Aspects regarding the tribological evaluation of sintered composites obtained from mixture of copper with carbon fibers

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Abstract. This paper presents a study of the tribological properties of sintered composite materials made from combination of copper with short carbon fibers. Sintered composite materials are more effective if refer to specific properties per unit volume compared to conventional isotropic materials. Potential advantages of copper - carbon composite materials are: high resistance to breakage and high value ratios strength/density; resistance to high temperatures; low density and high resistance to wear; low or high friction coefficient. The sintered composite materials used in this research work are obtained combining different percentages of copper with short carbon fibres with iron and lead in order to investigate the variation of the friction behaviour. Varying the percentage of copper from 92,2% to 97,6% and the percentage of short carbon fibres from 7,8% to 2,4%, five different composite materials are obtained and tested. Friction tests are carried out, at room temperature, in dry conditions, on a pin-on-disc machine. The friction coefficient was measured using abrasive discs made from steel 4340 having the average hardness of 40 HRC, and sliding velocity of 0,6 m/sec. The main objective of this research work it was to identify a combination of materials with improved friction behaviour. The experimental results revealed that the force applied on the specimen during the tests, is playing a very important role regarding friction coefficient and also the wearing speed. Graphite particles are conveyed consistently inside the net, enhancing scraped spot safety and voltage drop over normal composite material. The static tests demonstrated that this new kind of sintered composite material has preferable electrical execution over previous brush material in the same conditions, and the element tests demonstrated that the temperature climb is not enormous when the brush with this new composite material is exchanged on with huge current and the surface scraped spot is littler amid sliding. The new method of obtained sintered composites, using high-energy and high speed is adequate for production of tribological parts.

1. Introduction
In the last few years, carbon fibres have become an interesting reinforcement for polymeric composites from economically and ecologically points of view. There is increase in the environmental awareness in the world which has aroused an interest in the research and the development of biodegradable and high performance materials. Carbon fibres can be obtained from natural resources as graphite mineral. With the increase of global energy crisis and ecology risk, the unique advantages...
of carbon fibres such as abundant, non-toxic, non-irritation of the skin, eyes, or respiratory system, non-corrosive property, plant-based fibre reinforced polymer composites have attracted much interest owing to their potential of serving as alternatives reinforcement to the synthetic [1,2].

In all the applications where are used, carbon fibre composites has emerged more efficient and easy to recycle than glass or other kind of synthetic fibres and appeared a good alternative for the following reasons: carbon fibre production has consumed less energy than other fibre and thus lesser pollution emissions, the higher volume fraction of carbon fibres for similar performance has decreased the volume and weight of base synthetic polymer matrix, the lower weight simultaneously with higher volume has improved the fuel efficiency and reduced emission in the use phase [3,4].

Copper alloys are at the moment extensively used in tribological engineering parts, such as bearing and bushings. Due to its properties, the copper alloy is considered as a solid lubricant which has been developed as self-lubricating material under medium or high load conditions. On the other side, carbon fibers have high strength and modulus combination with the good lubrication effect and the wear resistance. It is a good candidate as an additive in the metal matrix composites. Copper–graphite composites are widely known as materials for sliding electrical contacts, due to high thermal and electrical conductivities closed to pure copper and a low friction coefficient caused by a graphite lubricating ability [5–10].

The final parts obtained by sintered metal powders deliver outstanding physical and chemical characteristics, which are influenced by the composition and the structure of the existing phases and the size, shape and distribution of grains. The main characteristic of a material obtained by sintered metal powders is the presence of residual porosity in the structure. Adjusting the remaining porosity of the product, for the same chemical composition allows obtaining parts having desired (and dissimilar) physical and mechanical characteristics.

The stability of sintered composites in a severe environment depends upon its adequate mechanical properties with non-porous and smooth surfaces because these properties are profoundly affected by the action of water [11]. It has also been reported that dissolution or degradation in surface layers may take place in materials that remain in contact with different fluids and some loss of unbound components is suspected may be along with fluid uptake into the basic structure. This fluid uptake in discrete zones of the material may exert unwanted residual pressure thus resulting in softening, degradation or leakage of the materials [12, 13].

The apparent density is one of the important characteristics of composite materials obtained by sintered metal powders and thus of the parts obtained from such materials. For parts having simple geometric form, the apparent density can be determined by weighing and calculating the volume based on the dimensions of the part. For parts with complex shape, the apparent density is determined by hydrostatic weighing. This property is influenced by many factors, including: nature of the metallic powders which are used; dimensions of the powders particle; the required compaction pressure; the amount and type of lubricant used for compaction; the sintering conditions as temperature, time, atmosphere; the chemical composition of the sintered material.

The dimensional variation of parts obtained from composite materials by sintered metal powders is also an important parameter, which must be taken into account. Thus, the application of exact compensation in order to avoid dimensional variations that occur at sintering allows the manufacture of parts without subsequent calibration.

The mechanical properties of composite materials sintered from metal powders are influenced by several factors, among which the main role is played by porosity and the internal shape of the pore, which depend on the characteristics of powders and sintering conditions. The main mechanical properties of composite parts obtained by sintered metal powders are: tensile strength; hardness; bending strength; elongation and fatigue.

For the composites made by sintered metal, in order to obtain better friction behaviour, the most important mechanical property is the hardness. This is a function of binding forces between the particles, the density and the material resistance in the tested area.
The friction materials sintered from mixtures of metallic and non-metallic powder and used in the manufacture clutches and brakes are tested additionally to determine: the friction coefficient; wear resistance; galling tendency; smooth braking capacity; the heat dissipation capacity.

2. Tribological evaluation of sintered composites from copper-carbon fibers

For applications which requires higher temperature and low friction, and in particular, in the case of high-speed sliding from the electrical contacts, the composite copper-carbon fibres is a suitable material that meets many of the requirements of such applications: high melting temperature, mechanical strength and ductility large enough, high thermal and electrical conductivity, low friction and low speed wear.

Due to a certain degree of immiscibility between copper and carbon fibers, for normal temperatures, it is recommended to improve this feature by using easily fusible metallic binders (as Sn and Pb) or by using carbon fiber coated with various metals, depending on its subsequent use.

By using metal binder it is possible to increase the incipient wetness of the matrix components during the sintering processes. Due to the high temperature from the sliding surface, in critical friction conditions it was observed melting state during the binder phase.

These binders limit the operating range in case of practical applications. In addition the electrical conductivity of copper is very sensitive to impurities. For example, in case of electric brushes, which have to bear high density of current, it is necessary a small electrical resistivity.

Strengthening by processes having high energy and high speed simultaneously, is an alternative and attractive technological process based on the following features: fast processing in order to minimize internal oxidation time; high-speed heating and cooling; local microencapsulation by preferential heating and melting at the interface with carbon-fiber; very dense products can be made with improved mechanical properties by simultaneously forging during unloading.

Figure 1 shows the tool configuration and the mould cavity used in consolidation process. The characteristics of powders and mixtures of the used powders are shown in tables 1 and table 2.

The mould cavity was loaded with approximately 80g of mechanically mixed with copper and carbon-fiber. Thereafter, the powder was pressurized to about 460 MPa, with the purpose of consolidation and bonding of powder particles. After discharge, the pressure was maintained for another 5 minutes, in order to achieve a heat transfer through the pistons, thus obtaining in the end a consolidated product.

Figure 1. Tool and mould configuration cavity used in strengthening the homopolar generator.
Table 1. Characterization of the copper powder.

| No. | Specific feature                              | UM  | Value |
|-----|----------------------------------------------|-----|-------|
| 1   | Dimensions (under 44µm)                      | mesh| 325   |
|     | Chemical composition                         |     |       |
| 2   | Cu                                           |     | 99.52 |
|     | Fe                                           |     | 0.08  |
|     | Pb                                           |     | 0.05  |
| 3   | Insoluble (SiO₂, Al₂O₃)                      |     | 0.05  |

Table 2. Constituents of the consolidated powder mixes.

| No. | Mixture                      | A   | B   | C   | D   | E   |
|-----|------------------------------|-----|-----|-----|-----|-----|
| 1   | Cu (%)                       | 95.2| 95.2| 97.6| 97.6| 97.6|
| 2   | Carbon fibre (%)             | 4.8 | 4.8 | 2.4 | 2.4 | 2.4 |

The measurements regarding the relative density are presented in table 3. The relative density is defined as the average of the densities measured relative to the theoretical values for each mixture. It is noted that sample D has the highest relative density from all the analyzed and consolidated samples.

Table 3. Relative density of the consolidated composite samples.

| Sample         | Relative density (g.cm⁻³) |
|----------------|----------------------------|
|                | A   | B   | C   | D   | E   |
| Relative density | 0.89| 0.90| 0.89| 0.97| 0.89|

Table 4 presents the superficial hardness of these compressed composites. In the table are included a sample with copper-graphite obtained by powder metallurgy using conventional sintering (11% graphite, 2% Pb, 5% Sn) called control sample, as well a tenacious sample with high percentage of copper, with the purposes of comparison with the analyzed samples. Samples strengthened by high energy high speed method, shows hardness values with 14 ÷ 46% higher than those of conventional control sample.

Table 4. Superficial hardness of the composite samples.

| No. | Sample   | Specific energy (kJ/kg) | Superficial hardness |
|-----|----------|-------------------------|----------------------|
| 1   | Martor   | -                       | 45.8                 |
| 2   | A        | 2059                    | 54.8                 |
| 3   | B        | 2125                    | 52.3                 |
| 4   | C        | 1650                    | 66.3                 |
| 5   | D        | 2037                    | 66.8                 |
| 6   | E        | 2285                    | 66.3                 |
| 7   | F(Cu)    | -                       | 75.1                 |
| 8   | B        | 2125                    | 52.3                 |
| 9   | B        | 2125                    | 52.3                 |
| 10  | B        | 2125                    | 52.3                 |
| 11  | Powder Cu| 2000                    | 70.5                 |

The electrical conductivity during the process is shown for each sample individually in table 5. In order to determine the friction coefficient and the wear rate for various mixtures between copper-carbon fiber reinforced through high energy high speed method, was used a testing machine with pin on disc. The discs used were made from 4340 steel with an average hardness of 40 HRC.
Table 5. Changes in conductivity during the consolidation of composite samples.

| Sample   | Specific energy (kJ/kg) | Electrical conductivity |
|----------|-------------------------|-------------------------|
| A        | 2059                    | 6890                    |
| B        | 2125                    | 6160                    |
| C        | 1650                    | 8500                    |
| D        | 2037                    | 6570                    |
| E        | 2285                    | 5660                    |
| Powder Cu| 2000                    | 21400                   |

The tests were carried out in air without external lubrication at the room temperature. The sliding speed was of 0.6 m/s. Friction and strain results are presented in table 6. It is noted that all composite samples present outstanding tribological characteristics. The spectroscopic analysis indicates existence of an interfacial layer (figure 2), which contribute to a substantial decrease of the friction coefficient for all analysed samples from composite, with respect to the samples made from copper.

![Figure 2](image)

**Figure 2.** Electron spectrum of a typical film of graphite formed at the sliding interface.

Table 6. Variation of the friction coefficient and composite sample wear.

| No. | Load (N) | Diameter sample (mm) | Load/area (N/mm²) | Friction coefficient | Wear speed (mm/Nm x 10⁶) |
|-----|----------|-----------------------|-------------------|----------------------|--------------------------|
| 1   | 4.46     | 3.16                  | 0.57              | 0.120                | 0.01                     |
| 2   | 4.46     | 3.30                  | 0.52              | 0.144                | 0.07                     |
| 3   | 4.46     | 3.22                  | 0.55              | 0.097                | 0.10                     |
| 4   | 4.46     | 3.18                  | 0.56              | 0.201                | 4.13                     |
| 5   | 4.46     | 3.23                  | 0.54              | 0.172                | 1.51                     |
| 6   | 4.46     | 3.15                  | 0.57              | 0.172                | 2.87                     |
| 7   | 4.46     | 3.05                  | 0.61              | 0.280                | 58.50                    |
| 8   | 4.46     | 2.66                  | 0.80              | 0.150                | 3.21                     |
| 9   | 8.92     | 2.78                  | 1.46              | 0.207                | 3.81                     |
| 10  | 13.40    | 2.87                  | 2.07              | 0.133                | 8.16                     |

The above presented results demonstrate the fact that the new method of powders consolidation, high energy and high speed is suitable for the production of parts with a good tribologic behaviour, from mixture of copper and carbon fibers.
3. Conclusions
In comparison with pure copper, the wear resistance of the composites obtained by copper and carbon fibers is greatly improved. When the percentage of carbon fibres increases, the friction coefficient simultaneously with wear mass loss decreases but the hardness of the microstructure increases. Increasing of the load and rotating speed, leads to an increase of friction coefficient and wear mass loss, correspondingly.

For pure copper and copper with short carbon fibres composites, the wearing process is adhesive and delaminating wear, respectively. The short carbon fibres improve tribological behaviour of the sintered copper composites by deformation obstruction, clogging the balminess of copper and forming a graphite film on the worn surface. The friction coefficient of copper-carbon composites is considerably less than that of pure copper, the reduction of the friction coefficient observed in an congestion of the carbon fibres at the grain boundaries with resulting in delamination of thinner wear flakes.

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