Advanced Graphite/Metal Composite Materials for High Voltage Automotive Applications

Radu Mirea
Romanian Research and Development Institute for Gas Turbines COMOTI, Romania
radu.mirea@comoti.ro (corresponding author)

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ABSTRACT

This study presents the development and characterization of four graphite-based/metal composite materials suitable for high-voltage applications in the automotive industry, specifically for use as current collector materials in trolleybuses. The composites were processed utilizing different combinations of graphite types (granulated natural graphite, natural graphite flakes, and graphite chemically coated with copper), binders (coal tar pitch and commercial resin Novolac), and metallic additives (electrolytic Cu powder, Sn powder, and MoS_2). The structural, mechanical, and functional properties of the four composite materials were investigated. The composites exhibited similar hardness values, but their coefficients of friction differed due to variations in chemical composition and processing methods. In terms of mechano-electrical wear, despite their similar hardness and mechanical strength, the materials exhibited different wear patterns based on their electrical conductivity and voltage drop. The novelty of this study lies in the introduction of a new technological process for obtaining carbon/metal composite materials used in the manufacture of sliding contacts for current collector heads. The suggested materials are anticipated to reduce the wear on the electrical wire, thereby lowering maintenance expenses. The most suitable material was selected for further development by the end beneficiary.

Keywords-graphite; carbon-metal composites; high voltage; pitch

I. INTRODUCTION

Addressing climate change and its effects is a pressing concern for nations worldwide. The transportation industry, which contributes approximately 20% of global carbon dioxide emissions, remains a key target for reducing carbon output. Although the COVID-19 pandemic led to a substantial decrease in worldwide emissions, the transportation sector still generated nearly seven gigatons of carbon emissions in 2020. As economies recover, the demand for transportation is anticipated to grow, potentially leading to increased emissions if no action is taken [1].

Emphasizing public transportation over individual car use is essential for decreasing CO_2 emissions in the transportation sector. Allocating resources to high-quality, low-emission public transit systems enhances equality by providing access, particularly to those unable to afford private vehicles, and has positive implications for safety. Public transportation users have the lowest per-person emissions among motorized modes of travel, but they are exposed to higher levels of air pollution. Transitioning from public transportation to electric power, especially in developing nations, is a top priority [1].

In the United States and Canada, the significance of public transportation in sustainability and equity has garnered increased attention, with the electrification of buses serving as a crucial component for achieving energy transformation and equity objectives [2]. The European Union is also demonstrating substantial progress, with the Netherlands being at the forefront of electric bus adoption and other nations such as Luxembourg, Sweden, and Germany following suit under the auspices of the European Green Deal, which aims to have reduced net greenhouse gas emissions by a minimum of 55% by 2030 [3]. Despite the significant growth in the electrification of public transport evidenced in the EU and US over the past decade, further efforts are required to fully transition from diesel-powered buses and rail networks to electric alternatives [3].

European capitals possess extensive bus and tram networks and trolleybuses, which derive power from dual overhead wires. Initial trolley shoes manufactured from cast iron proved inadequate due to their abrasive nature, necessitating the development of carbon/metal composites. These composites exhibit mechanical and electrical properties comparable to those of copper while demonstrating enhanced mechanical characteristics [4, 5].

Carbon/metal composites are utilized in diverse industrial sectors, including high-voltage capacitors [6], and offer advantages, such as reduced mass, resistance to corrosion, and design flexibility in high-voltage applications [7]. In the automotive industry, these composites exhibit superior strength and hardness, are cost-effective, and can be subjected to heat treatment for various applications [8, 9].

The experiments conducted in this research aimed at the technological processing of electro-graphitic materials to obtain carbon/metal composite materials that can be used as current collectors for trolleybuses. The properties of the suitable material must be aligned with the specifications required for a semi-finished product, which is necessary for manufacturing products deployed in the operation of traction motors and public transport vehicles.

The novelty of this study lies in introducing an innovative technological process for creating carbon/metal composite materials employed in manufacturing sliding contacts for current collector heads. In addition, it presents the characteristics of the newly developed materials.

II. MATERIALS AND METHODS

Four different composite materials were developed for the sliding contacts. The four materials were evaluated experimentally and their suitability for the intended application was assessed using various testing methods. The first two composite materials contained coal tar pitch as a binder, but differed in the type of graphite included, which acted as a lubricant. The composite named Copper-Graphite-Novolac (GNS) contained granulated natural graphite, whereas the other, named CFS, contained natural graphite flakes. The third composite, CGN, entailed a phenol-formaldehyde resin (commercially known as Novolac) as a binder and granulated graphite. Finally, the fourth material involved Novolac as a binder and graphite chemically coated with copper.

A. Composite Material 1: GNS

The composite GNS was obtained by mechanically mixing natural granulated graphite, electrolytic Cu powder, Sn powder, and MoS_2, with coal tar pitch to bind the mixture. The bonding between the carbon particles and metallic particles was achieved utilizing a carbon binder (coal tar pitch). Table I lists the materials used for the CNS production.

TABLE I. MATERIALS INCLUDED IN CNS

Raw material	Quantity [%]
Granulated natural graphite (>100 μm)	18
Electrolytic copper powder	60
Sn powder	7
Molybdenum disulfide (MoS_2)	5
Coal tar pitch	10

B. Composite Material 2: CFS

The CFS composite was similar to GNS, except that graphite flakes were used as the carbon source, as shown in Table II.

TABLE II. MATERIALS INCLUDED IN CFS

Raw material	Quantity [%]
Flake natural graphite	18
Electrolytic copper powder	60
Sn powder	7
Molybdenum disulfide (MoS_2)	5
Coal tar pitch	10

Figure 1 depicts a flow chart describing the process for obtaining the composite materials, CNS and CFS.

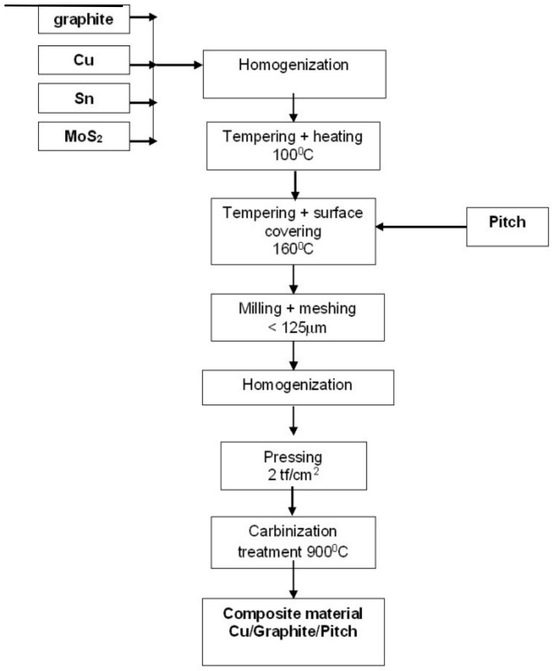

Fig. 1. Flowchart of CNS and CFS production.

C. Composite Material 3: CGN

An isotropic structure composite was developed in which the bond between the carbon particles and metallic particles was achieved through the organic binder Novolac. The powder mixture was coated with a binder to achieve improved compactness and structural uniformity. Table III lists the raw materials that were mixed to produce CGN. For cross-linking the binder, 5% of HMTA (hexamethylenetetramine), relative/relevant to the Novolac, was added.

Figure 2 illustrates the detailed steps for producing the CGN composite material. Compared to CNS/CFS, the CGN manufacturing requires fewer heating steps and lower temperatures.

TABLE III. MATERIALS INCLUDED IN CGN

Raw material	Quantity [%]
Granulated natural graphite (>100 μm)	15
Electrolytic copper powder	60
Sn powder	7
Novolac (which includes 5% HMTA)	18

D. Composite Material 4: Copper-plated Graphite Powder (CGA)

This composite was obtained using graphite chemically coated with copper and the organic binder Novolac. In this composite, the bonding of the graphite particles with Cu is physical in nature. The addition of the binder aimed to densify and increase the hardness without the metal forming a continuous network.

The method followed for chemically plating graphite with copper involves a series of steps, which are presented in Figure 3. The Cu ions were reduced according to the following reactions, resulting in metallic Cu that was bonded with graphite. Bonding was realized by the π electrons of graphite, which allowed the formation of a metallic layer on the surface:

$$2Cu^{2+} \xrightarrow{\text{reduction}} 2Cu^{+}$$

$$2Cu^{+} \rightarrow Cu^{2+} + Cu^{0}$$

The obtained Cu-plated graphite was then used for the formation of the CGA composite material, as displayed in the flowchart in Figure 4.

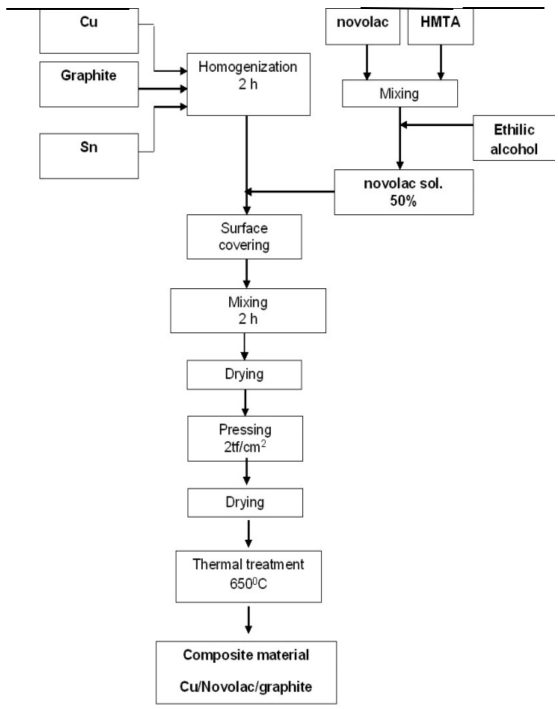

Fig. 2. Flowchart of CGN production.

III. RESULTS AND DISCUSSION

All the obtained composite materials were characterized from structural and mechanical points of view, and the results are presented below.

The initial density (before thermal treatment) of the composite mixture and the final density (after thermal treatment) of the composites were determined. In addition, the hardness and mechanical stress were evaluated. Finally, the electrical resistivity of the composite materials was estimated. The results are exhibited in Table IV.

The density of the materials was calculated by their dimensions and weight, which was measured with an electronic balance provided by Kern (model ALT 220-4NM). The electrical resistivity was measured using an M9115 Electrical Resistivity System provided by Grace Instruments. The HB hardness was measured using an EMCO-Test M4C025G3M apparatus. From a structural point of view, the obtained materials were analyzed under an optical microscope at 50x magnification. The microscope was provided by AXIO fitted with a Lumix camera.

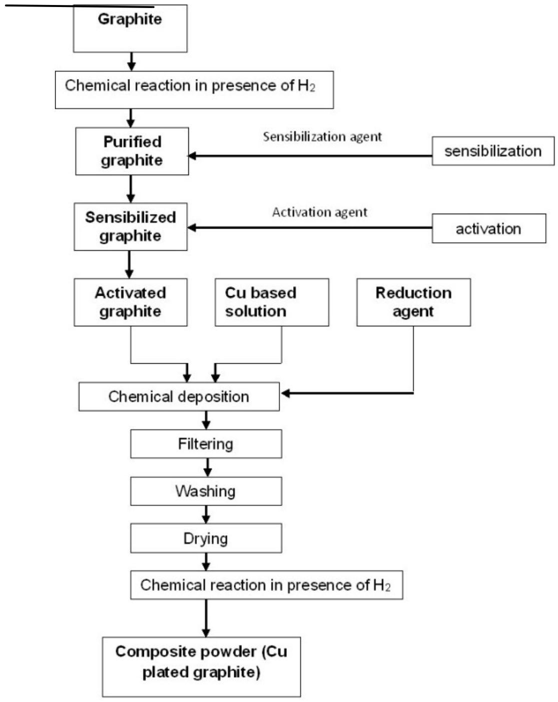

Fig. 3. Flowchart for obtaining Cu-plated graphite.

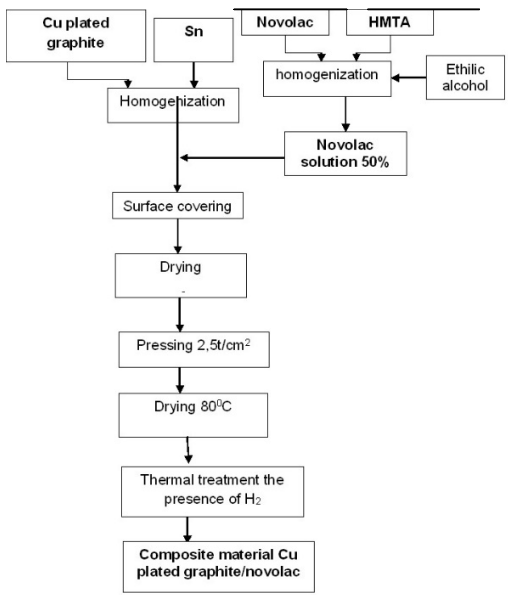

Fig. 4. Flow chart of CGA production.

TABLE IV. CHARACTERISTICS OF THE COMPOSITES

Material	Initial density (g/cm^3)	Final density (g/cm^3)	Electrical resistivity (μΩm)	Hardness HB10/40 (kgf/mm^2)	Mechanical strength (MPa)
CNS	3.4	3.6	157	107.6	32.7
CFS	3.4	3.6	151	100	30.5
CGN	3.0	3.2	100	93	25
CGA	3.6	3.7	7.5	99	38

According to Table IV, the density increased after the thermal treatment, with GCA showing the highest value. Moreover, CGA demonstrated the highest mechanical strength (38 MPa) and lowest electrical resistivity (7.5μΩm). Thus, CGA is stronger, denser, and more conductive than the other materials, allowing electric current to pass with less resistance and causing less heating.

As evidenced in Figure 5, all materials displayed high homogenization and structural integrity. Moreover, after the thermal treatment, no visible pores were observed within the structure of the material.

Functional characterization was performed to determine the electric discharge at both the working and maximum imposed currents, friction coefficient, and mechanical wear after 1000 h of work. The setup shown in Figure 6 includes an array of equipment that measures the electrical parameters. The used equipment ensured equivalent force and conditions to those applied in a real trolleybus. Furthermore, a copper wire similar to those used for trolleybus lines was continuously moved for 1000 h while the above-mentioned apparatus was applying the force.

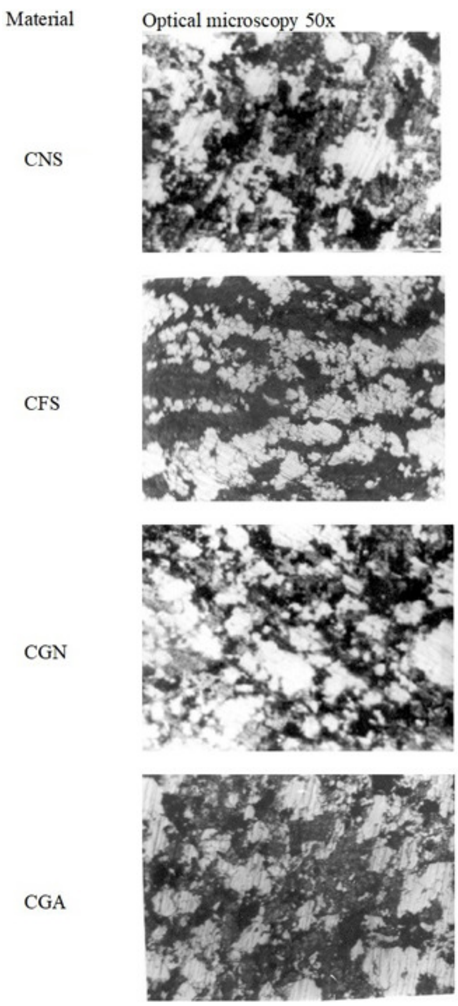

Fig. 5. Optical images of the four composite materials.

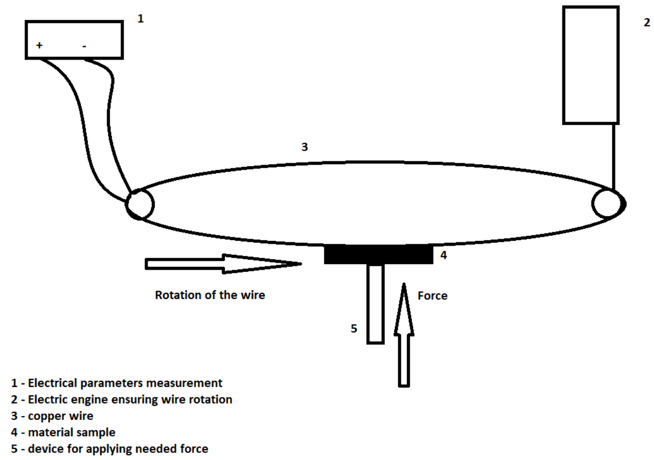

Fig. 6. Schematic of the functional characterization setup.

Table V showcases the electric discharge and applied electric load for all the composite materials. The CGN composite material exhibited the lowest electric discharge. However, the graphite-based materials, CNS and CFS, demonstrated higher values.

TABLE V. ELECTRIC DISCHARGE AND ELECTRIC LOAD

Material	Electric load (min/max) J (A/cm^2)	Electric discharge 2Ue (V)
CNS	25	2
	50	3.20
CFS	25	3.40
	50	5.03
CGN	25	1.2
	50	1.93
CGA	25	1.2
	50	2.04

Table VI depicts the friction coefficient and mechanical wear after 1000 hours of work. The materials were tested under controlled conditions using a new trolleybus wire, and the speed of the trolleybus was kept constant at 60 km/h.

TABLE VI. FRICTION COEFFICIENT AND MECHANICAL WEAR AFTER 1000 HOURS OF WORK.

Material	Friction coefficient at 60 km/h (μ)	Mechanical wear (mm)
CNS	0.11	23
CFS	0.05	38
CGN	0.27	13
CGA	0.3	26

As expected, the graphite-based materials, CNS and CFS, displayed lower friction coefficients but higher wear owing to their lower mechanical strength. Interestingly, CGN demonstrated the lowest mechanical wear, even though its friction coefficient was several times higher than that of the graphite-based materials.

Other researchers have focused on alloying copper with either Al-Sn/Si and/or Pb and then inserting the alloy within the material of the sliding contact [10]. Even though the obtained materials showed similar hardness to the one studied in this paper, the testing of the materials was performed only for 27 km, and no discharge testing was carried out.

A comparison of the HB wicker hardness between the composite materials studied in the current paper and in the literature is illustrated in Figure 7.

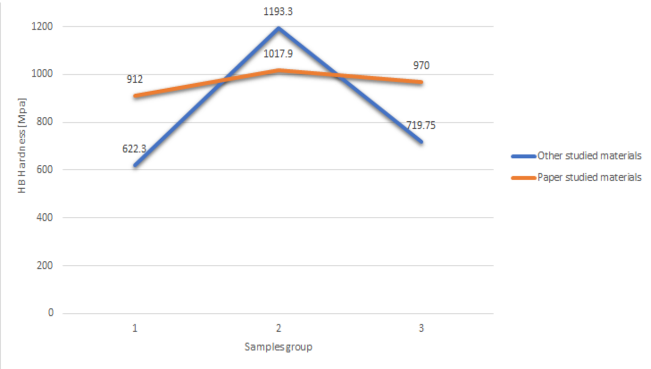

Fig. 7. Comparison of hardness with other studied materials.

Figure 7 shows that the HB hardness of the materials examined in this study exhibited greater consistency, ranging from 912 to 1017 MPa. In contrast, the values reported in other studies demonstrated a broader range, extending from 622 to 1193 MPa.

As previously stated, although other investigated materials from the literature exhibit superior mechanical properties, they have not been subjected to testing over such extended distances, and as demonstrated in [10], they have already experienced mechanical wear. In contrast, the materials examined in this study displayed mechanical wear ranging from 13 to 38 mm after 1000 h of operation.

At present, the commonly employed sliding contacts are typically made of cast iron, which offers high mechanical and wear resistance. However, during electrical discharge, these contacts generate small iron particles that gradually cause mechanical wear on the copper wire, resulting in expensive replacements. Although the materials examined in this study may produce copper debris during electric discharge, these particles possess mechanical properties similar to those of the wire. Consequently, they do not cause wear on the wire, which makes them more appropriate and cost-effective alternatives for use in sliding contacts.

IV. CONCLUSIONS

This work developed and characterized four graphite-based metal composite materials, which can be used as current collector materials in trolleybuses. The four materials, named GNS, CFS, CGN, and CGA, were processed utilizing different combinations of graphite, metal powders, and binders. The materials were characterized structurally, mechanically, and functionally to determine their suitability for the intended application.

Upon analysis of the composite characteristics, it was determined that despite the similar hardness values, the four materials exhibited distinct coefficients of friction under identical testing conditions. These differences were attributed to variations in the chemical composition and processing methods. Specifically, the composites incorporating a coal tar pitch binder and molybdenum disulfide as a lubricant (CNS and CFS) demonstrated significantly lower coefficients of friction compared to those with a Novolac binder containing only graphite as a lubricant (CGN and CGA). The composite CGA fabricated from copper-plated graphite powder exhibited the highest coefficient of friction, which can be attributed to the inhibition of the lubricating properties of graphite owing to the copper coating.

From the perspective of mechano-electrical wear, it can be observed that although the materials displayed similar hardness and mechanical strength, they presented differential wear patterns contingent upon electrical conductivity and voltage drop. In more detail, the copper-graphite pitch composites (CNS and CFS), which demonstrated the highest electrical resistivity and voltage drop, experienced the most significant wear. In contrast, the Copper-Graphite-Novolac (CGN) composite exhibited the lowest wear, possessing relatively high electrical resistivity and the lowest voltage drop. Regarding the composite based on Copper-plated Graphite Powder (CGA), the comparatively high wear can be attributed to the fact that, despite having very low electrical resistivity, the phenomenon of copper migration from the network occurs more easily.

The results of this study were obtained under laboratory conditions. Consequently, testing in real-world environments is necessary to accurately evaluate whether the most promising composite is suitable for the intended purpose of the study. The most appropriate composite material was selected for further development by the end beneficiary. The proposed materials are expected to cause less wear on the electrical wire when used as sliding contacts, thereby reducing maintenance costs.

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