value of Cu-GNS composites be above 50% for industrial applications at high temperatures [36].

### 4. Conclusion

In this study, microstructural analysis, XRD analysis, microhardness and electrical conductivity measurements were performed to determine the effects of production parameters on the physical and mechanical properties of Cu-GNS composite samples produced by powder metallurgy method. The results obtained in the study are summarized below.

- As a result of ball milling, spherical-shaped Cu powders turned into flaky form. Additionally, cracks and fractures were detected in the Cu particles exposed to work hardening due to excessive deformation.
- No significant micropores were found in copper samples without GNS. On the other hand, it was determined that the increase in GNS content caused agglomeration and porosity at the grain boundaries. This had a negative effect on the mechanical properties and electrical conductivity of the composites.
- It was determined that the GNS content and compression pressure were more effective on the relative density values of Cu-GNS composites compared to the sintering temperature. The copper samples without GNS sintered at 850°C and pressed at 700 MPa pressure exhibited the highest relative density value (94.9%). On the other hand, the sample containing 1.5% GNS sintered at the same temperature and pressed at 500 MPa pressure had the lowest relative density value (87.4%).
- The hardness values of the Cu-1.5 GNS composite samples were relatively lower than those of the Cu-1 GNS composite samples. This decrease in hardness values was attributed to agglomeration and porosity. Furthermore, the effect of sintering temperature and pressing pressure on the change in hardness was found to be unclear.
- It was determined that the content of GNS and compression pressure were more effective than the sintering temperature on the electrical conductivity of Cu-GNS composites. The electrical conductivity of the composites decreased with the increasing amount of GNS. The highest and lowest electrical conductivity were determined as 76.59 IACS (0% GNS-500 MPa- 950°C) and 43.49 IACS (1.5% GNS-500 MPa- 850°C), respectively.

## 5. References

- 1. M. S. Abd-Elwahed, A. Wagih, I. M. R. Najjar, Ceramics International, 46(1) (2020) 56.
- 2. Y. Q. Qin, Y. C. Wu, X. M. Huang, Y. Wang, J. W. Cui, Y. Hong, Y. C. Zheng, Advanced Materials Research, 1061 (2015) 7.
- B. Huang, Y. Hishinuma, H. Noto, T. Muroga, Fusion Engineering and Design, 140 (2019) 33.
- 4. Ö. Güler, N. Bağcı, Journal of Materials Research and Technology, 9(3) (2020) 6808.
- 5. S. Islak, D. Kır, S. Buytoz, Science of Sintering 46(1) (2014) 15.
- 6. P. Zhang, J. Jie, Y. Gao, H. Li, Z. Cao, T. Wang, T. Li, Materials Science and Engineering: A, 642 (2015) 398.
- 7. Z. Zhang, Y. Sheng, X. Xu, W. Li, Advanced Engineering Materials, 17(9) (2015) 1338.

- M. Darabi, M. Rajabi, B. Junipour, M. T. Noghani, Science of Sintering, 50(4) (2018) 477.
- 9. X. Li, S. Yan, X. Chen, Q. Hong, N. Wang, Journal of Alloys and Compounds, 834 (2020) 155182.
- 10. M. Pul, U. Erdem, Z. O. Pehlivanli, Science of Sintering, 55(1) (2023) 29.
- 11. J. Dutkiewicz, P. Ozga, W. Maziarz, J. Pstruś, B. Kania, P. Bobrowski, J. Stolarska, Materials Science and Engineering: A, 628 (2015) 124.
- 12. W. Li, D. Li, Q. Fu, C. Pan, RSC advances, 5(98) (2015) 80428.
- 13. M. Cao, D. B. Xiong, Z. Tan, G. Ji, B. Amin-Ahmadi, Q. Guo, G. Fan, C. Guo, Z. Li, D. Zhang, Carbon, 117 (2017) 65.
- 14. M. Cao, D. B. Xiong, L. Yang, S. Li, Y. Xie, Q. Guo, Z. Li, H. Adams, J. Gu, T. Fan, X. Zhang, Advanced Functional Materials, 29(17) (2019) 1806792.
- 15. F. Luo, X. Jiang, H. Sun, D. Mo, Y. Zhang, R. Shu, L. Xue, Vacuum, 207 (2023) 111610.
- R. Shi, H. Xie, X. Zhang, D. Zhao, C. Shi, C. He, J. Sha, E. Liu, N. Zhao, Applied Surface Science571 (2022) 151314.
- 17. F. Chen, J. Ying, Y. Wang, S. Du, Z. Liu, Q. Huang, Carbon, 96 (2016) 836.
- 18. K. Chu, C. Jia, Physica Status Solidi A, 211(1) (2014) 184.
- 19. N. Khobragade, T. Maity, A. Świderska-Środa, G. Stanislaw, W. Łojkowski, P. N. Babu, S. Pal, D. Roy, Materials Characterization, 195 (2023) 112524.
- 20. J. F. Li, L. Zhang, J. K. Xiao, K. C. Zhou, Transactions of Nonferrous Metals Society of China, 25(10) (2015) 3354.
- 21. C. Salvo, R. V. Mangalaraja, R. Udayabashkar, M. Lopez, C. Journal of Alloys and Compounds, 777 (2019) 309.
- 22. T. Varol, A. Canakci, Metals and materials international, 21(4) (2015) 704.
- 23. B. W. Wei, D. Qu, C. F. Hu, F. Z. Li, T. L. Zhou, R. J. Xie, Z. M. Zhou, Advanced Materials Research, 833 (2014) 310.
- 24. T. Theivasanthi, M. Alagar, Archives of Physics Research, 1(2) (2010) 112.
- 25. T. Wejrzanowski, M. Grybczuk, M. Chmielewski, K. Pietrzak, K. J. Kurzydlowski, A. Strojny-Nedza, Materials & Design, 99 (2016) 163.
- 26. Y. Zalaoglu, B. Akkurt, M. Oz, G. Yildirim, Journal of Materials Science: Materials in Electronics, 28(17) (2017) 12839.
- 27. B. Akkurt, G. Yildirim, Journal of Materials Science: Materials in Electronics, 27(12) (2016) 13034.
- J. F. Li, L. Zhang, J. K. Xiao, K. C. Zhou, Transactions of Nonferrous Metals Society of China, 25(10) (2015) 3354.
- 29. E. B. Moustafa, M. A. Taha, Applied Physics A, 126(3) (2020) 1.
- P. Hidalgo-Manrique, X. Lei, R. Xu, M. Zhou, I. A. Kinloch, R. J. Young, Journal of Materials Science, 54 (2019) 12236.
- A. Saboori, M. Pavese, C. Badini, P. Fino, Metallurgical and Materials Transactions A, 49(1) (2018) 333.
- 32. M. A. Taha, M. F. Zawrah, Ceramics International, 43(15) (2017) 12698.
- 33. W. D. Callister, Materials science and engineering an introduction, John Wiley. (2007).
- 34. Y. A. Sorkhe, H. Aghajani, A. T. Tabrizi, Materials & Design, 58 (2014) 168.
- 35. E. B. Moustafa, M. A. Taha, Applied Physics A, 126(3) (2020) 1.
- 36. N. J. Grant, A. Lee, M. Lou, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 103 (1984).

*Сажетак:* Ова студија је истраживала механичка и електрична својства композитних материјала бакарне матрице ојачаних графенским нанолистовима.

Композитни материјали су произведени методом металургије праха, са неколико тежинских процента нанолистова графена (0, 0,5, 1 и 1,5) додатих праховима бакарне матрице. Мешани прахови су једносмерно компактирани у челичном калупу на различитим притисцима (500, 600 и 700 MPa) и синтеровани у атмосфери аргона на различитим температурама (850, 900 и 950°С). Надаље, синтеровани узорци су подвргнути анализи микроструктуре, мерењу тврдоће и електричне проводљивости. Резултати су показали да је микроструктура испољила порозност и агломерацију са повећањем количине нанолистова графена, што је резултирало смањењем релативне густине до 87,4%. Највећа електрична проводљивост била је 76,59 IACS (0% GNS-500 MPa-950°С), док је најнижа била 43,49 IACS (1.5% GNS-500 MPa-850°С). Додатак графенских нанолистова је резултирао релативним повећањем тврдоће до 1%. Кључне речи: GNS-Си композити, металургија праха, електрична проводност.

© 2023 Authors. Published by association for ETRAN Society. This article is an open access article distributed under the terms and conditions of the Creative Commons — Attribution 4.0 International license (<u>https://creativecommons.org/licenses/by/4.0/</u>).

