

I. ABOUT PROCESSES OF CARBON NANOSTRUCTURES FORMATION ON THE CATHODE UNDER ELECTRIC ARC DISCHARGE CONDITIONS

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Introduction

One of the most accepted and efficient methods of carbon nanomaterials (CNM) synthesis is electric arc evaporation of graphite [1]. The products that are formed in plasma in the result of graphite anode evaporation and contain CNM deposit on the cathode and cold reactor walls. Different characteristic of the nanomaterials produced are studied using the prepared samples. In this case low emphasis are placed on the physical and chemical processes occurring both on the electrodes and in the plasma itself.

The present work states the authors' opinion and proposes the model (scheme) of CNM formation as a deposit on the cathode. The basis for this model is the behaviour of particles in electromagnetic field at the extremely high gradients of pressure and temperature on electric arc radius.

Results and discussion

To understand better the mechanisms of CNM formation in the arc interelectrode space, it is necessary to conceive physics of the processes occurring in this place of space that affect inevitably the formation and composition of arc discharge produced at the expense of processes of anode destruction.

It should be noted that the influence of both electrical and magnetic fields on the resulting carbon particles is crucial in carbon nanostructures formation. In this case the interelectrode carbon arc can be considered as a pigtail of electric current having its own magnetic field. Magnetic lines of the arc are concentric circles locked around the arc column center. A charged particle in the arc column will be moved along the contracting coil from the anode to the cathode by interference of these factors.

In plasma forming between the graphite electrodes, contrary to the metallic conductors, there exist two main counter flows of charged particles, electron flow and cation flow, in the interelectrode space. The latter consists of carbon cations, carbon clusters and positively charged fragments of graphene sheets. The velocity of positively charged particles will be dependent on

electromagnetic field formed between the electrodes.

Contrary motion of electrons and positively charged particles results in their collisions. However, in distinction to the metallic matrix, cations in the arc, like electrons, move forming their own magnetic field. When oppositely charged particles collide, energy of their interaction depends on their impulse. Collisions may result in both destruction of existing structures and their atomization and neutral atoms ionization.

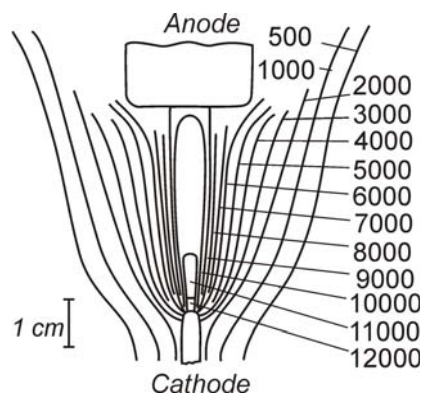


Fig.1. Distribution of temperature zones (K) along the electric arc axis between the graphite electrodes at a current of 200 A [2].

Charged particles concentrations in the cross-section of the electric arc column are unequal. Electrons move closer to the arc axis. More positively charged particles are kept in the arc bundle by magnetic field. The temperature of the arc central region is evaluated to be about $1 \cdot 10^4$ °C (Fig. 1) and decreases sharply along the radius to periphery. The volume occupied by carbon atoms is increased more than 5500 times by graphite going to the vapor state.

Neutral particles due to temperature and pressure gradients move from the arc axis to periphery and get to the volume filled with helium atoms.

When positively charged particles move, their rotational motion, which is formed by electromagnetic field in the electric arc column, lowers to a larger extent the rate of their diffusion from the axis to periphery and draws them to the column axis thus forming ionized hot gas.

Hence, the longitudinal magnetic field causes to rotate the arc column consisting of different charged particles around its axis and to draw. The change in the particle concentration along the axis of the arc column leads to the change in frequency of their collisions with electron flow.

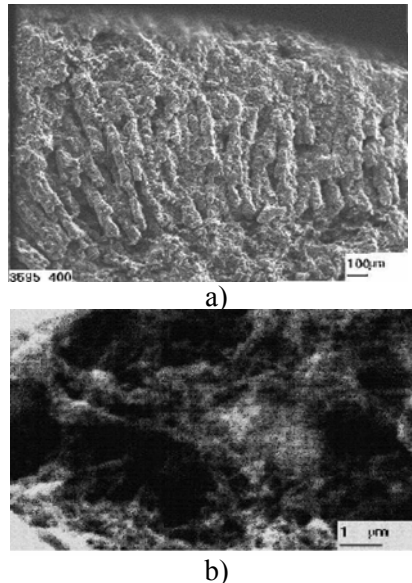


Fig.2. The deposit core: a) overall view of conglomerates consisting of nanotubes bundles; b) nanotubes bundles.

The action of electromagnetic field on charged particles in the arc column makes contribution to their condensation on the cathode and formation of different carbon nanostructures.

Experimental studies have shown [3, 4] that the deposit formed on the cathode consists of two parts: a friable core formed by multi-wall nanotubes (MWNT) having a minimum number of structural defects, and strong bark (Figs.2 and 3) formed by layered graphite-like structures containing a lower number of MWNT.

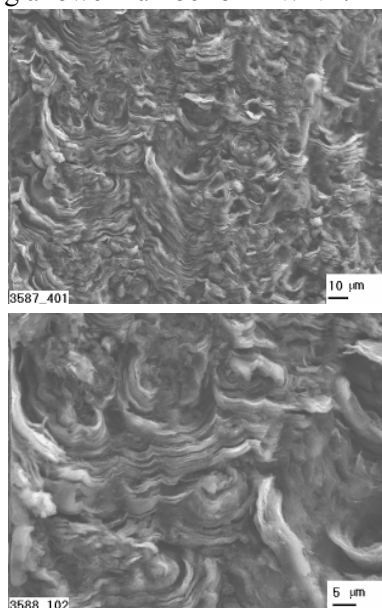


Fig.3. The deposit shell formed by layered graphite-like structures.

On this basis, the processes occurring between the carbon electrodes in the arc can be represented schematically (Fig.4). In arc discharge, the electron beam bombarding the anode initiates in this place the process of graphite cleavage into graphene single-layer sheets and packets consisting of several graphene sheets. As this takes place, the edge bonds break (Fig.5), and some number of electrons is knocked out the carbon atoms in graphene. This causes the sheets and packets to gain a positive electric charge.

The positively charged particles that move from the anode to the cathode along the arc axis under the action of electromagnetic field collide persistently with electron flow.

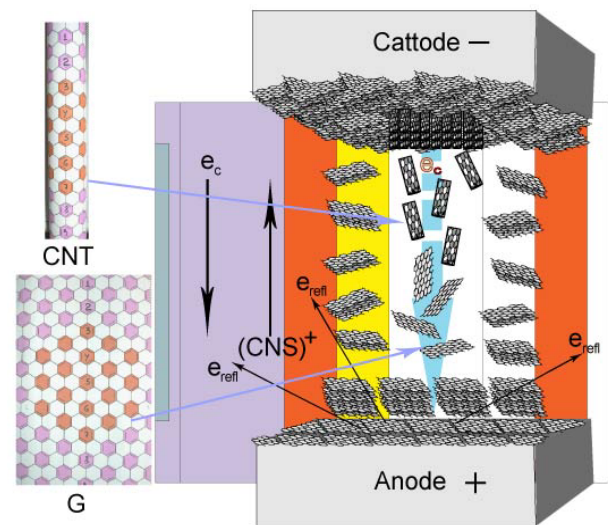


Fig.4. The schematic diagram of deposit formation: e_c – electron flow of a power up to 8 kW ($U=25-30$ V, $I=300$ A) that moves from cathode to anode; e_{refl} – reflected electrons; $(CNS)^+$ – positively charged carbon nanostructures; G – graphene sheets; CNT – carbon nanotubes.

In this case the part of graphene sheets are partially destructed and carbon is atomized. The packets can disintegrate into graphene sheets. The graphene sheets that possess high surface energy of open sides and uncompensated bonds at the edges roll up to form a deposit core (like structural elements having low electrical resistance), and the packets of graphene sheets (having higher mass to charge ratio) that contain more than one sheet form a deposit shell. Turbulence of moving particle flux also favors rolling up the graphene sheets.

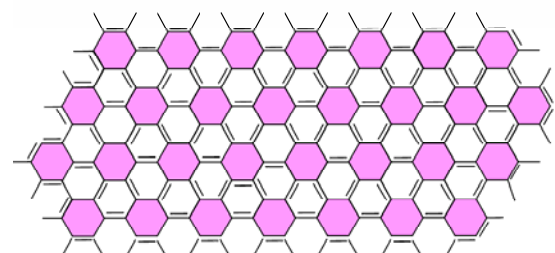


Fig.5. Graphene sheet with dangling ("broken") edge bonds.

At the moment of their formation in the arc and on the cathode surface, CNTs have high temperature that causes a deposit core to form from pure carbon because at such temperatures all metals and compounds sublime. When atoms of refractory metals from groups IV, V and VI are present in the vapor phase, the latter metals form carbides that are constituents of the core as low-temperature parts of the deposit.

Adsorbing on the cathode surface, particles locate in such a way that a newly formed carbon layer has minimum electrical resistance because at the moment of its formation the layer becomes a current conductor and electron flux with a current of 100-300 A flows through it (i.e. through the structural units, its constituents) [3, 4].

Conclusions

The consistent model of the processes of products formation on the cathode – conglomerates of multi-layer nanotubes in the deposit core and layered graphite-like structures in the deposit bark has been proposed on the basis of literature data on physical processes occurring in plasma of electric discharge and authors' experimental results on the graphite electric arc evaporation and sputtering.

Hence it has been shown that at the stage of its formation, the deposit material has already coded to be sustained high current loads. For this reason, nanostructural constituents of the deposit that are multi-layer carbon nanotubes can be used

in power blocks of nanoelectron circuits due to their electromechanical properties.

Acknowledgment

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