Arc Erosion Behaviors of Ag-GNPs Electrical Contact Materials Fabricated with Different Graphene Nanoplates Content

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Abstract: In order to clarify the arc erosion behavior of Ag-GNPs electrical contact materials, Ag-GNPs electrical contact materials with different graphene nanoplates content from 0.5wt.% to 2.0wt.% were prepared by powder metallurgy. The microstructure, density, and electrical conductivity were investigated in detail. The weight loss, surface morphologies of the Ag-GNPs materials after arc erosion were characterized, and the arc erosion mechanism of Ag-GNPs materials was discussed. The experimental results show that high GNPs content decreases the densities and electrical conductivity of the Ag-GNPs materials. The Ag-GNPs electrical contact material with 1.5wt.%GNPs presents the best anti-arc erosion performance, which has the lowest weight loss and shallowest arc erosion pits after arc erosion under DC 25V/15A.
Keywords: Ag-GNPs electrical contact material; graphene content; arc erosion; properties

1. Introduction

Silver-based electrical contact materials, including Ag-Ni, Ag-graphite, Ag-CdO, Ag-SnO_2, Ag-ZnO and Ag-REO, are widely used in low voltage apparatus due to their high electrical conductivity, low contact resistance and good arc erosion resistance[1-6]. In conventional Ag-graphite electrical contact material, with the increase of graphite content, its resistance to welding is improved, but electrical conductivity, strength and processing ability decline, which motivated further research into similar materials, such as Ag-CNTs, Ag-G-CNTs and Ag-graphene[7-10].

Graphene, which has a two-dimensional layered structure of carbon atoms, has extraordinary mechanical, thermal and electrical properties [11-12]. Graphene nanoplates (GNPs) with few graphene layers possess similar properties but are easier to produce in large quantities [13-14]. Therefore, GNPs instead of single layer graphene has been widely used as reinforcement for metal-based composites, in particular, for silver-based electrical contact composites[15-17]. For example, Yang et al. fabricated graphene nanoplates (GNPs) reinforced pure Al (GNPs/Al) composites prepared by the pressure infiltration method. They reported that the reaction between pure Al matrix and graphene could be inhibited by using graphene with fewer defects and the mechanical properties of the composites could be significantly improved by the addition of GNPs[18]. Gao et al. studied the effect of graphene contents on the mechanical properties and thermal conductivity of the graphene/copper composite. With increasing the graphene contents, the ultimate tensile strength and thermal conductivity of the composites initially increase and later decrease. However, the elongation to fracture of the composite gradually decreases[19]. However, little information is available on the arc erosion behaviors of GNPs reinforced metal-based composites in literature.

In this investigation, the newly Ag-GNPs electrical contact materials were fabricated by powder metallurgy method. The effect of GNPs content on the microstructure and properties of Ag-GNPs electrical contact materials was investigated, and the mechanism of arc erosion was discussed.

2. Experiment

2.1 Materials and preparation

Graphene nanoplates with 99% in purity and an average thickness of 60-120 nm were supplied by Chengdu Organic Chemistry Co. Ltd., China, which showed a flake shape with wrinkles, as seen in Fig.1(a). Atomized commercial purity silver powders with 99.95% in purity and 10-50μm in diameter were bought from Sinoplatinum Metals Co. Ltd., China, which presented a spherical shape, as seen in Fig.1(b). The Ag-GNPs electrical contact composites were prepared by powder metallurgy method. A schematic diagram of the fabrication process in present study is given in Fig.2. Compositions with 0.5, 1.0, 1.5 and 2.0wt.% GNPs and copper powder were accurately weighed and ball milled for 8h at a milling speed of 200rpm and ball-to-powder weight ratio of 5:1 to ensure uniform mixing. The mixed powders were cold compacted using a closed cylindrical die in a hydraulic press machine with a uniaxial pressure of 400MPa. The green compacts were sintered at 900℃ for 0.5h under argon atmosphere in a tubular furnace with a heating rate of 10℃/min. The sintered compacts were made to wires of 8mm in diameter by hot extrusion press at 800℃ under 100MPa, which were further cold drawn to wires of 1.36mm in diameter. For electrical contact experiment, a part of the sample wires were made into the shape of a rivet shape.

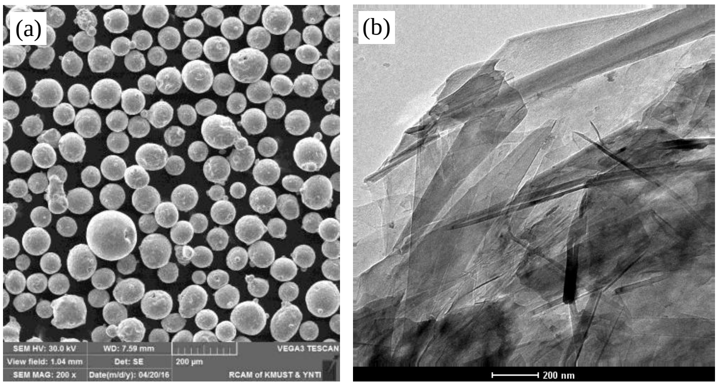

Fig.1 Morphologies of the silver powders (a) and graphene nanoplates (b)

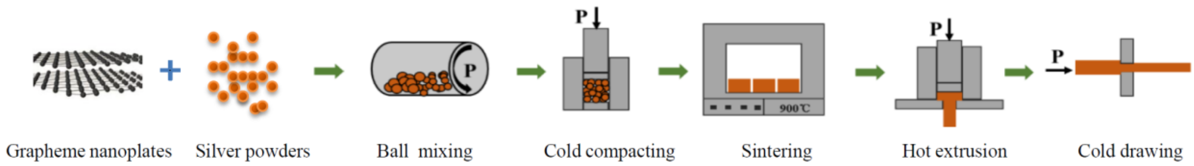

Fig.2 Schematic of fabrication process of Ag-GNPs electrical contact materials

2.2 Measurement

The density of the Ag-GNPs electrical contact materials was measured by Archimedes' method. The theoretical density of compacts was calculated from the simple rule of mixtures taking the fully dense values for silver (10.53g/cm^{-3}) and graphene nanoplates (2.2g/cm^{-3}). The electrical conductivity was determined by measuring the alloy samples using FD101 metal conductivity tester, and every sample was tested for two times. Microstructure and arc erosion surface morphology were investigated using a scanning electron microscope of Hitachi S-3400N. The electrical contact experiment was held by the JF04C contact tester. The arc erosion experimental parameters are shown in Table 1.

Table 1 Parameters of arc erosion experiment

Voltage /V	Current /A	Contacts distance /mm	Contact pressure /N	Load	Surrounding
25	15	1.0	0.686	Resistive load	Air

3. Results and discussion

3.1 Microstructures

SEM images of the Ag-GNPs electrical contact materials show homogeneously distributed GNPs within the silver matrix for the range of the study, as seen in Fig.3. Silver matrix and GNPs could be clearly distinguished from the micrographs. The dark areas indicate the uniformly distributed GNPs and the grey areas indicate the silver matrix. The Ag-GNPs electrical contact materials with a lower GNPs content (0.5, 1.0 and 1.5wt.%) exhibited a significantly lower agglomeration content while the Ag-GNPs electrical contact materials with a higher GNPs content (2.0wt.%) showed a higher agglomeration content. This indicates that the powder metallurgy method may not be suitable for Ag-GNPs composite reinforcing with a higher weight percentage of GNPs. Presence of any interfacial products was not observed from the microstructure which confirms that no reaction takes place between silver and GNPs during the sintering process. Due to the low solubility of carbon in silver only mechanical bonding between two phases occurs.

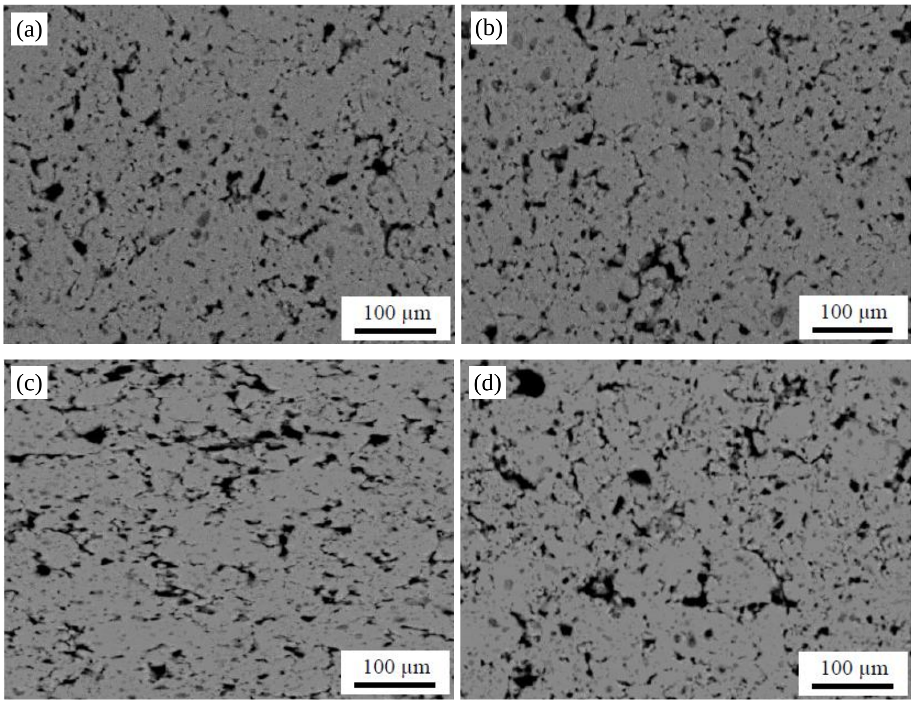

Fig.3 SEM images of Ag-GNPs materials: (a)0.5% GNPs, (b)1.0% GNPs, (c)1.5% GNPs and (d)2.0% GNPs

3.2 Density

The change of density with the increase in the amount of GNPs of the Ag-GNPs electrical contact materials is given in Fig.4. As seen in Fig.4, a decrease of in the theoretical density of Ag-GNPs electrical contact materials was observed with increasing the weight percentage of GNPs. This was because the density of GNPs was lower than that of pure silver. It was observed that the highest density values were 9.32g/cm^3 and 10.11g/cm^3 for green and sintered Ag-0.5wt.%GNPs material respectively while the lowest density values were8.16 g/cm^3 and 8.93 g/cm^3 for green and sintered Ag-2.0wt.%GNPs material respectively. As seen in Fig.4, the sintered densities of the Ag-GNPs materials were higher than the green density of the Ag-GNPs materials for all GNPs contents. The sintering process, which involves a high temperature and a long time, provided an easier diffusion of atoms. This improved the ability of the specimens to sinter and resulted in better physical properties, such as density and porosity, being reached. This also can be attributed to GNPs rearrangement and an increase of the contact regions between the silver particles.

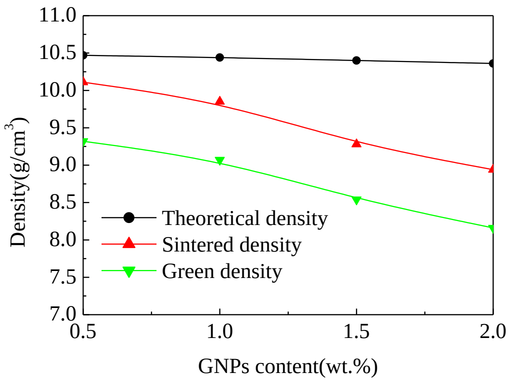

Fig.4 Density of Ag-GNPs electrical contact materials with different GNPs content

When GNPs were added to the silver matrix, the distance between silver powders increased, and, thus, the sintering ability was reduced. Owing to the melting point of GNPs higher than that of silver, sintered density mostly depends on the distance between silver matrix powders in the Ag-GNPs materials. The agglomeration of GNPs reduced the sintered density of the Ag-GNPs materials because the agglomeration regions acted as a resistant barrier to silver particle boundary diffusion during the sintering process.

3.3 Electrical conductivity

The effect of the GNPs content on the electrical conductivity of the green and sintered Ag-GNPs electrical contact materials is given in Fig.5. The electrical conductivity of green Ag-GNPs materials decreased with the addition of GNPs to the Ag matrix. The electrical conductivity of the green Ag-0.5wt.%GNPs material was 78.2%IACS while that of the green Ag-2.5wt.% GNPs material was 44.2%IACS. The decreasing trend of electrical conductivity with GNPs content in the green Ag-GNPs materials can be attributed to an increase in the amount of porosity. After sintering, the electrical conductivity of all Ag-GNPs materials increased significantly with the sintering process. The electrical conductivity of the sintered Ag-0.5wt.%GNPs material was 84.8%IACS, which may be attributed to microstructural change and consistency. The reduction rate of the electrical conductivity of the sintered Ag-GNPs materials with increasing the GNPs content is smaller than that of the green Ag-GNPs materials. This can be attributed to the significantly increased porosity and agglomeration amount in the green Ag-GNPs materials. The agglomeration amount increased with increasing the GNPs content, and the agglomeration regions caused electron scattering within the particle boundaries.

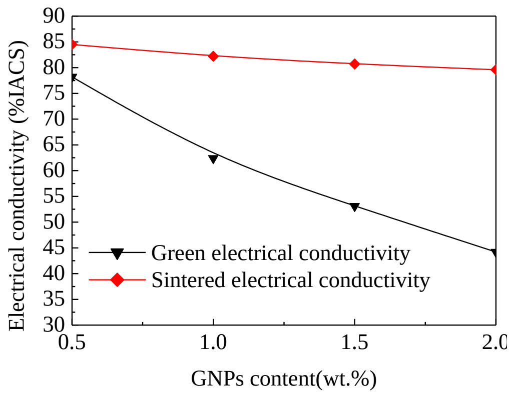

Fig.5 Electrical conductivity of Ag-GNPs electrical contact materials with different GNPs content

3.4 Arc erosion behaviors

The change of weight loss over 30000 times operations under DC 25V/15A with GNPs content of Ag-GNPs electrical contact materials is given in Fig.6. There is a part of the weight loss to the environment after arc erosion. During arcing, the molten silver flows under on the surface at the action of the arc and the liquid bridges break off at the moment of breaking operation. The splashes of molten silver cause a large amount of material loss. The weight loss to environment of Ag-1.5wt.%GNPs material contacts is only 21mg after 30000 times operation, which is lower than that of other Ag-GNPs contacts. The result indicates that the Ag-1.5wt.%GNPs electrical contact material has the best ability of anti-arc erosion for all Ag-GNPs materials. It is indicated that the appropriate content of GNPs in the silver matrix can reduce the splatter erosion of liquid silver and prevent the weight loss.

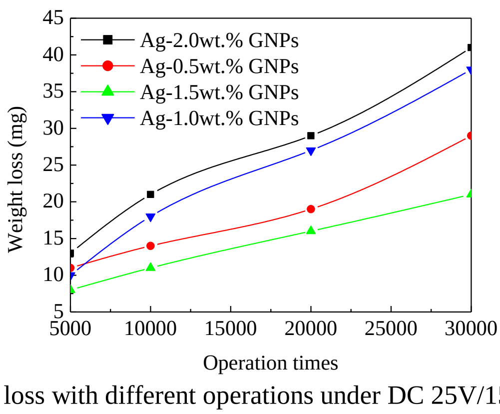

Fig.6 The change of weight loss with different operations under DC 25V/15A of Ag-GNPs materials

Fig.7 shows the surface morphologies of the Ag-GNPs electrical contact materials after 30000 times operations under DC 25V/15A. From Fig.7, it can be seen that a number of large and deep erosion pits formed on the surface of Ag-GNPs electrical contact material, which was attributed to the concentrates of arc erosion. The erosion pit exhibited a paste-like morphology. This was because the non-wetting between silver and GNPs, which resulted in the splashing and solidification of molten silver during arc erosion. However, the erosion pits on the surface of Ag-1.5wt%GNPs materials became very shallower and relatively flat, see Fig.7(c). Furthermore, with the increase of GNPs in the Ag-GNPs materials, as shown in Fig.7(d), the erosion pits became more rough and uneven in surface. Importantly, the splash and solidification of molten silver were not effectively suppressed, although the content of GNPs is increased. From the SEM results, it can be deduced that the suitable content and well-dispersed GNPs in Ag-GNPs electrical contact material are favorable for the decrease of arc erosion and splash of molten silver.

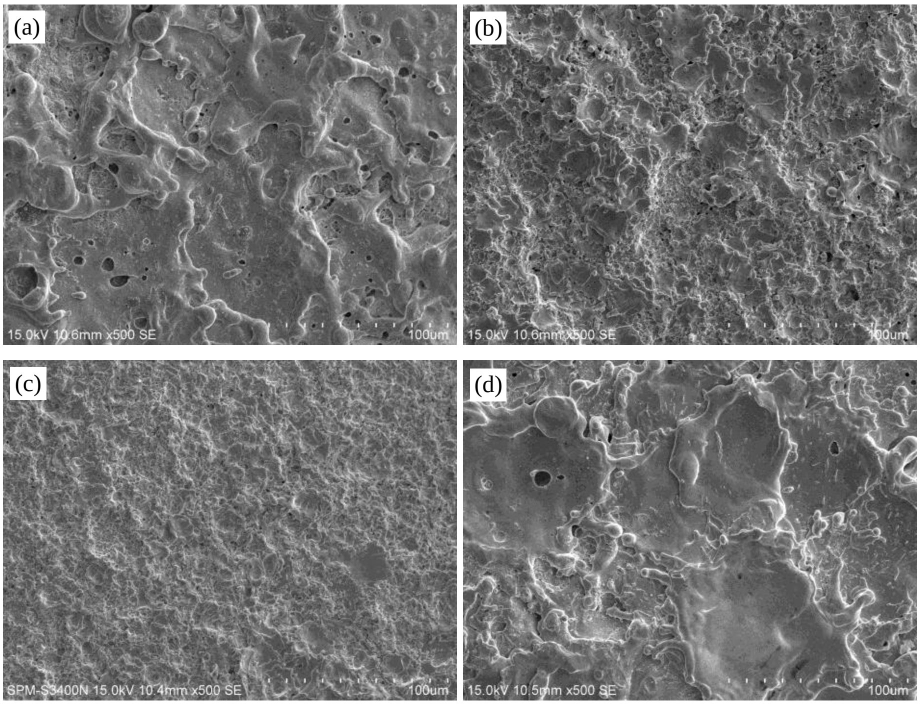

Fig.7 Surface SEM of Ag-GNPs materials: (a)0.5%GNPs, (b)1.0%GNPs, (c)1.5%GNPs and (d)2.0%GNPs

Fig.8 shows the schematic diagram of molten pool formation of Ag-GNPs electrical contact materials during arc erosion. Under arc energy action, temperature on the surface of the contact material will increase, silver will melt when temperature reaches the melting point of silver (961.93℃), while GNPs are still in solid state due to its higher melted point. A silver molten pool containing GNPs is formed due to the melting of silver. Under the action of buoyancy, GNPs in molten pool will move from down to up because the density of GNPs (2.2g/cm^3) is smaller than that of silver (10.5g/cm^3). GNPs are mainly distributed above silver layer when the melted silver rapidly cools. As a result, GNPs are mainly distributed on the surface of molten pool. With the increase in the amount of GNPs, the GNPs on the surface are easier to gather and decrease in electrical contact performances for the Ag-GNPs materials, in particular, for the Ag-GNPs materials with GNPs content more than 1.5wt.%.

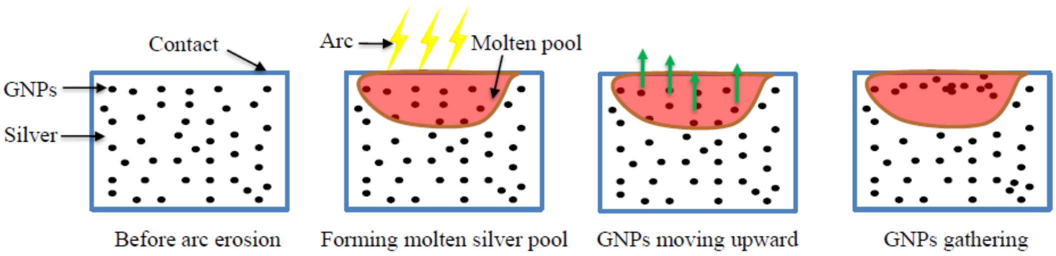

Fig.8 Schematic diagram of molten pool formation of Ag-GNPs contact during arc erosion

4. Conclusions

A newly Ag-GNPs electrical contact material was successfully fabricated by powder metallurgy method. High GNPs content is easy to give rise to graphene agglomeration in the silver matrix and decrease the densities and electrical conductivity of the Ag-GNPs material. The Ag-GNPs electrical contact material with 1.5wt.%GNPs presents the best anti-arc erosion performance, which has the lowest weight loss and shallowest arc erosion pits after 30000 times operations under DC 25V/15A. During arc erosion, GNPs in molten pool will move from down to up and gather together. The newly developed Ag-GNPs material may be substitute for traditional Ag-Graphite or Ag-Ni as a new electrical contact material.

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5. References

[1] Chen J H, Chen S, Li M Y, et al. High speed imaging observation on molten bridge of $AgSnO_2$ electrical contact material[J]. Rare Metal Materials and Engineering, 2017, 46(12): 3613-3620.
[2] Li G, Fang X, Feng W, et al. In situ formation and doping of Ag/SnO_2 electrical contact materials[J]. Journal of Alloys and Compounds, 2017, 716: 106-111.
[3] Wu C, Y D, Weng W, et al. Influence of alloy components on arc erosion morphology of Ag/MeO electrical contact materials[J]. Transactions of Nonferrous Metals Society of China, 2016, 26(1): 185-195.
[4] Findik F, Uzun H. Microstructure, hardness and electrical properties of silver-based refractory contact materials[J]. Materials & Design, 2003, 24(7): 489-492.
[5] Ray N, Kempf B, Wiehl, et al. Novel processing of Ag-WC electrical contact materials using spark plasma sintering[J]. Materials & Design, 2017, 121: 262-271.
[6] Li H, Wang X, Liu Y, et al. Effect of strengthening phase on material transfer behavior of Ag-based contact materials under different voltages[J]. Vacuum, 2017, 135: 55-65.
[7] Wang J, Feng Y, Li S, et al. Influence of graphite content on sliding wear characteristics of CNTs-Ag-G electrical contact materials[J]. Transactions of Nonferrous Metals Society of China, 2009, 19(1): 113-118.
[8] Bai R G, Ninan Neethu, Muthoosamy K, et al. Graphene: a versatile platform for nanotheranostics and tissue engineering[J]. Progress in Materials Science, 2018, 91: 24-69.
[9] Feng Y, Zhang M, Xu Y. Effect of the electric current on the friction and wear properties of the CNT-Ag-G composites[J]. Carbon, 2005, 43(13): 2685-2692.
[10] Wang S, Xie M, Li A K, et al. Preparation and performance of a new type of Ag-CNTs electrical contact materials[J]. Nonferrous Metals Science and Engineering, 2015, 6(5): 40-44.
[11] Liu J, Khan U, Coleman J, et al. Graphene oxide and graphene nanosheet reinforced aluminium matrix composites: powder synthesis and prepared composite characteristics[J]. Materials & Design, 2016, 94: 87-94.
[12] Berman D, Erdemir A, Sumant A V. Graphene: a new emerging lubricant[J]. Materials Today, 2014, 17(1): 31-42.
[13] Ponraj N V, Azhagurajan A, Vettivel S C, et al. Graphene nanosheet as reinforcement agent in copper matrix composite by using powder metallurgy method[J]. Surfaces and Interfaces, 2017, 6: 109-196.
[14] Chen F, Ying J, Wang Y, et al. Effects of graphene content on the microstructure and properties of copper matrix composites[J]. Carbon, 2016, 96: 836-842.
[15] Chu K, Wang X H, Li Y B, et al. Thermal properties of graphene/metal composites with aligned grapheme[J]. Materials & Design, 2018, 140: 85-94.
[16] Yin S, Zhang Z, Ekoi E J, et al. Novel cold spray for fabricating graphene-reinforced metal matrix composites[J]. Materials Letters, 2017, 196: 172-175.
[17] Varol T, Canakci A. Microstructure, electrical conductivity and hardness of multilayer graphene/copper nanocomposites synthesized by flake powder metallurgy[J]. Metals and Materials International, 2015, 21(4): 704-712.
[18] Yang W, Zhao Q, Xin L, et al. Microstructure and mechanical properties of graphene nanoplates reinforced pure Al matrix composites prepared by pressure infiltration method[J]. Journal of Alloys and Compounds, 2018, 732: 748-758.
[19] Gao X, Yue H, Guo E, et al. Mechanical properties and thermal conductivity of graphene reinforced copper matrix composites[J]. Powder Technology, 2016, 301: 601-607.