Correlation Between Formation of the Plasma Jet and Synthesis of Graphene in Arc Discharge

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Abstract—Arc discharge is one of the widely utilized methods for synthesis of different carbon nanostructures, including carbon nanotubes and graphene, due to its high-quality product and eco-friendly processes. This paper presents the results on arc controllability during the synthesis by means of external magnetic field, which, in particular, may lead to synthesis of graphene. Images of the arc are recorded simultaneously through two viewports of the chamber, and the synthesis of graphene is associated with the formation of the plasma jet in the $J \times B$ direction.

Index Terms—Arc synthesis, graphene, magnetic field, plasmas jet.

Carbon nanostructures, such as carbon nanotubes and graphene, attract a deluge of interest of scholars nowadays due to their very promising application for molecular sensors, field-effect transistors, superthin and flexible electronic devices, and so on [1]. Arc discharge is one of the most practical and efficient methods, which can provide nonequilibrium processes and a high influx of carbon material to the developing structures at relatively higher temperature. Therefore, the resulting carbon nanostructures have few structural defects and better crystallinity [2].

In order to improve the controllability of synthesis of carbon nanostructures in arc discharge, nonuniform magnetic fields were applied [3]. It was demonstrated that the magnetically enhanced arc discharge can increase the length of single-walled carbon nanotubes [4] and provide conditions for one-step synthesis of large-scale and high-quality graphene flakes [5]. In this paper, we visually demonstrate controllability of an arc plasma jet by means of external magnetic field in conditions of atmospheric anodic arc and associate graphene synthesis with directing of the arc jet in the $J \times B$ direction.

Experiments were carried out in a cylindrical stainless steel chamber with 254-mm length and 152-mm diameter. Initially, the chamber was pumped down to a pressure of less than $10^{-1}$-torr vacuum and then filled in by helium with a purity of 99.995%. The anode was attached to a linear drive system, which keeps the predetermined gap distance according to the desired arc voltage after the discharge is initiated via contact ignition. All experiments were done with an arc current of about 75 A, a discharge voltage of 30 V, a gap distance of about 3 mm, and a helium pressure of around 500 torr. The cathode was made of graphite with a diameter of 13 mm, while the anode contains a hollow graphite rod with outer and inner diameters of 5 and 3.2 mm, respectively. Carbon powder, catalyst powder of nickel (300 mesh), and yttrium (40 mesh) were mixed and filled into the graphite rod with a total molar ratio of 56 : 4.2 : 1. A cuboid permanent magnet (Alnico, Grade 8) with dimensions of $25 \times 25 \times 100$ mm$^3$ was placed inside the chamber at about 30-mm distance from the interelectrode axis and creating magnetic field $B$ in the range from 0.02 to 0.1 T (depending on magnet positions) in the gap [see Fig. 1(a)]. Without one magnet, we changed the magnetic field in the interelectrode gap by varying the position of the magnet with respect to the anode. Fig. 1(a) shows the case when the interelectrode gap was placed at a distance of about $h = 75$ mm from the bottom of the permanent magnet and presents the magnetic field distribution simulated by FEMM 4.2 software. Fig. 1(d) shows another configuration, when the interelectrode gap was located at about $h = 95$ mm from the bottom of the permanent magnet. The direction of the magnetic field at the electrode periphery is shown in Fig. 1(c) and (f), corresponding to the magnetic configurations of $h = 75$ and 95 mm, respectively.

The video snapshots obtained simultaneously from the front and right viewports of the chamber are shown in Fig. 1(b) and (g) for $h = 75$ mm and in Fig. 1(e) and (i) for $h = 95$ mm. These images illustrate significant perturbation of the arc plasma column in the presence of external magnetic field in comparison with the axially symmetric arc column observed for $B = 0$ [4]. It should be noted that change of magnet position (we tested magnet shift along the $z$-axis and turning the magnet over) results in deviation of arc jet flow in the $x$-direction corresponding to the direction of $J \times B$ force. It was also observed that geometry of the arc plasma column did not change when removing the nickel catalyst from the anode, meaning that the influence of magnetic field on nickel catalyst particle motion does not affect the overall geometry of the plasma column.

Fig. 1(h) and (j) shows the graphene flakes as well as few-layer graphene obtained from the sample taken at the surface of the magnet in the location that corresponded to the arc plasma jet. The typical size of a graphene flake is around 15 $\mu$m. Thus, we associate the synthesis of graphene observed in this work...
with effective delivery of carbon particles and heat flux along the arc plasma column to the sample.

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**References**


