Delayed plasma formation on Ti-coated copper and duralumin conductors in strong magnetic fields

I M Datsko\textsuperscript{1}, N A Labetskaya\textsuperscript{1}, D V Rybka\textsuperscript{1}, S A Chaikovsky\textsuperscript{1,2}, V V Shugurov\textsuperscript{1} and V A Vankevich\textsuperscript{1}

\textsuperscript{1} Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Sciences, Akademichesky Avenue 2/3, Tomsk 634055, Russia
\textsuperscript{2} Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, Amundsen 106, Ekaterinburg 620016, Russia

E-mail: datsko@ovpe.hcei.tsc.ru

Abstract. The paper reports on experiments investigating the plasma formation at the surface of exploding cylindrical copper and duralumin conductors with Ti coatings of different thickness in a magnetic field of up to 400 T. The experiments were performed on the MIG high-current generator at a current rise time of 100 ns and current amplitude of up to 2.5 MA. In a magnetic field of 350–400 T, the plasma on Ti-coated copper and duralumin conductors (conductivity ratio about 27 and 16, respectively) arose 30–40 ns later than on bare copper and duralumin. The instant of plasma formation for Ti-coated copper and duralumin conductors was respectively in 100 and 80 ns from the onset of current flow. Dependences of the instant of plasma formation at the conductor surface upon the Ti coating thickness are presented.

1. Introduction

Fast rising megagauss magnetic fields lead to a skin explosion and plasma formation on current-carrying electrodes [1, 2]. In megaampere generators, such plasma at electrode surfaces may expand, bridging the interelectrode gap and decreasing the efficiency of energy transport to the load. Thus, one of the main tasks in designing load units for multi-megaampere generator is to lengthen the time to plasma formation at electrode surfaces in a magnetic field comparable to or higher than the surface explosion threshold and to decrease the plasma expansion velocity. For efficient energy transfer, e.g., in Z-pinches, it is sufficient not to allow the plasma to bridge the gap during the current rise time. This can be attained by decreasing the plasma expansion velocity through the use of electrode materials with a large ion mass [3, 4] or by increasing the time to plasma formation at electrode surfaces in a magnetic field comparable to or higher than the surface explosion threshold. As has been shown [5, 6], electrodes coated with a less conductive layer can withstand a magnetic field of up to 300 T with no surface explosion, and depositions of such coatings make possible complex two-layer conductor configurations.

Here we investigate the formation of plasma on copper and duralumin conductors with Ti coatings of different thickness at a magnetic field of up to 400 T.

2. Experiment

The experiments were performed on the MIG high-current generator with a current rise time of 100 ns and current amplitude of up to 2.5 [7]. The diagnostic complex of the generator
Figure 1. (a) Scheme of load unit with its coated part shown in blue and (b) photo of a Cu conductor with a Ti coating.

comprised Rogowski coils, magnetic probes, voltage dividers, vacuum photodiodes (XRD), and an HSFC Pro four-frame optical camera with an exposure of 3 ns per frame. The generator load represented copper or duralumin conductors of diameter 2 and 3 mm with Ti coatings of thickness 5–80 µm deposited on their near-cathode part using a QUINTA vacuum ion plasma setup designed at the Laboratory of Plasma Emission Electronics, IHCE SB RAS [8]. The setup allows surface cleaning, activation, and plasma-assisted coating deposition in a single vacuum cycle and provides uniform coatings on parts of diameter less than 2 mm and height up to 5 cm with a coating thickness inhomogeneity of less than a percent.

The load unit of the MIG generator is shown schematically in figure 1. The load consists of two sections: a cylindrical part with a coating spanning from the cathode flange to about the load center (coated conductor) and a cylindrical part spanning from the load center to the anode flange sliding contact (bare copper or duralumin conductor). The diagnostic length (return conductor) was 15 mm.

The cylinders gradually increasing in thickness (toward the cathode) were made on a turning machine to a surface finish class of 6.3. The surface roughness estimated from microscope images was ±10 µm. Any special surface treatment was not conducted because the character and the time of plasma formation at conductor surfaces in a skin explosion depend weakly on the degree of surface finish with a roughness of 1–100 µm [9, 10]. Besides, for Al electrodes, the threshold magnetic field for the formation of thermal plasma is invariant to surface roughness variations from 25 µm to submicron values [11]. The experiments were performed in a vacuum chamber pumped by an oil-vapor pump to a pressure of 10⁻⁴ Torr.

The plasma glow of coated and bare conductors was recorded with an HSFC Pro four-frame optical camera at a minimum exposure of 3 ns. The instant at which the plasma arose at the surface was determined in vacuum ultraviolet using two x-ray diodes for bare and coated conductors, respectively. The sensitivity of such a detector has its maximum at 10–15 eV and drops steeply in both the short- and long-wave region; in our diagnostic geometry, the instant of rapid signal rise corresponds to a temperature of ≈ 2 eV in the black body approximation [5,12]. Note that in the visible region (optical camera), the conductor surface starts glowing at a plasma temperature of less than 1 eV, whereas its explosion occurs at 2 eV. That is, in our experiments, the diode signals corresponding to 2 eV always appeared later than the point recorded by the camera.
Figure 2 shows typical waveforms of the current and diode signals for a duralumin conductor of diameter 2 mm with a Ti coating 50 µm thick. The current amplitude reaches 2 MA, suggesting that the maximum magnetic field at the surface is 400 T [5]. The formation of plasma with a temperature of about 2 eV on the bare conductor surface occurs at 60 ns from the onset of current flow and on the coated conductor at 115 ns.

3. Results and discussion

Figure 3 presents optical images of a duralumin conductor with a Ti coating of thickness 50 µm deposited on its near-cathode part, as shown in figure 1(b). Similar optical images were taken for different experimental conditions and were processed to estimate the delay of plasma formation at the surface of bare and coated conductors with respect to the onset of current flow.

To exclude possible light effects from one conductor part to the other, Ti coatings were also deposited lengthwise duralumin conductors of diameter 2 mm to have half a conductor coated and the other bare. Thus, the radiation from that part of a conductor where plasma is formed earlier does not directly get on the other part and does not influence the delay of plasma formation.

Figure 4 shows optical images of a duralumin conductor with a Ti coating deposited along its lower half. It is seen that the plasma at the coated part appears at the same points in time as in the previous variant of deposition, i.e., the light effect of bare conductors on the plasma formation at their coated part is negligible.

The plasma formation at the conductor surface can be delayed by increasing its in-depth conductivity, which decreases the Joule heat at the surface and increases the time to plasma generation [5, 6]. Using a numerical simulation technique [5], current density distributions in depth of conductors of diameter 2 and 3 mm with no and with Ti coatings up to 100 µm thick were obtained for nonlinear magnetic field diffusion with amplitudes and time dependence observed in experiments. Figure 5 shows calculated in-depth current density distributions for duralumin conductors of diameter 2 mm with no and with a Ti coating of thickness up to 50 µm. The calculation demonstrates that almost from the rise of a magnetic field, the current density distribution in the coating is near-uniform and the maximum current density occurs in the more conductive base material. The heat energy density on the surface of the coated conductor at
Figure 3. Optical images of a duralumin conductor of diameter 2 mm with a Ti coating 50 µm thick deposited on its near-cathode part at different points in time from the onset of current flow.

Figure 4. Optical images of a duralumin conductor of diameter 2 mm with a Ti coating 50 µm thick deposited on its lower half at different points in time from the onset of current flow.

Figure 5. In-depth current density distributions for duralumin conductors (a) without and (b) with a Ti coating 50 µm thick in a maximum magnetic field of 400 T at different points in time.

The instant of maximum current (100 ns) is several times lower than that on the bare conductor surface. If the heat energy density in the coating is lower than the material sublimation energy, the surface can escape explosion.

Figure 6 presents diagrams obtained by processing all optical images taken. The data suggest, like elsewhere [6, 13], that the glow at the surface of bare copper conductors in a magnetic field of up to 300 T appears at 90 ns from the onset of current flow, whereas the glow at the surface of copper conductors coated with Ti from 20 to 80 µm arises at 280–500 ns depending on the coating thickness. The same is observed for duralumin conductors of diameter 3 mm with Ti coatings 20–80 µm thick, though plasma on them arises somewhat earlier compared to coated copper conductors. The plasma on bare duralumin conductors appears at 80 ns, and on coated duralumin conductors, it appears at 90–300 ns depending on the coating thickness, see figure 6(a).

A somewhat different dependence on the coating thickness is observed for copper and duralumin conductors of diameter 2 mm at a magnetic field of ≥ 400 T. The delay of plasma
Figure 6. Instant of plasma formation $\tau$ with respect to the onset of current flow versus the Ti coating thickness for copper and duralumin conductors at a magnetic field of (a) 300 and (b) 350–400 T; $d_{\text{Ti}} = 0$ is the time at which a plasma arises on the bare materials.

formation for coated copper is 120 ns and that for coated less conductive duralumin is a mere 90 ns from the onset of current flow. This suggests that the instant of plasma formation depends on the conductivity ratio of a coating and base material.

For Ti-coated copper conductors at a magnetic induction of 350–400 T, see figure 6(b), there exists an optimum coating thickness of 20–60 $\mu$m at which the time interval $\tau$ from the onset of current flow to that of plasma formation is maximal and is 110–120 ns. The glow on the bare copper surface appears at 70 ns, and the maximum delay of plasma formation on the Ti-coated copper surface with respect to the bare one is about 40 ns.

The plasma glow on bare duralumin conductors of diameter 2 mm appears at 50 ns and expands with time (figure 4), whereas the coated part does not emit in the visible range up to 75–90 ns from the onset of current flow; that is, the delay of plasma formation for coated duralumin with respect to bare ones is about 35 ns at a Ti coating thickness of 50–70 $\mu$m.

4. Conclusion
Thus, we have investigated the dynamics of plasma formation on copper and duralumin conductors with vacuum deposited Ti coatings in fast rising magnetic fields of up to 400 T. The research data demonstrate that Ti-coated copper and duralumin conductors provide a considerable delay of plasma formation at a coating thickness of more than 20 $\mu$m. At a maximum magnetic field of 350–400 T, the longest delay of plasma formation from the onset of current flow is observed for copper conductors of diameter 2 mm with Ti coatings 60 $\mu$m thick and is 110–120 ns. For Ti-coated duralumin conductors, this delay is about 90 ns. The delay of plasma formation on the coated conductors is about 40 ns with respect that on the bare ones.

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