Delay in plasma generation on copper and duralumin conductors coated with titanium or zirconium

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Abstract. Skin explosion investigations have been performed for homogeneous and double-layer cylindrical conductors made of copper and duralumin and coated with titanium or zirconium. Titanium and zirconium have close values of electrical conductivity and sublimation energy density, whereas the ionic mass of zirconium is twice that of titanium. The experiment was carried out on the MIG high current generator at a current of amplitude up to 2.5 MA and rise time 100 ns. The plasma generated on the conductor surface was imaged using a four-frame optical camera with a frame exposure time of 3 ns. The internal structure of the surface plasma was examined using transmission images of the plasma exposed during 2-3 ns to the x radiation with $h\nu>0.8$ keV generated by an X-pinches. It has been demonstrated that the time delay to the plasma formation on the surface of double-layer copper and duralumin conductors with a deposited zirconium or titanium layer is comparable for Zr and Ti (with the conductivity ratio equal to 26-27 for a homogeneous copper conductor and a deposited layer and to 8.2-8.5 for a homogeneous duralumin conductor and a deposited layer), and it is shorter for double-layer duralumin conductors than for double-layer copper conductors. In a magnetic field lower than 300 T, plasma formation on the surface of a double-layer copper conductor started about 400 ns later than on the surface of a duralumin conductor and 250 ns later than on the surface of a duralumin conductor. When the field was increased to 350-400 T, the delay time to plasma formation decreased to about 35 ns. For double-layer conductors, the difference in expansion velocities between titanium and zirconium surface plasmas was insignificant.

1. Introduction

It is well known that in fast-rising megagauss magnetic fields, a skin explosion and plasma generation may occur on the electrode surfaces of the generator load [1, 2]. The expansion of the plasma and the ejection of charged particle flows from the plasma surface may cause early closure of the electrode gap and reduce the efficiency of conversion of the electrical energy stored in the generator to the energy deposited into the load. An important goal in designing load units for multimegampere generators is to lengthen the time to the onset of plasma generation on the electrode surfaces at sites where the magnetic field induction is comparable to or greater than a critical value (at which a surface explosion occurs) and to reduce the expansion velocity of the plasma. The time to the onset of surface
plasma generation can be increased, for instance, by using double-layer electrodes [3, 4], and the plasma expansion velocity can be reduced by using electrode materials of heavier atomic masses [5, 6]. A significant time delay to plasma formation in magnetic fields up to 400 T was observed [4, 7] for double-layer copper and duralumin conductors with the outer layer of lower conductivity (titanium) of thickness more than 20 µm. For the outer layer, another material can be used whose conductivity is more than 15 times lower than that of the electrode material and the sublimation energies of both are comparable [8]. For the experiment to be presented, zirconium was chosen as the material of the low-conductivity outer layer for copper and duralumin conductors. Under normal conditions, this metal, with its ion mass being almost twice that of titanium, compares to titanium in conductivity and sublimation energy density. Therefore, not only the onset of generation of the surface plasma can be delayed, but also its expansion velocity can be reduced due to the larger ionic mass of the outer layer.

2. Experimental arrangement
The experiment was carried out on the MIG high current generator capable of producing currents of amplitude up to 2.5 MA and rise time 100 ns [9]. The diagnostic equipment of the MIG includes Rogowski coils, magnetic probes, voltage dividers, and vacuum x-ray diodes (XRDs). The plasma generation onset time and the plasma expansion velocity were determined from optical images obtained using an HSFC Pro four-frame optical camera with a frame exposure time of 3 ns.

The generator load was a cylindrical copper or duralumin conductor of diameter 2 or 3 mm whose near-cathode part was coated, using vacuum deposition, with a titanium or zirconium layer of thickness ~50 µm. The plasma-assisted coating deposition was carried out on the QUINTA facility [10]. The load unit is shown schematically in figure 1. The load consisted of two parts: a cylinder with a low-conductivity layer deposited on the segment from the cathode flange to about the middle of the load (double-layer conductor) and a solid cylinder extending from the middle of the load to the sliding contact of the anode flange (homogeneous copper or duralumin conductor). This made it possible to perform measurements for surface plasma generation on double-layer and homogeneous conductors and compare the data obtained for different types of conductors.

![Figure 1. Schematic of the MIG load unit (a) and photos showing the arrangement of the X-pinch unit in the MIG vacuum chamber (b).](image)

The cylindrical part of the load (and, accordingly, the diagnostic window of the return current lead) was increased from 10 to 15 mm to avoid the edge and near-contact region effects on the measurements. The loads were lathe-fabricated, with 6.3 surface finish, as cylinders gradually increasing in diameter toward the cathode. According to the images taken with a microscope, the surface roughness was ±10 µm. The cylinders were not subjected to additional surface treatment, as it was previously shown [11] that in a skin explosion of a conductor, the pattern and onset time of the
surface plasma generation depend slightly on the surface finish in the roughness range from 1 to 100 µm. In addition, it was shown [12] that for aluminum electrodes, the change in surface roughness from 25 µm to a submicrometer level had no effect on the magnetic field threshold for the generation of thermal plasma. The experiment was carried out in a vacuum chamber evacuated with an oil vapor pump to a pressure below 10⁻⁴ Torr. The internal structure of the surface plasma was examined using transmission images of the plasma exposed during 2-3 ns to the x radiation with \( hν > 0.8 \) keV generated by an X-pinch. For this purpose, an X-pinch-loaded lock-in generator [13] developed at the Institute of High Current Electronics (Tomsk) was used. The generator produced an X-pinch current of amplitude up to 250 kA and rise time 150-200 ns. This provided the formation of an x-ray (\( hν > 0.8 \) keV) pulse of duration (FWHM) no more than 2 ns. The X-pinch current was measured with a Rogowski coil placed in immediate vicinity to the load. The waveform of the X-pinch X-radiation was recorded using an Al-cathode XRD placed downstream of a filter that provided detection of x-rays in the range \( hν > 0.8 \) keV. The size of the x-ray source was evaluated using a camera obscura. The switching system locked the probe X-pinch x-ray pulse in synchronism with the MIG current pulse to within ±10 ns. The small size of the X-ray source (no more than 2 µm) provided space-resolved pictures of the exploded conductor. A feature of the generator is the use of a low-inductance flexible multi-cable line to transfer energy from the generator to the displaceable case in which the X-pinch load was mounted. This provided a simple and fine adjustment of the X-ray system and made it possible to place the X-pinch load near the test plasma object immediately in the vacuum chamber of the MIG load unit, as shown in figure 1b. In this case, the X-pinch driver could be located at any convenient site near the chamber.

For the probe radiation of photon energy 3-5 keV, the mass absorption coefficients of substances with moderate-charge nuclei are in the range 100-1000 cm²/g [14]. This makes it possible to obtain highly contrast shadow images of objects of density 0.01-0.001 g/cm² linearly distributed along the line of sight. With that, the proper test object thickness for condensed aluminum, copper, zirconium, and titanium is 4-40, 1.1-11, 1.6-16, and 2.2-22 µm, respectively. Besides taking shadow images of a test object, it was possible to perform absolute measurements of the mass density distribution for the expanding surface plasma by using step attenuators made of the material of the test conductor [15]. In our experiment, two shadow images, one of the exploded conductor and the other of the step attenuator made of the same material, were recorded on one film. The optical density of a film, \( D \), is known to be proportional to the intensity \( I \) of the radiation having passed through a test material layer of thickness \( h \). Therefore, at the points where the images of the plasma and of a step of the attenuator are identical in density, the plasma and the attenuator step will have the same mass per unit length along the line of sight.

Figure 2 shows the arrangement of the radiography of an exploded conductor. The magnification ratio of the system was 4.2. Images were recorded on MikratORTO and RF-3 films disposed one after another. Upstream of the films, a filter stacked of two 2-µm-thick kimfoil films, each having a deposited aluminum layer of thickness 0.2 µm to protect the test plasma from the visible radiation of the X-pinch, and 6-µm-thick polypropylene film were placed. The step attenuator was prepared by magnetron deposition of copper or duralumin on the polypropylene filter at about 100 nm intervals through the thickness. The overall filter transmitted more than 20% of the probe radiation with photon energies over 1.5 keV (see figure 2b).

3. Experimental results

It was observed [4, 7] that at fields of up to 300 T, for a copper conductor with an outer deposited titanium layer of thickness 20-80 µm, the plasma generation on its surface started 200-400 ns later compared with a homogeneous copper conductor. When the magnetic field was increased to 350 T and more, the delay in plasma generation decreased to 35-40 ns. The delay in plasma generation between the two types of conductor was accounted for by the lower Joule heat density released in the surface layer of the double-layer conductor that resulted from the lower conductivity of the outer layer, and, hence, the lower current density it carried.
Figure 2. Arrangement of the shadow x-ray probing of an exploded conductor (a) and the transmission curve of the used filter stack (b).

In a numerical simulation, the current density distribution over the conductor thickness at different times was obtained. The distribution plots for a double-layer (copper plus titanium) conductor showed that the current density in the titanium layer was distributed nearly uniformly almost from the very beginning of the magnetic field pulse and that the current density maximum occurred in the copper conductor at any time. Estimates obtained for magnetic fields lower than 300 T indicated that the thermal energy density at the surface at the time when the current was a maximum (the 100th nanosecond) was lower than the sublimation energy of titanium, and an explosion might occur on the surface of the double-layer conductor [4].

Figure 3a presents optical images of the homogeneous and double-layer parts of copper conductors with external diameter of 3 mm and titanium or zirconium layer thickness of 50 µm taken at different times from the onset of current flow. The images were obtained with an HSFC Pro camera. The low-conductivity layer was deposited on the cathode side of the conductor, as shown in figure 1.

Similar images for copper conductors of diameter 2 mm are presented in figure 3b. By processing similar images taken under different experimental conditions, the times at which light emission occurred from the homogeneous and the double-layer parts of the conductors and the delays of its occurrence relative to the onset of current flow through the generator were determined.

A series of shots performed with loads of this type has shown that at the surface of the double-layer conductor with an outer zirconium layer, light emission of low intensity occurred from the non-expanding surface plasma within 350-400 ns from the onset of current flow, and the expansion of the plasma column became appreciable at the 525th nanosecond. For the copper conductor with a
deposited titanium layer, similar processes occurred 50–100 ns later. The light emission from the homogeneous copper conductor of diameter 3 mm was usually detected within 90–100 ns from the onset of current flow. When the magnetic field at the surface of the conductor was increased to 400 T and more, that is, when the conductor diameter was reduced to 2 mm, the delay in plasma generation on the surface of the conductors was substantially shorter. Within 115 ns from the onset of current flow, light emission from the double-layer conductors was observed for both materials of the deposited layer. Appreciable light emitted from the 2-mm copper conductor was detected within 65–70 ns from the onset of current flow.

For the duralumin conductors, as can be seen from figure 4, light emission from the double-layer part began at about the 200th nanosecond from the onset of current flow for both deposited materials, and the surface plasma started expanding at about the 250th nanosecond. This is substantially earlier compared with the double-layer conductors coated with titanium and zirconium.

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To elucidate the reason for the shorter delay of the light emission from the double-layer duralumin conductors, the conductivity of D16T alloy used for them was measured. It turned out (see table 1) that the conductivity ratios were 26–27 for a homogeneous copper conductor and a deposited layer and 8.2–8.5 for a homogeneous duralumin conductor and a deposited layer for Zr and Ti, respectively. It seems that the lower the conductivity ratio for the base conductor and coating materials, the shorter the delay to the onset of plasma generation.

Table 1. Material properties.

|        | Conductivity, $\sigma$ (Ω⋅m)$^{-1}$ | Mass, $m_i$ (g/mol) |
|--------|------------------------------------|---------------------|
| Ti     | $2.18 \cdot 10^6$                  | 47.9                |
| Zr     | $2.26 \cdot 10^6$                  | 91.2                |
| Al     | $3.67 \cdot 10^7$                  | 27                  |
| D16T   | $1.85 \cdot 10^7$                  | –                   |
| Cu     | $5.93 \cdot 10^7$                  | 63.5                |

Figure 5 presents images of the light emitted by the duralumin conductor of diameter 3 mm with a 50-µm-thick titanium layer deposited on the cathode side that were taken in the visible self-radiation at later times from the onset of current flow (figure 5a) and x-ray shadow pictures of exploded similar duralumin loads illuminated by the X-pinch radiation (figure 5b). All pictures show the top half of the load. The x-ray pictures contain the image of an Al step attenuator with layers of thickness 250, 500, 750, 1000, and 1250 nm (from left to right) and, for scale, the shadow picture of a copper wire of diameter 180 µm. As the HSFC Pro camera, the X-pinch unit, and the load were lined up, we can see the onset of visible radiation from the X-pinch on one picture (600 ns) of figure 5a. The X-pinch was out of focus; therefore its image is blurred. Both the x-ray and the visible pictures clearly show the surface plasma of the homogeneous duralumin conductor that expanded. The plasma expansion velocity evaluated from the HSFC Pro visible pictures was $(2.5–4) \cdot 10^5$ cm/s. The plasma expansion
was accompanied by large-scale instabilities. X-ray probing has shown that in this case, the surface density of the expanding material of the load was high. As a consequence, the 1.25-µm thickness of the aluminum filter was too small to allow for comparing the aluminum step filter and the duralumin (exploded and expanding) load in radiation absorptivity on the line of sight. For the homogeneous conductors, the expansion velocity of the tongues of instabilities reached (1.5–2)·10⁶ cm/s.

At the same time, the double-layer part of the conductor expanded slower than the homogeneous part, with a velocity of (2–2.5)·10⁵ cm/s and instabilities did not develop. At earlier times from the onset of current flow (200-300 ns), the expansion velocity of the double-layer part was even lower, namely, (0.2–0.8)·10⁵ cm/s. The difference in surface plasma expansion velocity between a double-layer conductor coated with titanium and that coated with zirconium was insignificant for both the copper and the duralumin conductors.

![Figure 5. Images of the top part of the duralumin conductor of diameter 3 mm with a 50-µm-thick titanium layer deposited on the cathode side that were taken in the visible self-radiation at later times from the onset of current flow (a) and x-ray shadow pictures of exploded similar duralumin loads illuminated by the X-pinched radiation (b).](image)

4. Conclusion

Thus, it can be stated that the time delay to the onset of plasma generation is determined by the conductivity ratio of the base material and the deposited material with close values of their sublimation energy densities. The ionic mass of the deposited material has little effect on the expansion velocity of the deposited layer plasma. This indirectly supports the simulation data indicating that the current density in the deposited layer is too low for resistive heating to result in its explosion. The low current density is due to the fact that current density is a maximum inside the base conductor having higher conductivity.

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