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Short Communication

Dependence of Nanoparticles Synthesis Energy Consumption in the Gas Spark Discharge on Circuit Parameters

D.A. Mylnikov*, A.A. Efimov, V.V. Ivanov

Moscow Institute of Physics and Technology, 9, Institutsky per., 141700 Dolgoprudny, Russia

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In this paper, we study the specific energy of titanium dioxide nanoparticles synthesis in a spark discharge in the air by varying the parameters of a discharge circuit. The dependence shows a maximum at a capacitor voltage of about 2 kV and a monotonic decrease with increasing voltage.

Keywords: Spark discharge, Nanoparticle synthesis, Specific energy consumption.

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1. INTRODUCTION

High-performance preparation of nanoparticles is of interest in terms of applications in nanoelectronics, aerosol printing [1] for the manufacture of a variety of devices - from transistors [2] to the solar cells [3] and different gas sensors [4, 5]. Nanoparticles synthesis in the gas spark discharge by electrode erosion is a method to obtain the smallest particles, down to atomic clusters [6].

A large number of researchs exists related to performance and quality of the nanoparticle synthesis in the spark discharge. In particular, researchers previously studied the effect of various parameters on the size and the mass output rate of the nanoparticles synthesis [7, 8], the agglomeration of particles and its restriction [9]. Various schemes of pulse current generators and various kinds of electrodes such as round rods and less common pin-to-plate were tested [10]. The measurements have being performed at different interelectrode gaps from 0.5 up to 3 mm and at different operating voltages of storage capacitor. The important task for industrial production is to improve the energy efficiency of nanomaterials synthesis. Until now, usually either mass yield of particles was studied or the specific energy consumption of the synthesis as a ratio of the total primary energy storage capacitor to the weight of the nanoparticles. In this paper, we address the impact of the electric circuit parameters and determine the specific energy consumption, taking into account only the energy delivered directly to the discharge gap. The results are also applicable to the electric discharge machining of materials. The presented method of the accurate measuring of the energy released in the discharge gap is interesting, for example, to research a minimum ignition energy in the study of a combustible mixtures safety.

After the turn on of the discharge circuit, consisting of the storage capacitor, the discharge gaps and lead wires damped oscillations occur. But only the part of the stored energy is delivered within the electrode gaps. Because the capacitor and the lead conductors have resistance, the energy is lost in them in the form of Joule heat. The discharge circuit can also include switching elements such as power transistors [7], which are also characterized with active losses. Only that portion of the active energy, which is released in the interelectrode gap, should be considered as useful energy, since it is spent on the evaporation of the electrode material followed by formation of nanoparticles. It is released in the anode and the cathode voltage drop region near the electrodes and in the spark discharge arc, where it spends on heating and expansion of the spark channel, plasma formation, and energy radiation. Near-electrode areas of the voltage drop and the discharge arc have they equivalent resistance, the ratio of this resistance and the resistance of the whole circuit determines the part of the storage capacitor energy released in the gaps. We developed the technique allowing one to measure accurately the energy release in the discharge gap and thus to calculate the true specific energy consumption of the nanoparticles synthesis, taking into account only the energy supplied into the gap. This value is of great scientific interest than the value usually measured using the total energy of the storage.

2. EXPERIMENTAL SETUP

The experimental setup was described in [11]. The discharge circuit consists of the storage capacitor of 1.0 uF and the three discharge gaps connected in series. All measurements were performed using titanium electrodes in the form of rods 10 mm in diameter. The capacitor was charged by the high voltage power source to a predetermined voltage below the self-breakdown voltage. Then a high-voltage triggering pulse with duration of about 5 ms and voltage of 20 kV was applied to the middle electrodes pair, which led to a consistent breakdown of all gaps and the discharge process begins. The system allows to set the rate of the charging and breakdown cycle in the range of 1 to 10 Hz.

Method of measuring the energy amount released in the discharge gaps was described in [12]. We used a custom-made capacitive voltage divider with the division coefficient of 1 : 1050, and a current sensor in the form of a Rogowski coil. The signal from the Rogowski coil is proportional to the derivative of the current, so it

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[*] mylnikov.da@yandex.ru

was integrated to determine the current numerically. The energy release in the part of the circuit with electrode gaps is calculated according to the formula

$$E(t) = \int_0^t I(\tau)U(\tau)d\tau$$

where $I(\tau)$ and $U(\tau)$ are the current through the gaps and the measured voltage, respectively, and the integral is taken over the discharge time. For accurate measurements of the phase of the voltage and current signals and for a noise reduction the measuring system was shielded against electromagnetic interferences.

A chamber with discharge gaps is included in the sealed gas circuit in which a compressor feeds a stream of purified air at the rate of 80 l/min. Nanoparticles formed in the electrode gap, are carried away by the air stream and collected by the Thermovent HEPA filter, the collecting efficiency of which is as great as of 99.99 %. Collection of nanoparticles lasted for 2 hours for each measurement: the filter was weighed before and after the collection procedure.

The characterization of the collected nanoparticles was produced by using a transmission electron microscope JEM-2100 (JEOL, Japan).

3. RESULTS AND DISCUSSION

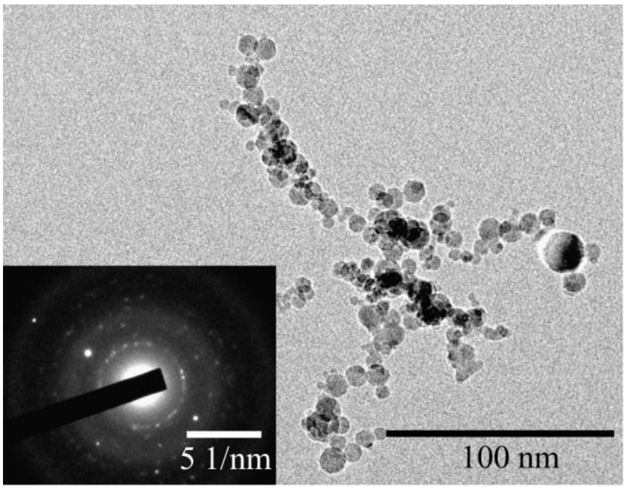

Fig. 1 – Images of the titanium oxide nanoparticles obtained by a transmission electron microscope (TEM). Inset shows an electron diffraction pattern

Analysis of TEM images (Fig. 1) shows that the average primary particle size of 15 nm, they are combined into agglomerates.

The dependence of the energy fraction supplied to the discharge gap was measured for voltages from 2.5 to 6 kV at gaps from 0.5 to 0.8 mm, and then approximated by a polynomial of 2nd degree down to the voltage of 1 kV (Fig. 2a).

It can be seen that an increase in the initial capacitor voltage causes the decrease of the proportion of the energy released in the discharge gaps. This can be explained by the fact that with increasing the current a plasma active resistance in the electrode gap decreases by the formula ([13]):

$$R \square \int \frac{1}{I(\tau)^2} d\tau$$

where $I(\tau)$ is a current through the gap.

Resistance of the leads and the internal resistance of the capacitor remains constant, resulting in less energy release in the discharge gaps and the more release in the capacitor.

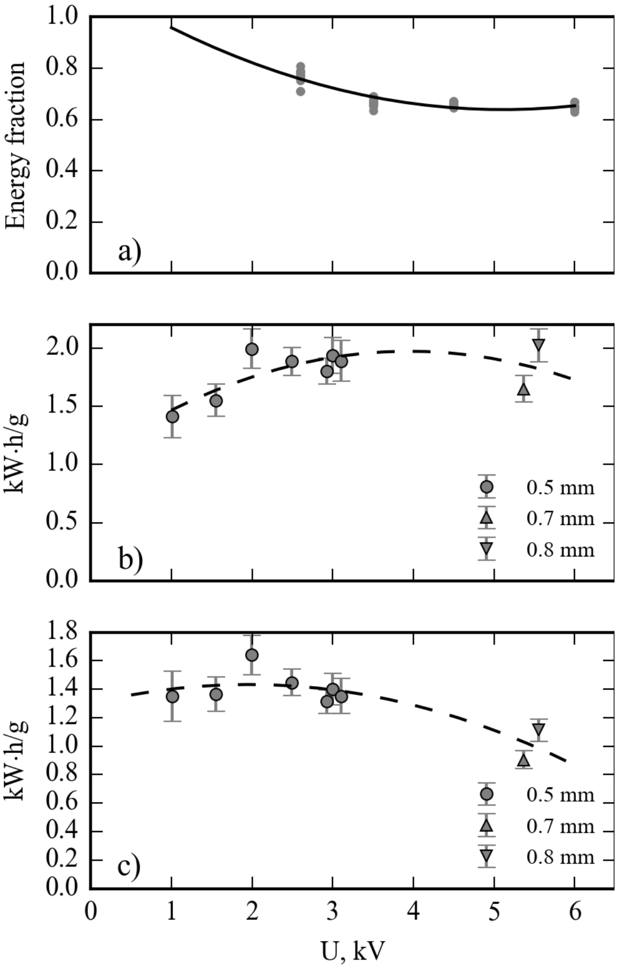

Fig.2 – a) The dependence of the fraction of energy released in the discharge gaps with respect to the initial capacitor voltage. The width of the gap between electrodes is of 0.5 mm. b) Dependence of the specific energy consumption of the synthesis on the storage capacitor voltage. Full energy of the storage capacitor used. Gaps between electrodes are of 0.5, 0.7 and 0.8 mm. c) Specific energy consumption in relation to the energy released in the discharge gap

Fig. 2b shows a plot of the specific energy consumption for the different values of the charging voltage and at two nearby values of the inter-electrode gap. The energy consumption was calculated using the total energy of the capacitor. The energy consumption is slightly smaller at the voltages of 1-2 kV and approximately constant at the voltage greater than 2 kV.

Based on the relationship shown in Fig 2a, it is possible to calculate the specific energy of synthesis taking into account only the energy supplied directly into the electrode gap, this results in the change of the energy consumption dependence (Figure 2c). At voltages between 1 and 2 kV the specific energy consumption increases. Then we see a decrease, with an increase of the voltage from 2 to 5.5 kV the energy is halved. The relationship is not monotonic, but consists of two sections, increasing and decreasing, it shows that two factors affect the specific energy consumption. Reduction of energy consumption at high voltage can be explained by the fact that at high voltages we have more hot plasma and ions bombard the electrodes more actively, resulting in the increase in the temperature and the erosion level of an electrodes surface. Because operation at higher voltages allows one to obtain a higher mass yield of nanoparticles, in conjunction with our result that this regime is more energy efficient one may conclude that such regimes should be preferred in the generation of nanoparticles in a spark discharge.

4. CONCLUSIONS

In this study, we have measured the specific energy consumption of the titania nanoparticles on the discharge circuit parameters in the gas spark discharge. We have taken into account the structure of the discharge circuit, as besides the electrode gaps it contains storage capacitor, and lead conductors, it can include also various switches, such as transistors. For the calculation of the specific energy consumption the energy released directly in the discharge gaps was taken, in contrast to other studies, which usually takes the total initial energy of the storage capacitor. We have shown that the energy consumption decreases with increasing voltage. This method will allow to optimize the synthesis of nanoparticles regimes and select circuit parameters for the industrial production of nanoparticles in a more energy-efficient mode.

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