Delayed large-scale instabilities on Ti-coated duralumin conductors

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Abstract. The paper reports on experiments showing that duralumin conductors coated with Ti, compared to bare duralumin conductors, are able to delay and suppress the growth of large-scale instabilities on their surface. The experiments were performed on the MIG terawatt high-current generator at a current rise time of 100 ns and current amplitude of up to 2 MA, and the plasma and the instabilities arising at the conductor surface were recorded with a four-frame optical camera at an exposure of 3 ns per frame. The most considerable effect of suppression was found for Ti coatings of thickness 20–70 µm at a magnetic field of about 300 T. As the magnetic field at the conductor surface was increased to ≈ 400 T, the effect did occur but was less pronounced.

1. Introduction

The high level of current in multi-megaampere generators brings the problem of electromagnetic energy transport via vacuum-insulated transmission lines because the electromagnetic energy density in the load region is so high that the conducting surface may explode [1–5] forming a plasma and decreasing the efficiency of energy transport to the load. For this reason, surface explosions of heavy metal arrays and large-scale instabilities are studied on terawatt current-pulse generators [6–8].

When a megaampere current flows in a heavy metal array, it drives a shock wave and a nonlinear magnetic diffusion wave inward the conductor. Such nonlinear diffusion is possible only in a sufficiently strong magnetic field [9, 10] which is higher than

\[ B_0 \approx \sqrt{\frac{8\pi}{\beta}}, \]  

where \( \beta = (\rho c_V)^{-1} \partial \delta / \partial T \), \( \rho \) is the density of a conductor, \( c_V \) is its heat capacity at a constant volume, and \( \partial \delta / \partial T \) is the temperature derivative of its resistivity. The magnetic induction \( B_0 \) for most of the metals is several tens of tesla, which corresponds to a conductor surface magnetic pressure of ≈ 1 GPa. Therefore, the shock wave induced by the magnetic pressure on the conductor surface propagates together with a nonlinear diffusion wave. The latter can initiate thermal instabilities whose structure is determined by the resistivity of matter as a function of its temperature and density [11–14].
The diffusion of a magnetic field into metal results in explosion of the metal surface and in formation of dense low-temperature plasma. The magnetic field at the conductor surface for its explosion measures

\[ B_s \approx \sqrt{8\pi\Lambda_0}, \]

where \( \Lambda_0 \) is the metal sublimation energy under normal conditions. The magnetic induction \( B_s \) for most of the metals ranges from 200 to 400 T \([15, 16]\). For Al and Ti \( B_s \) is 270 and 310 T, respectively. Because plasma confinement by a magnetic field is unstable, magneto Rayleigh–Taylor instabilities can develop at the plasma surface \([17, 18]\).

The use of a conductor coated with a less conductive layer makes it possible to attain a higher magnetic field at the conductor surface, compared to ordinary bare conductors, before the formation and expansion of plasma. As has been shown, it is sufficient to coat a conductor with a layer about 20–80 \( \mu \)m thick to delay the plasma formation at its surface by 200–500 ns with respect to the onset of current flow at a magnetic field of up to 300 T \([19]\). The induction of the magnetic field at the outer boundary of the conductor was determined from the well-known expression for induction of the magnetic field of a cylindrical conductor, using an experimental current waveform and a value of the conductor radius equal to the initial one. It is reasonable to further investigate the behavior of plasma and instabilities at the surface of conductors with coatings of different thickness.

Here we report on a comparative experimental study of large-scale instabilities at the surface of duralumin conductors with Ti coatings differing in thickness and bare duralumin conductors differing in initial diameter.

2. Experiments

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 \([20, 21]\). The diagnostic complex of the MIG generator comprised Rogowski coils, magnetic probes, voltage dividers, and an HSFC Pro four-frame optical camera with a minimum exposure of 3 ns per frame. The load unit of the MIG generator is shown schematically in figure 1(a). The generator load represented cylindrical duralumin (D16T) conductors of diameter 2 and 3 mm with a Ti coating of thickness 20–70 \( \mu \)m deposited on their near-cathode part using a QUINTA vacuum ion plasma setup designed at the Laboratory of Plasma Emission Electronics, IHCE SB RAS \([22, 23]\). The deposition technology allows one to obtain not only coatings \( \geq 50 \) nm thick but also two-layer electrodes of complex configurations. Figure 1(b) shows typical waveforms of the generator current.

Figure 2 shows optical images of duralumin conductors of diameter 2 and 3 mm without and with Ti coatings of thickness 20, 50, and 70 \( \mu \)m at different points in time from the onset of current flow. It is seen from figure 2 that at \approx 300 ns, the surface of the duralumin conductor of diameter 3 mm (at a magnetic field of up to 300 T) reveals clearly defined large-scale instabilities with an amplitude of \approx 340 \( \mu \)m, while the conductor with an outer Ti layer 20 \( \mu \)m thick is perturbed to less than 50 \( \mu \)m (comparable with the resolution of the optical system), and those with an outer Ti layer 50 and 70 \( \mu \)m thick are free of instabilities at all. With time, at about 560 ns, the amplitude of large-scale instabilities on the bare conductor increases greatly and reaches 980 \( \mu \)m, the instability amplitude on the conductor coated with a 20 \( \mu \)m Ti layer measures about \approx 250 \( \mu \)m, and the conductors with a Ti layer of thickness 50 and 70 \( \mu \)m reveal only slight perturbations of not greater than \approx 70 \( \mu \)m. Note that in this case, the maximum induction compares with \( B_s \) determined by expression (2): \( B_s \approx 270 \) T for aluminum and 310 T for titanium.

At a conductor diameter of 2 mm (at a magnetic field of up to 400 T), the delay of instabilities gets shorter: the instability amplitude for the bare and coated conductors at \approx 170 ns is 290
Figure 1. Schematic of the load unit (a) and typical waveforms of the generator current (b).

Figure 2. Images of duralumin conductors of diameter 2 and 3 mm without and with Ti coatings of thickness 20, 50 and 70 µm at different points in time from the onset of current flow.

and 190 µm, respectively. In this case, the maximum induction is much higher than $B_s$ for aluminum and titanium.
Figure 3 presents average instability amplitudes $A$ and average conductor expansions $\Delta w$ at $\approx 300$ and 560 ns for different Ti layer thicknesses. The instability amplitude $A$ and the expansion $\Delta w$ are determined as follows:

$$A(t) = \frac{D_{\text{max}}(t) - D_{\text{min}}(t)}{2}, \quad \Delta w(t) = \frac{D_{\text{min}}(t) - D_0}{2},$$

where $D_{\text{max}}(t)$ and $D_{\text{min}}(t)$ are the averages of maximum and minimum conductor diameters at points in time $t$; $D_0$ is the initial conductor diameter.

As can be seen from figure 3, increasing the coating thickness from 50 to 70 $\mu$m adds little to the delay of instabilities. Besides, it is inexpedient to deposit vacuum coatings thicker than 100 $\mu$m on complex-shaped surfaces. The data in figures 2 and 3 suggest that the coating not only slows down the growth of instabilities but it also restrains the expansion of the conductor, i.e., decreases the difference between its minimum radius at certain points in time ($\approx 300$ and 560 ns) and its initial radius. The larger the coating thickness, the lesser the conductor expansion, see figure 3(b).

3. Conclusion

Thus, it can be concluded that the deposition of a Ti coating 20–70 $\mu$m thick on a duralumin conductor greatly decreases the growth of large-scale instabilities on its surface compared to that observed on bare duralumin conductors. The effect of suppression is considerable when the magnetic induction on the conductor surface is comparable with $B_s$ determined by expression (2) and is less pronounced when the magnetic induction increases to about $B/B_s \approx 1.3–1.5$.

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