Arc ignition at heating of graphite by fixed current

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Abstract. Arc ignition after the destruction of graphite samples under prolonged heating by electric current was described. Evidences of liquid film formation on the graphite surface at a temperature of 3.3 kK were presented.

1. Introduction

An occurrence of arc after destruction of conductor, which is heated by electric current, is usually the result of reaching the melting temperature. In work [1] using this method the melting graphite in argon atmosphere was studied and parameters of the triple point of carbon were estimated: $T_{tp}=4$ kK, $p_{tp}=10.5$ MPa. Other researchers, who used pulsed heating of graphite by electric current or laser radiation, got a higher temperature of the triple point: $T_{tp}=4.8$ kK, $p_{tp}=11$ MPa [2]. At present, these parameters of the triple point of carbon are generally accepted; however the results of the studies [3-5] directly contradict this point of view.

According to the phase diagram of carbon, which was suggested in work [3], the graphite transforms into carbyne at a temperature above 2.6 kK. The time of phase transition “graphite-carbyne” depends on the temperature: at the temperature of 2.8 kK graphite entirely transforms into carbyne during $10^5$ s, and at the temperature of 3.8 kK this process lasts for a few seconds [3]. Thus, the melting temperature of graphite should depend on the duration of heating. According to work [3], the triple point in the "vapor-carbine-liquid" system exists at the temperature of 3.8 kK and a pressure of 20 kPa. The evidences of formation carbyne and other carbon phases after prolonged graphite exposure at temperature of 3.0-3.8 kK were presented in works [4-7]. The experiments on melting graphite when heating process lasted from 1 to $10^3$ s were described in work [5]. The parameters of the triple point of carbon ($T_{tp}=4$ kK, $p_{tp}=0.1$ MPa), which were obtained in work [5], are close to those that were given in work [3].

In work [6], we described the arc that arose after graphite sample exposure at a temperature of about 3 kK for duration of about $10^3$ s. According to work [6] at a temperature of about 3.3 kK, the liquid film was observed on the graphite surface. This paper presents the study of ignition stage of this arc.

2. Experimental set

We used installation that has been described in works [6, 7]. The samples were made from rods of spectral graphite with diameter of 6 mm. In the central part of the rod its diameter was decreased up to 3 mm on the length of 20 mm. Resistivity of used graphite at room temperature was $\rho_0=11$ Ohm·μm; its density was 1.7 g/cm$^3$; the total impurities in graphite was less than 0.01%. Samples that fixed in molybdenum holders were heated by DC in argon atmosphere.
We measured the current through the sample and the voltage drop on it. The voltage on the sample in transient regimes was recorded using oscillograph adapter AKTAKOM. The process of sample destruction was controlled by videography at a speed of 25 frames/s and exposure time of 0.5 ms. The sample temperature was measured by luminance pyrometer IS-140 at the wavelength of 0.9 \( \mu \)m with 0.9 mm spatial resolution and temporal resolution 10 ms. The true graphite temperature was determined using the data of emissivity factors [6].

3. Experimental results and discussion
Heating current (120-190 A) was chosen so that the initial temperature in downtown the grooving \( T \) was 2.7 -2.9 kK. During exposure with the fixed current (10-100 minutes) sample temperature and voltage drop on it monotonically increased that is explained by the local growth of graphite resistivity [7]. When the temperature exceeded \(~3.2\) kK, an "explosion" of sample occurred, and the arc discharge appeared.

In this work the video frames and voltage oscillograms at sample # 175 in the initial time of arc were compared. Argon pressure was 51 kPa. Sample current before the "explosion" was 138 A; after the destruction of the sample and occurrence the arc with voltage of about 20 V the current decreased to 132 A. Before "explosion" the sample temperature increased at the speed of \(~1\) K/s. When the temperature reached \(~3.2\) kK, the arc discharge arose, and during \(~10\) ms temperature abruptly increased from 3.2 to 3.4 kK. In this experiment the pyrometer determined the temperature of anode part of the sample. During the first 10 s after "explosion" the anode temperature changed mainly in the range of 3.4 to 3.6 kK.

Figure 1 shows video frames of the sample destruction. Figure 1a shows the moment of "explosion"; the cathode part of the sample is to the right. One can see the intense plasma glow near the surface, on the previous frame (40 ms earlier) this glow was absent. Figure 1b, which was filmed 0.76 s after Figure 1a, shows the gap between the cathode and anode of about 0.2 mm wide. In the previous frame the gap was not visible, and through of 0.12 s it disappeared. Figure 1c was obtained 2.2 s after Figure 1a. As one can see, the gap between the cathode and anode is absent. Figure 1d presents the sample 10.8 s after Figure 1a. On this frame the bridge between cathode and anode is still visible; in the next shot it is absent. The anode temperature at this moment was of 3.4 kK.

Figure 1. Frames of the sample destruction.

Figure 2 shows the snippets of oscillograms of sample voltage in moments of time corresponding to the frames on Figure 1. Before the "explosion" the voltage drop on the sample was of 12 V. Figure 2a presents the oscillogram in the moment of "explosion", when during 0.5 ms voltage has
increased to 35 V. The voltage of about 30 V was maintained for ~10 ms, and then it decreased to ~26 V. At this moment there was a series of voltage pulses having duration of 10 ms and an amplitude of 35 V; the interval between pulses was of about 60 ms. The pulses begun 0.12 s after “explosion” and lasted about of 0.5 s until the visual gap between cathode and anode part of the sample not appeared.

Figure 2. Oscillograms of sample voltage: 2 ms/div, 10 V/div.

Figure 2c shows the oscillogram at the time corresponding to the Figure 1c. The breakdowns on Figure 2c demonstrated that for a short period of time the voltage on the sample tried to restore to the value of 12 V, which was on the sample before “explosion”. Decreasing of voltage drop to 12 V could cause short-term extinction of the arc. The anode temperature was decreased to 3.1-3.2 kK in this time.

Figure 2d shows the waveform at the time of the disappearance of the jumper. The destruction of the "bridge" between the electrodes had a little effect on the voltage drop on the sample. This voltage also slightly changed when the initial gap between the electrodes appeared (Figure 1b and Figure 2b).

In this experiment, the final gap between the cathode and the anode was formed approximately 11 s after the surge, i.e. ~10 s after the appearance of the initial gap (Figure 1b). This scenario of the gap formation between the electrodes was often observed in our experiments. Along with this there was another type of sample destruction when the sample was locally heated in area with size of ~3 mm in which there was a gradual decrease in the diameter of the grooving due to the evaporation and ejection of micro particles [6]. In this case, the gap between the cathode and the anode was also installed via ~0.5 s after the jump of the voltage was monotonically increased, were observed much less the other two.

The presented results demonstrate that the destruction of the graphite sample after prolonged exposure at high temperature has the appearance of stretched electric "explosion". This "explosion" starts with qualitative change in the character of voltage growth on the sample, where a smooth increase in voltage with a rate of 10 mV/s transforms to a sharp jump in the voltage value of ∆U~20 V (Figure 2a). In the initial time sample integrity is retained, so the power surge is associated with a sharp increase in resistivity. This indicates the rapid growth of content in the sample of carbon phases with high resistivity. Carbyne and diamond-like structures, for example, can play the role of such carbon phases. If one assumes that the longitudinal size of the region with high resistivity is ~5 mm (Figure 1a) then the estimated value of specific resistivity is ρ~250 Ω*µm. That is approximately 20 times higher than the initial resistivity of graphite. This is an estimation of the average over the cross section of the resistivity of the sample material; the local value of the resistivity could be significantly more. The breakdowns shown on Figure 2c can be considered as indirect confirmation of the existence of local regions with high resistivity.

The increase in the resistivity of the sample may indicate an appearance of liquid carbon; according to the hypothesis [3], it is formed by melting the carbon phases with low electrical conductivity.
Apparently, at the initial time of arc burning on the electrode surface there is a competition of two processes – the formation of the melted film and its destruction under the action of the arc. Under the influence of these mechanisms ultimately, the film is formed with a low electrical conductivity, the thickness of which is such that it does not prevent the current transfer.

In work [6] the existence of the melt film on the graphite surface was justified by the peculiarities of the electrodes geometry. First, the anode geometry in the form of mace preserved with a substantial reduction in the anode length. The anode has gained such geometry in time of gap formation (Figure 1d). Second, we often observed the temporal disappearance of the initial gap between the cathode and anode that usually appeared via ~0.5 s after the arc ignition. Both of these features can be explained by the flow of the melt film along the electrode surface under action of the plasma pressure. When this film comes on the colder part of the anode, it solidified, forming a step with height of ~0.1 mm [6].

The appearance of the electrode surface after exposure to the arc also indicates the existence of melt film. When the arc duration was of about 1 s the droplet and hemispherical formations with size of 0.1-0.3 mm were observed on the original surface of electrodes. If the arc existed above 5-10 s, then appearance of the electrode surface in the zone of influence of the arc became a sleek and "melted". Apparently, in the initial moment of time the size of the melt zone was of 0.3-0.5 mm, and then the area of the melting covered the entire working surface of the electrodes.

Earlier we have noted [6] that in our experiments the occurrence of the arc was determined not only by the sample temperature, but also by exposure time at high temperature. This effect is confirmed by the thermogram of sample # 181 presented in Figure 3. In this experiment, the increase of heating current from 160 A to 174 A caused the temperature rise from 3.15 to 3.35 kK. In this regime the movement of “shadows” was observed near the sample surface that resulted in brief decrease of the pyrometer readings [6]. The current of 174 A was maintained for 10 s, and then it was decreased to 130 A. The arc occurred later via 440 s when the current was 142 A. Figure 3 demonstrates that sample temperature at the moment of arc appearance (~3.2 kK) was significantly less than at the regime of short-term overheating (~3.35 kK).

![Figure 3. Thermogram of sample # 181.](image-url)

In our experiments the minimum temperature of graphite, at which its melting was observed, was about of 3.2 kK that corresponds to a brightness temperature of 3.05 kK. Similar "low" melting point of graphite was registered in work [5], wherein the color temperature of the melt film flowing on the
sample was equal of 3.04-3.09 kK. However, the authors of work [5] concluded that this temperature was too low for melting, and they measured, in fact, the temperature of solid graphite, along which transparent liquid carbon flowed.

4. Conclusion

The presented results confirm the conclusions of the work [6] that the melt film with thickness of the order of 0.1 mm arises on the surface of graphite electrodes at a temperature of 3.2-3.3 kK. The appearance of the liquid phase of carbon at such “low” temperature is possible only after long, more than $10^2$ s, the exposure of graphite at a temperature of about 3 kK. Under these heating conditions the formation of carbon phases with lower, compare to graphite electrical conductivity, takes place. Apparently, the scenario of formation of liquid carbon was close to what was proposed in work [3].

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