Characterisation of Copper-Chrome-Reduced Graphene Oxide Electrical Contact Materials Using Powder Metallurgy Technique

Aseel S. Hamza1, Abdul Raheem K. Abid Ali¹, Saad Hameed Al Shafaie²
¹College of Materials Engineering, Babylon University, Babylon, Iraq
²Corresponding author: aseeldulamv@yahoo.com

ABSTRACT Copper-chrome alloys are known as contact material alloys with a premium capability for circuit interruption, endurance and erosion resistance and high voltage in a vacuum interrupter. In this research, the alloy fabricated by powder metallurgy mixed Cu, Cr and reduced graphene oxide (rGO). rGO was prepared by electrochemical exfoliation in H₂SO₄ at 11.5v, 0.5pH and dried by exposure to sunlight. rGO was incorporated to characterise the properties. Optical microscopy, X-ray diffraction (XRD), field emission scanning electron microscope (FESEM), energy dispersive analysis (EDS) and Raman spectroscopy were used to determine the identification of phases, morphology, chemical composition and crystal structure orientation of the alloy. Optical microscopy images showed the formation of two distinct areas: a bright area containing Cr-particles and a dark area containing Cu-grains. The XRD patterns exhibited peaks of FCC-Cu, BCC-Cr, Cr₃O₄ and Cr₇C. FESEM revealed the presence of the Cr phase and Cu matrix as well as rGO sheets, while EDS indicated the presence of Cu, Cr, C and O. The Raman peak assessed the degree of rGO disorder in the alloy. The hardest specimen (92 Kg/mm²) was sintered Cu-20%Cr-1%rGO. Electrical resistance exhibited a minimum value of 12.21 μΩ for the sintered Cu-20%Cr-2%rGO alloy and 6.23 μΩ for aged specimens; compressive strength had the highest value (425.235 MPa) for the sintered Cu-20Cr-1.5%rGO alloy.

1. Introduction

Electrical contact is the interface between the members carrying electrical current in electronic devices that ensure the continuity of the electric circuit and the unit containing the interface [1]. The desired properties of the materials used in electrical contact applications depend on the performance required. The perfect material must have high conductivity, be chemically inert, have a large contact area, high wear resistance, low friction and be low in cost for materials and production [2]. Copper is commonly used in industrial applications because of its excellent electrical and thermal conductivity properties as well as good ductility, toughness, corrosion and oxidation resistance [3]. Copper matrix alloys are characterised by good strength, excellent self-lubricating performance and high electrical conductivity [4]. Over the past 50 years, Cu-Cr-based contact alloys have been established for use in medium voltage tools, such as circuit breakers and contactors in a voltage range of 1 kV–75 kV [5]. Generally, Cu-Cr electrode alloys are manufactured by sintering, and Cr particles improve blocking performance due to its role in refining [6]. However, Cu-Cr system alloys contain only two elements and do not form a single solid solution without being highly entropic [7]. Regarding the drawbacks and expansion of the application of copper and its alloys, it is necessary to develop its properties with heat treatment or a fabrication process of composites to produce new composites with high electrical and thermal conductivity and good mechanical properties [8]. The introduction of secondary particles...
as filler, such as graphene in Cu-based alloys, improves their mechanical properties while maintaining good thermal and electrical properties [9]. The graphene–copper alloys exhibit the excellent effect of interfacial bonding and reinforcement [10]. However, many studies focus on the reinforcement of copper composites by a single rGO and determine the effectiveness of the alloying element for the modification of copper–graphene composites [4].

In recent years, an impressive variety of approaches have been developed for the synthesis of Cu-Cr composites. The powder metallurgy technique is a common approach providing a simple pathway for bulk metal-matrix composite production [11]. There are several research papers on Cu-Cr alloys, starting with studies by Mula et al. on Cu-Cr-silicon carbide (SiC) alloys fabricated by a microwave sintering process. The hardest alloy and the best electrical conductivity were ≈2.4 GPa and 60.3% of international annealed copper standard (IACS), respectively, for the alloy of 94% Cu, 6% Cr and 4% SiC sintered at 900 oC. This is perhaps due to the presence of ultra-fine grains, proper bonding between particles and good densification [12]. Gill et al. [13] studied a new Cu-Cr-multiwall carbon nanotube (MWCNT) composite, and the Raman peak assessed the stresses induced and the degree of disorder of MWCNTs in the composite. Transmission electron microscopy (TEM) test indicated oxide and carbide formations, and scanning electron microscopy (SEM) test revealed the existence of MWCNTs. Corrosion resistance was determined by cyclic potentiodynamic polarisation (ASTM F2129-08) in a phosphate buffer saline solution at 37 oC. Imai et al. investigated the properties of a Cu-chromium-vapour-grown carbon fibre (VGCF) alloy manufactured by powder metallurgy and revealed a small decrease in yield strength, while electrical conductivity was higher than that of the Cu-Cr alloy. The Cr concentrated on VGCF using SEM-Energy-dispersive X-ray spectroscopy (EDS) analysis and detected Cr23C6 by TEM analysis [14]. Ozgur et al. studied a Cu-Cr-C alloy manufactured by powder metallurgy. X-ray analysis referred to the formation of Cr-nitride and carbide compounds during sintering and measurements for density increased with an increase of elements [3]. Another study on a Cu-Cr-W-C alloy was conducted by Yanli et al. to examine welding tendencies and the ability to withstand the voltage by adding W and C elements. The force of welding was reduced and arc erosion areas increased [15]. Luo et al. studied a GO/silver-reinforced Cu matrix and demonstrated improvements in thermal and electrical properties compared to pure Cu [16]. Zhang et al [4] studied Cu-Cr-rGO alloy prepared by wet-mixing, mechanical blending and freeze-drying to obtain the Cu/Cr/rGO mixture powders. Spark plasma sintering for solid-phase sintering assist in faster densification of the mixture powders. A layered rGO network and Cr particles distributed in the copper matrix, compressive yield strength and the hardness of the Cu-Cr-rGO alloys were greater than those of pure copper and single rGO-added alloy and increased with increasing Cr. The rGO/Cr hybrid second phases are believed to be beneficial to the strengthening of the copper matrix.

This study prepared the Cu-Cr-rGO alloy using powder metallurgy. The rGO was prepared by the electrochemical exfoliation of graphite in acidic-based H2SO4 electrolyte. The obtained GO solution was ultrasonicated and taken in a petri-dish to dry in the sunlight for a few hours, resulting in the formation of rGO. Sunlight has been used for drying in many studies [17, 18]. Copper, chrome and rGO were mixed, compacted and sintered by powder metallurgy processing; the sintered specimens were aged. The characterisation of alloys was achieved by XRD, EDS, FESEM and Raman analyses and their hardness and electrical resistance properties were studied. Figure 1 displays a diagram of the experimental procedure.
Figure 1 Block diagram of the experimental procedure

2. Materials and Experiment Details

2.1 Materials

In this study, copper, chrome and rGO were used; their properties and proportions are illustrated in Table 1. Cu and Cr were purchased from a trade market. The rGO was synthesised by electrochemical exfoliation in an H$_2$SO$_4$ electrolyte at 0.5 pH and 11.5 volts; it was sonicated and then dried in sunlight.

Table 1 Materials used for the alloys in terms of grain size, source and percentage

| Element | Cu   | Cr   | rGO |
|---------|------|------|-----|
| Particle size | 45 µm | 63 µm | ~100 nm |
| Source   | Korea | Germany | Prepared by electrochemical exfoliation |
| Wt. %    | Wt. % | Wt. %  |
| Base alloy | 80   | 20   | 0   |
| A1       | 79.5 | 20   | 0.5 |
| A2       | 79.5 | 20   | 1   |
| A3       | 78.5 | 20   | 1.5 |
| A4       | 78   | 20   | 2   |
2.2 Experiment details

Powder metallurgy processing was developed for the synthesis of copper-based alloys. The elements were mixed for 4 h according to the ratios in Table 1, then they were pressed at 617 MPa to produce disc samples with a diameter of 14 mm and a thickness of 4 mm. Compacted specimens were sintered in a vacuum by heating them to 400 °C then soaking them 30 min; they were then heated to 850 °C and soaked for 3 h. A heating and cooling rate of 7 °C/min was used in sintering, and the sintered specimens were heat-treated by ageing at 450 °C for 2 h, according to previous studies.

3. Characterisation and Testing

3.1 Microstructure analysis

The identification of microstructures was characterised by light optical microscopy (LOM) and FESEM. LOM with a magnification of 20X in an Olympus microscope was used in the metals department of the Materials Engineering College at Babylon University; the microscope was manufactured in Japan. As seen in Figure 2, the disc samples were wet ground, cleaned with water and dried with hot air. After drying, they were stored in polyethene zip-lock bags with silica gel and polished with a fine diamond and a fine cloth then etched with a solution of 5 gram FeCl$_3$ + 10 ml HCl + 100ml H$_2$O. FESEM investigated the grain size and surface morphology of the powders and sintered specimens and was conducted in the Razi Metallurgy Research Centre in Iran.

![Figure 2 Samples of as-sintered Cu20Cr0.5rGO](image)

3.2 XRD analysis

XRD analysis was performed on the rGO and sintered specimens to confirm the chemical compositions of the materials. This was conducted at the Razi Metallurgy Research Centre in Iran.

3.3 EDS analysis

EDS was conducted at the Razi Metallurgy Research Centre to estimate the chemical composition of the surface of the rGO powder and sintered specimens.

3.4 Raman analysis

The Raman spectrum displays peaks of D and G bands; D was due to structural imperfections created by the attachment of oxygenated groups on the carbon basal plane. Therefore, peak intensity was used as a measure for the degree of disorder. A broad G band, the characteristic of all sp$^2$-hybridised carbon networks, arose from the first-order scattering. Another peak, usually called the 2D peak, was the overtone of the D peak, which reflected the number of graphene layers. It is attributed to double resonance transitions leading to the production of two opposite momentum phonons. This is different
from the D peak, which is active in the presence of defects, while the 2D peak is active in the absence of any defects. Generally, the integrated intensity ratio of ID/IG indicates the degree of oxidation and the size of sp² ring clusters in an sp³/sp² hybrid network of carbon atoms [19].

3.5 Hardness analysis

The Vickers macro-hardness test was used to measure hardness with 500 N load for 15 s [11] using the micro-hardness tool model HVS-1000 in the metallurgical laboratory of the Materials Engineering College at Babylon University. Four readings were recorded for each sample. This test shows the variation in hardness, maybe due to the existence of different materials, pores and agglomeration in the surface of the sample.

3.6 Electrical resistance analysis

Electrical resistance was measured for the sintered and aged specimens using an AT512 Precision Ohmmeter in the Polymeric Materials department of the Materials Engineering College at Babylon University. This is shown in Figure 3.

3.7 Compressive strength analysis

Room temperature compressive strength was characterised for sintered alloys using cylindrical specimens with dimensions of 10 mm diameter and 16 mm height. The alloys were 80%Cu20%Cr with different percentages of reduced graphene oxide (0.5, 1, 1.5 and 2%). The test was conducted in the Ceramic Materials department of the Materials Engineering College at Babylon University and is shown in Figure 4.
4. Results and Discussion

The rGO was prepared by electrochemical exfoliation and added to the Cu-Cr alloy using the powder metallurgy process. Thermal decomposition can occur to the residual oxygen-containing groups on the rGO nano-sheets and may be removed during the sintering operation. This process is associated with the evolution of gases and causes porosity in the sintered body [16]. One possible solution to this problem is to preheat the green compact at lower temperatures (such as 400 °C) before the final sintering at high temperature. There was a general agreement that the reduction process is never complete up to 800 °C. Crucial questions about the mechanism of binding and growth of the elements also remain open, and the interaction between rGO and the metal remains uncertain. The elements may be non-covalently bound or may have formed metal–C bond. Metal–O–C bonds can also form from the residual oxygen of rGO [20].

4.1 XRD results

XRD analysis exhibited diffraction peaks in the rGO powders and alloys. Diffraction peaks for rGO were absent in the XRD analysis of alloys and were attributed to the total content of the carbon phase below the sensitivity limit [21], as shown in Figure 5. XRD analysis of the exfoliated graphite powders showed peaks at 2θ≈90 and 2θ≈24.5, similar to the peaks of rGO [22]. Figures 6–9 exhibit the XRD patterns of as-sintered specimens. Figure 6 shows peaks of the XRD pattern of the sintered Cu-Cr specimen, and its intensity refers to the ratio of the elements, exhibiting peaks of (111), (200), (220), (311) and (222) and planes at 2θ = 43.25, 50.5, 74 and 90 for FCC-Cu. For BCC-Cr, peaks were exhibited at [110], [200], [211], [220] and [310] and planes at 2θ = 44.5, 64.5, 81.75 and 98 in the agreed XRD plot [12]. The peaks of Cr in the as-sintered Cu-20%Cr-1%rGO and Cu-20%Cr-2%rGO materials in Figures 7 and 9 have slightly less intensity compared to the Cr peaks of the as-sintered Cu-20%Cr and Cu-20%Cr-1.5%rGO specimens in Figures 6 and 8. This is related to the carbide compounds formed due to the coupling of Cr with carbon during sintering treatment and the formation of carbides (Cr2C) at peaks mentioned previously and confirmed in [24]. The XRD peaks were identical to specific 2θ values for carbides that formed under conditions of 810 °C for 3 h that approach the conditions of the sintering process used in the current study (850 °C for 3 h) [25].

Chromium carbides observed on the as-sintered Cu-20%Cr-1%rGO and Cu-20%Cr-2%rGO specimens at peaks 2θ = 67.25, 75.5, 81.75 and 83°, as shown in Figure 7 and fewer quantities in Figure 9, disappeared for the Cu-20%Cr-1.5%rGO alloy in Figure 8. The defect nature of rGO led to the formation of carbide. Chu et al. obtained a good dispersion of graphene sheets in Cu matrix powder [16]. On the other hand, chromium oxide (Cr2O3) was confirmed under XRD spectral analysis at 2θ =24.5, 33.75, 36.25 and 54.75, due to the partial oxidation of the metallic components of samples containing high Cr; this agrees with [12, 3]. The absence of any components between Cu and C was widely agreed upon [26], but there is binding between Cu and residual functional groups of rGO layers, as shown in Figure 18. The diffraction patterns of the composites do not show any effect of graphene, which might be attributed to the small volume fraction and low scattering length of the carbon atom [27].
Figure 5 XRD of an as-received rGO powder

Figure 6 XRD of copper-based alloy (Cu-20%Cr)

Figure 7 XRD of sintered alloy (Cu-20%Cr-1%rGO)

Figure 8 XRD of sintered alloy (Cu-20%Cr-1.5%rGO)

Figure 9 XRD of sintered alloy (Cu-20%Cr-2%rGO)
Copper oxides did not appear in XRD analysis but were observed in Raman analysis. It was expected that residual graphene oxide may be reduced to rGO during the drying process of the graphene liquid and sintering processes at elevated temperatures as well as forming CuO and Cu₂O oxides [21]. The oxides have interfacial interactions with carboxyl or hydroxyl groups by chemisorption, and the bridge formed at oxygen-defect sites and van der Waals interactions between metal oxides and the pristine region of graphene was agreed upon [28].

4.2 Microstructure characterisation results

4.2.1 LOM results

Figure 10 shows the microstructure of as-sintered specimens; the unetched surface is illustrated in Figure 10 and the etched specimen is shown in Figure 11. The microstructure of the alloy shows the formation of two distinct areas with different morphologies: the bright area refers to the number of fine Cr-particles observed beside a few larger Cr-particles, which are elongated, and the dark area contains Cu-grains. The areas formed in this study are confirmed in [29].

4.2.2 FESEM results

Figures 12 and 13 demonstrate FESEM for copper particles and layers of rGO, respectively. Figures 14 and 15 show the microstructure of the as-sintered base and Cu-20%Cr-0.5%rGO alloy, respectively, in which the microstructure of the base alloy can be observed in Figure 14. It exhibits a Cu matrix (bold zone) and Cr phase (bright zone) with several Cr particles spread in a line-like shape in interdendritic and grain boundary positions; these were confirmed in [30]. Alteration of the microstructures was achieved in the Cu-Cr-rGO alloys after adding different percentages of rGO. Figure 15 shows important variations in the microstructure, which seems to be surrounding the Cr zone in graphene layers, and the grains become equiaxed after sintering treatment. Gr-sheet distribution into the metal matrix and along the grain boundaries assist the suppression of the grain growth of the copper due to high temperature, which is confirmed by [20].
Figure 16 shows a semi-coherent interface between the matrix and rGO, as well as an agglomeration of graphene oxide layers that can be seen clearly in Figure 17 due to the high activity of rGO layers. Multilayered rGO sheets were found and fixed in the matrix in thicknesses ranging from 50–125 nm; these work as lubricants under states of adhesive wear. Figure 18 exhibits binding between the matrix Cu and rGO layers after mixing.
4.3 EDS results

Figures 19 and 20 present the EDS analysis percentage of Cu, Cr, C and O as well as giving an indication of the formation of interfacial products, which asserts that reaction occurred between the elements during the preparation operation. rGO was induced into the matrix and because of the low solubility of carbon in copper, only mechanical bonding between the two phases occurred [31], but binding did occur with Cu and the functional groups in rGO layers [32], as seen in Figure 18.

![Figure 19](image1.jpg) EDS of Cu-Cr-1.5rGO alloy

![Figure 20](image2.jpg) EDS of Cu-Cr-2rGO alloy

4.4 Raman results

Figures 21 and 22 show D, G and 2D peak intensities versus the Raman shift for rGO powder and sintered alloy, respectively. rGO bears too many defects so its Raman spectroscopy is not sensitive [20]. Indeed, the ratio of intensities of D and G peaks change after mixing and sintering processes. The D peak intensity depends on the stress/strain defects at the grain interfaces of the multiphase material [21]. The position of the G peak increases and both the intensity of D and the ID/IG ratio decreases, all of which are expected consequences of greater graphitisation following reduction [33]. The sites for Raman peaks of D, G and 2D were 1,361 cm⁻¹, 1,598 cm⁻¹ and 2D=2,700–2,925 cm⁻¹; as-received rGO shifted to 1,388 cm⁻¹, 1,605 cm⁻¹ and 2D=2,800–2,950 cm⁻¹ of as-sintered alloy; this shift was small and referred to the strain formed [21]. The ratio of ID/IG (R) for rGO powder was 0.88, while the as-sintered specimen was 0.74. Prominent peaks of the Raman analysis were observed at 160, 450, 515 and 620 cm⁻¹. This may be corresponding to signals of copper oxides that agreed with results in [34].
Figure 21 Raman spectrums of the as-received rGO

Figure 22 Raman spectrums of the as-sintered Cu-Cr-rGO alloy

4.5 Hardness results

Figure 23 shows the surface micro-hardness values of as-sintered alloys that exhibited fluctuating variations. As noted, the hardness increased with the increase of rGO up to 1%, decreased at 1.5% and then increased at 2%. These results maybe because of the development of microstructures during the sintering process. For the Cu-20%Cr-1%rGO specimen, the increase in hardness may be due to the substantial hardening of Cr/rGO hybrids in the Cu matrix and the formation of carbides as shown in XRD analysis [4]. The Cu-20Cr-1.5%rGO specimen exhibited a decrease in hardness because carbides did not form in the alloy, leading to the segregation of a large number of graphene sheets at grain boundaries, less cohesion of the elements within the matrix, porosity and weak points in the Cu/Cr/rGO binding; it is not clear why carbides did not form [9]. The Cu-20Cr-2%rGO specimen exhibited increases in hardness due to the formation of chromium carbides (Cr2C) during the sintering process that led to good cohesion and wettability of the elements within the matrix; chromium atoms contained in the Cu matrix also reacted with rGO resulting in strong bonding. In this study, Cr produced oxides and carbides in conjunction with the oxidation/reduction process during sintering; these materials are hard and were detected by XRD and EDS analyses; this agreed with [3].


4.6 Electrical resistance results

Figure 2 shows the electrical resistance values of the sintered and aged alloys at 450 °C for 2 h. As noted, non-uniformity altered in resistance with an increase in rGO, but the values for as-aged samples were less than that estimated for the as-sintered samples. Electrical resistance changed with a fluctuating variation of as-sintered and aged alloys. The sintered Cu-20Cr-0.5%rGO specimen had a higher electrical resistance than that of the base alloy, which may be due to an increase in grain boundaries that decreases the electrical current. However, the electrical resistance decreased for the sintered Cu-20Cr-1%rGO specimen, which may be due to the formation of high oxides and carbides that led to an increase in wettability. Furthermore, the bonding between the matrix and added elements affected the electricity passing through the Cu-Cr matrix. Sintered specimens containing Cu-20Cr-2%GO had lower electrical resistance (12.21 µΩ) for as-sintered specimens than for as-aged specimens (6.23 µΩ). This may be due to the reaction between Cr and C in the rGO during the sintering process and the formation of carbides (Cr2C). Carbides increased the wettability and binding between the elements, which allowed electricity to easily pass through the Cu-Cr matrix. Cr decreased in the matrix and translated to chromium carbides, which have lower resistance [14]. Electrical resistance was measured for the aged samples and showed lower values than those measured in the as-sintered samples, meaning that the ageing treatment reduced the electrical resistance property. This behaviour can be explained by lowering the concentration of elements inside the grains due to their migration to grain boundaries during the ageing treatment [35]. This may also be due to long-range ordering and reduced point defects [36]. Partial reduction for GO may occur and measurements of electrical resistivity have been used to prove the complete reduction of graphene oxide [21].

![Figure 23 Micro-hardness of as-sintered Cu-Cr-rGO alloy](image-url)
Figure 24 Electrical resistance of as-sintered and aged Cu-Cr-rGO specimens

4.7 Compressive strength results

Figure 25 shows the compressive strength values of the sintered alloys. As noted, non-uniformity alteration in compressive strength increased with rGO. The sintered Cu-20Cr-0.5%rGO specimen had lower compressive strength than that for the base alloy, which may be due to the increase of pores and cracks formed during powder metallurgy processing; these form and fracture under compressive loading. The slightly increased compressive strength of the sintered Cu-20Cr-1%rGO specimen maybe because of the formation of oxides and carbides, which lead to increased wettability and bonding between the matrix and added elements; greater compressive strengths means fewer pores and cracks. The Cu-20Cr-1.5%rGO sintered specimen had increased compressive strength and had the highest value; this may be due to the remarkable reinforcement effect of graphene in the composite, which derives from its micro-layered structure that enhances the dispersion of graphene and prevents slippage between graphene flakes. The Cu-20Cr-2%rGO alloy observed a decrease in compressive strength; incorporating a high graphene and chrome content in the Cu matrix may have overstrained the lattice of copper atoms. Furthermore, the segregation and agglomeration of graphene particles could have disintegrated under pressure, leading to the formation of pores, and brittle fracturing as well as presence brittle carbides. There could also have been a mismatch between the constituents that increased the dislocation densities, leading to brittle fractures.

Figure 25 Compressive strength of as-sintered Cu20-Cr and Cu-20%Cr-x%rGO specimens (x=0.5, 1, 1.5 and 2%)
5. Conclusion

In summary, rGO was prepared by electrochemical exfoliation and added to Cu-Cr alloys by powder metallurgy to fabricate a Cu-Cr-rGO alloy. These materials play a significant role in the formation of chemical components, which has an important effect on the properties of the composites. The results of XRD, FESEM, EDS, Raman analyses, hardness, electrical resistance and compressive strength tests were obtained for the Cu-Cr-rGO alloys. The remarkable reinforced effect of rGO in the alloys was derived from the structure of the components formed during the sintering process, which enhances the uniform dispersion of graphene layers. The results of the study on the effect of rGO on the properties were:

- XRD, FESEM and Raman analyses approved the formation of rGO by electrochemical exfoliation; FESEM and Raman analyses also demonstrated the dispersion of rGO sheets in the Cu-Cr-based alloy.
- Hardness showed fluctuating values; the hardest material was the as-sintered Cu-20Cr-1%rGO specimen at 92 Kg/mm².
- Electrical resistance exhibited a lower value for the Cu-20%Cr-2%rGO as-sintered alloy (12.21 µΩ) than for the as-aged specimen (6.23 µΩ).
- Compressive strength increased with an increase of rGO up to 1.5%. This may be due to the graphene-reinforced composite that enhances the dispersion of graphene and prevents slipping between graphene flakes. Compressive strength decreased at 2%rGO due to copper atoms overstraining the lattice as well as the segregation and agglomeration of graphene particles that disintegrated under pressure. There was also a mismatch between the constituents that increased the dislocation density and led to brittle fractures. The sintered Cu-20Cr-1.5%rGO alloy displayed the highest compressive strength (425.235 MPa).

References

[1] Braunovic, M., Konchits, V.V., and Myshkin, N.K. (2006) "Electrical Contacts: Fundamentals, Applications and Technology" Taylor and Francis Group.

[2] Andre, B. (2011) "Nanocomposites for use in sliding electrical contacts" A doctoral dissertation from the faculty of science and technology, Uppsala University 879.

[3] Ozgün, O. and Ercetin, A. (2017) "Microstructural and mechanical properties of Cr-Cr reinforced Cu matrix composites produced through powder metallurgy method ", J. Nat. Sci., Vol. 6 No. 2.

[4] Zhang, X. J., Dai, Z. K., Liu, X. R., Yang, W. C., He, M. and Yang, Z. R. (2018) "Microstructural Characteristics and Mechanical Behavior of Spark Plasma-Sintered Cu–Cr–rGO Copper Matrix Composites" Germany, Acta Metall. Sin., Vol. 31, Issue 7, pp. 761-770.

[5] Gothkindikar, N.N., Vanjari, S.V. and Nigade, D. B. (2018) "Development of Copper-Chromium electrical contact materials by Powder Forging" India, I.J.A.R.S.E., Vol 7, special No.03.

[6] Kimura, W., Kume, Y., Kobashi, M., Kanetake, N. (2014) "Consolidation of Cr-Cu/Cu powder laminated material by compressive torsion processing " in 11th International Conference on Technology of Plasticity, Procedia Engineering 81, pp. 1169 –74.

[7] Gershman, I.S., Gershman, E. I., Mironov, A. E., Rabinovich, G. S. F. and Veldhuis, S. C. (2017)"On Increased Arc Endurance of the Cu-Cr System Materials", journal of Entropy,19, pp.386.
[8] Saboori, A., Moheimani, S. K., Pavese, M., Badini, C. and Fino, P. (2017) “New Nanocomposite Materials with Improved Mechanical Strength and Tailored Coefficient of Thermal Expansion for Electro-Packaging Applications”, J. Met., 7,536.

[9] Manrique, P. H., Lei, X., Xu, R., Zhou, M., Kinloch, I. A. and Young, R. J. (2019) "Copper/graphene composites: a review " Berlin, Germany, Journal of Mat. Sci., 54, pp. 12236–89.

[10] Sun, L. and Fugetsu, B. (2013) "Massive production of graphene oxide from expanded graphite " Japan, J. Mater. Sci. Lett., Volume 109, pp. 207-210.

[11] Konakov, V.G., Kurapova, O.Y., Solovyeva, E.N., Lomakin, I.V. and Archakov, I.Y. (2018) "Synthesis, Structure and Mechanical Properties of Bulk Copper-Graphene Composites" Russia, Adv. Mater. Sci. Eng., 57 ,pp.151-157.

[12] Mula, S., Sahani, P., Pratihar, S.K., Mala, S., Koche, C. C. (2011 ) "Mechanical properties and electrical conductivity of Cu–Cr and Cu–Cr–4% SiC nanocomposites for thermo-electric applications " Mater. Sci. Eng. A 528, pp. 4348–56.

[13] P. Gill and N. Munroe (2012) "Study of Carbon Nanotubes in Cu-Cr Metal Matrix Composites" J. Mater. Eng. Perform., 21, pp.2467–71.

[14] Imaï, H., Chen, K. Y., Kondoh, K., Tsai, H.Y. and Umeda, J. (2015) "Effect of Chromium Behavior on Mechanical and Electrical Properties of P/M Copper-Chromium Alloy Dispersed with VGCF" I.J.M.M.E. , Vol 9, No:7.

[15] Y. Chang, W. Zheng, Z. Zhou, Y. Zhai and Y. Wang (2016) "Preparation and Performance of Cu-Cr Contact Materials for Vacuum Switches with Low Contact Pressure" J. Electron. Mater., volume 45, pp. 5647–54.

[16] Ji, X., Qi, S., Ahmed, R. and Rifat, A. A. (2019) "Graphene-Reinforced Advanced Composite Materials" in Ozkan, C. (ed.) Handbook of Graphene, River Street, Hoboken, USA, Volume 4, pp. 27–90.

[17] Kumar, P., Subrahmanyam, K. S., Rao, C. N. R. (2011) "Graphene produced by radiation-induced reduction of graphene oxide", Int. J. Nanosci., vol. 10, issue 4 and 5, pp. 559-566.

[18] Hou, W. C., Chowdhury, I., Goodwin, D. G., Jr., Henderson, W. M., Fairbrother, D. H., Bouchard, D., and Zepp, R. G. (2015) "Photochemical Transformation of Graphene Oxide in Sunlight" Environ. Sci. Technol., 49, pp.3435–43.

[19] Zhao, J., Liu, L. and Li, F. (2015) "Graphene Oxide: Physics and Applications" Springer .

[20] Dimiev, A. M. and Eigler, S. (2017) "Graphene Oxide Fundamentals and Applications" Wiley , United Kingdom.

[21] Konakov, V. G., Archakov, I. Y. and Kurapova, O. Y. (2019) "Fabrication and Properties of Copper–Graphene Composites" in Ozkan, C. (ed.) Handbook of Graphene , River Street, Hoboken, USA, Volume 4, pp. 285–322.

[22] Thema, F. T., Moloto, M.J., Dikio, E.D., Nyangiwe, N.N., kotsedi, L., Maaza, M. and khenfouch, M. (2013) "Synthesis and Characterization of Graphene Thin Films by Chemical Reduction of Exfoliated and Intercalated Graphite Oxide", J. Chem. .

[23] Olofinjana, A.O, A. and Tan, K. S. (2010) "Processing of Cu-Cr alloy for combined high strength and high conductivity" A.J.S.T.D., Vol. 26 Issue 2 pp. 11-20.
[24] Schmuecker, S. M., Clouser, D., Kraus, T. J. and Leonard, B. M. (2017) "Synthesis of Metastable Chromium Carbide Nanomaterials and their Electrocatalytic Activity for the Hydrogen Evolution Reaction", *The Royal Society of Chemistry*, 46, pp. 13524–30.

[25] Anderson, K. R. and Groza, J. R. (2001) "Microstructural Size Effects in High-Strength High-Conductivity Cu-Cr-Nb Alloys", *Metallurgical and Materials Transactions-A*, Volume 32A, pp. 1211–24.

[26] Alam, S.N., Kumar, L. and Sharma, N. (2015) "Development of Cu-Exfoliated Graphite Nanoplatelets (xGnP) Metal Matrix Composite by Powder Metallurgy Route", *Graphene*, 4, pp. 91-111.

[27] Khobragade, N., Sikdar, K., Kumar, B., Bera, S. and Roy, D. (2019) "Mechanical and electrical properties of copper-graphene nanocomposite fabricated by high pressure torsion", *J. Alloys Compd.*, 776, pp. 123-132.

[28] Ahmad, M. and Naz, S. (2019) "Graphene-Based Composite Nanostructures: Synthesis, Properties, and Applications" in Ozkan, C. (ed.) Handbook of Graphene, River Street, Hoboken, USA, Volume 4, pp. 203–232.

[29] Hauf, U., Kauffmann, A., Weiss S. K., Feilbach, A., Boening, M., Mueller, F. E. H., Hinrichsen, V. and Heilmayer, M. (2017) "Microstructure Formation and Resistivity Change in Cu-Cr during Rapid Solidification", *J. Met.*, 7, pp. 478.

[30] Zhang, P., Jie, J., Li, H., Wang, T. and Li, T. (2015) "Microstructure and properties of TiB2 particles reinforced Cu–Cr matrix composite" New York, *J. Mater. Sci.*, 50, pp. 3320–28.

[31] Ayyappadas, C., Muthuchamy, A., Annamalai, A. Raja and Agrawal D. K. (2017) "An investigation on the effect of sintering mode on various properties of copper-graphene metal matrix composite" *Journal of Advanced Powder Technology* 28, pp.1760–68.

[32] Wang, L., Yang, Z., Cui, Y., Wei, B., Xu, S., Sheng, J. and Wang, M., Zhu, Y. and Fei, W. (2017) "Graphene-copper composite with micro-layered grains and ultrahigh strength" *Scientific Reports*, 7, Article number, 41896.

[33] King, A. A. K., Davies, B. R., Noorbehesht, N., Newman, P., Church, T. L., Harris, A. T., Razal, J. M. and Minett, A. I. (2016) "A New Raman Metric for the Characterisation of Graphene oxide and its Derivatives" *Scientific Reports*, 6, Article number: 19491.

[34] Boukhvalov, D. W., Kurmaev, E. Z., Urbańczyk, E., Dercz, G., Stolarczyk, A., Simka, W., Kukharenko, A. I., Zhidkov, I. S., Slesarev, A. I., Zatsepin, A. F. and Cholakh, S. O. (2018) "Atomic and electronic structure of graphene oxide/Cu interface" *Thin Solid Films* Volume 665, pp. 99-108.

[35] Islamgaliev, R. K., Nesterov, K. M., Bourgon, J., Valiev, R. Z. and Champion, Y. (2014) "Nanostructured Cu-Cr alloy with high strength and electrical conductivity" Russia, *J. Appl. Phys.* 115, 194301.

[36] Huuqing, L., Shuisheng, X., Pengyue, W., and Xujun, M. (2007) "Study on improvement of conductivity of Cu-Cr-Zr alloys" China, *Journal of Rare Metals*, Volume 26, Issue 2, pp. 124-130.