

Influence of surface finish on the plasma formation at the skin explosion

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Abstract. The paper reports on experiments to investigate how the quality of surface finish, i.e., surface roughness, influences the plasma formation in a skin explosion of conductors. The experiments were performed on a MIG terawatt generator with a current amplitude of up to 2.5 MA and current rise time of 100 ns. The plasma formation at the conductor surface and the evolution of the plasma boundary was recorded using a four-frame optical camera with an exposure time of 3 ns per frame. It is shown that the quality of surface finish little affects the onset of plasma formation in a skin explosion of stainless steel and St3 steel conductors at a magnetic field of up to 400 T.

1. Introduction

The electrical explosion of conductors is of unceasing interest due to its wide applications such as those for producing ultrahigh magnetic fields, imploding metal arrays, transporting energy in vacuum transmission lines, *etc.* One of the factors that limit the maximum magnetic induction in vacuum transmission lines of high-current pulse generators is the formation of plasma in a skin explosion [1–8], which occurs when the heat energy density reaches the sublimation energy density of a matter: the plasma bridges the interelectrode gap of a vacuum transmission line and decreases the efficiency of energy transport. Thus, one of the issues in designing the loads for high-current generators is to lengthen the time till the instant of plasma generation at the electrode surface and to decrease the rate of plasma expansion.

In this paper, we present experimental results showing how the quality of surface finish of conductors, i.e., their surface roughness, influences the plasma formation in a skin explosion.

2. Experiments

The experiments were performed on a MIG terawatt generator with a current amplitude of up to 2.5 MA and current rise time of 100 ns [9]. The diagnostic complex of the MIG generator included Rogowski coils, magnetic probes, voltage dividers, vacuum photodiodes, and an HSFC Pro four-frame optical camera with a minimum exposure of 3 ns per frame, allowing images of a load in the visible range at desired points in time. The generator load was stainless steel and



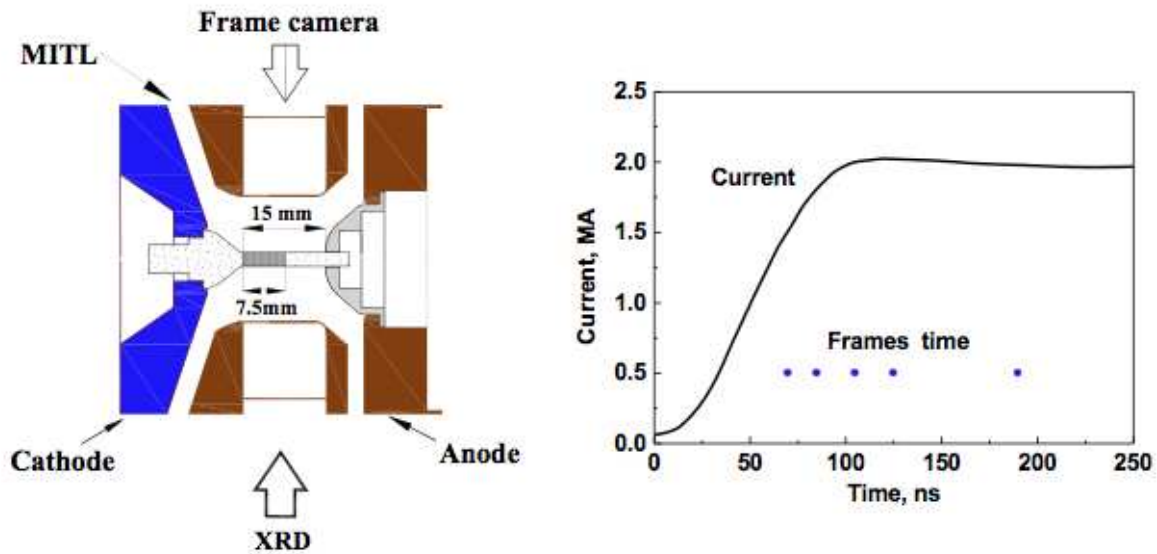


Figure 1. On the left: Load of the MIG generator; part of the load with varied surface roughness is marked by darker color. On the right: Typical waveform of the current with indication of time points for images in figure 2.

St3 steel conductors shaped as cylinders of diameter 2 mm and length 15 mm [10] half of which (about 7.5 mm) near either the cathode or the anode was treated by turning to a surface finish class of 6.3, corresponding to a roughness of maximum depth $40\text{ }\mu\text{m}$, while the other half was exposed to additional treatment to either increase or decrease the surface roughness. In a series of experiments, both halves of the conductors were exposed to additional treatment such that one part was polished and the other was made rough to a maximum depth of $\sim 100\text{ }\mu\text{m}$, being larger than normally made on a turning machine with a finish class of 6.3. At the instant of explosion, the skin layer depth calculated for metal conductivity under normal conditions was $250\text{ }\mu\text{m}$, which was larger than the maximum roughness depth. According to estimates with regard to nonlinear diffusion, the depth of magnetic field penetration is 3–4 times larger. Using the HSFC Pro camera, we recorded the surface plasma glow within differently treated conductor parts at a maximum magnetic field of up to 400 T.

Figure 1 shows a schematic of the load, in which part of the load with varied surface roughness is marked by darker color, and a typical waveform of the generator current with indication of time points for images in figure 2. The surface finish class equal to 6.3 was specified to allow wider variations in the roughness depth. According to microscope images, the surface roughness of the steel conductors after manufacturing was no greater than $20\text{ }\mu\text{m}$, and after polishing, it was reduced to a micron. Besides, the resolution of the HSFC Pro camera with an optical imaging system on the MIG setup was $\sim 40\text{ }\mu\text{m}$. The vacuum chamber in the experiments was pumped by an oil-vapor pump to a pressure of 10^{-4} Torr.

Figure 2 shows optical images of the surface glow for a stainless steel conductor of diameter 2 mm in $t = 70, 85, 110, 125$, and 190 ns after the onset of current flow and an image of its surface in reflected light before the experiment at $t = 0$. The additional treatment of this conductor consisted in polishing of its surface from the side of the cathode (from the point of gradual increase in diameter) through a length of $\sim 7\text{ mm}$ and in making the rest part of its surface rough to a depth of $\sim 100\text{ }\mu\text{m}$. After manufacturing, the conductor was treated in an ultrasonic bath with deionized water for 30 min, changing the water once, and after drying, the conductor was arranged in the load unit of the MIG generator for further pumping down.

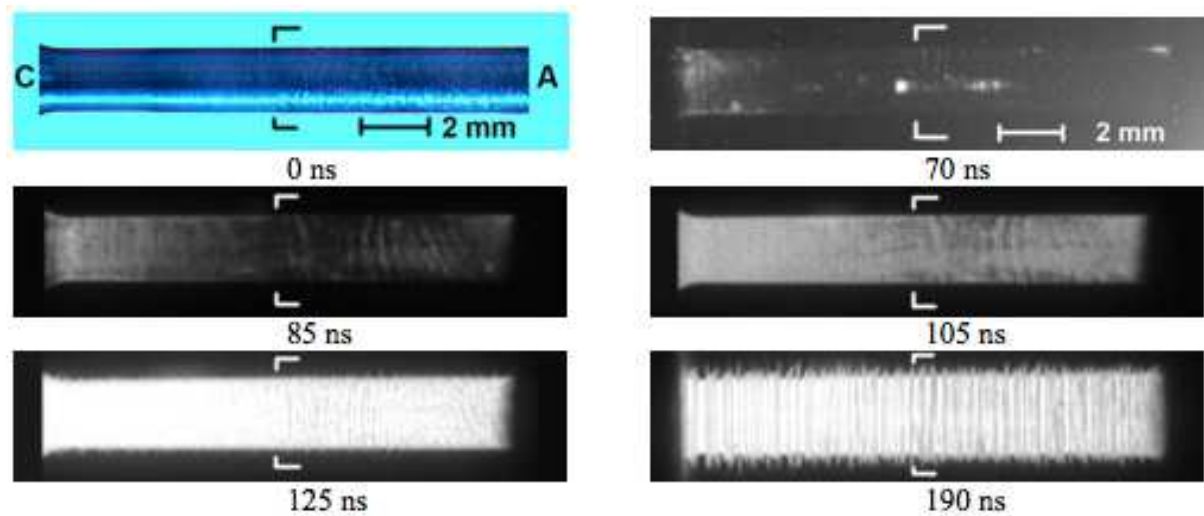


Figure 2. Image of the stainless steel conductor in reflected light at $t = 0$ and images of its surface glow with an exposure of 3 ns at different points in time after the onset of current flow. The rougher conductor region is marked by brackets.

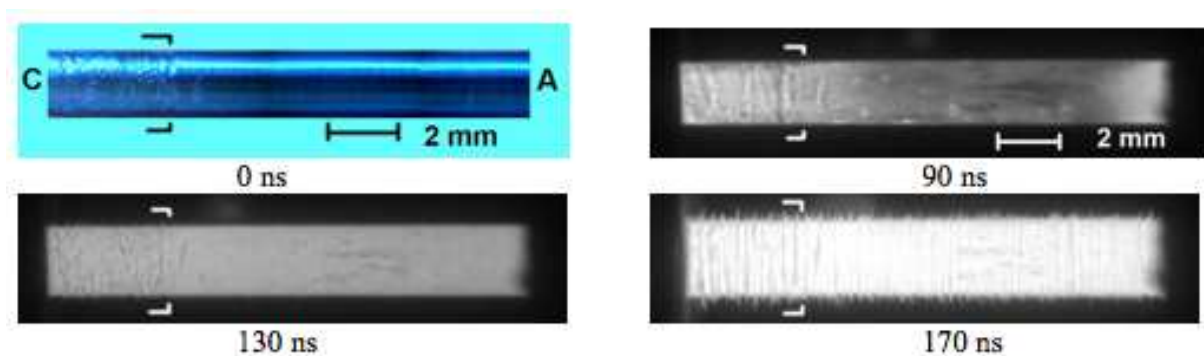


Figure 3. Image of the stainless steel conductor with rearranged locations of its rough and polished part at $t = 0$ and images of its surface glow at different points in time after the onset of current flow. The rougher conductor region is marked by brackets.

It is seen from the images that both parts of the conductor start glowing at about the same time but their glows differ. The glow of the polished near-cathode part is more homogeneous and probably it is therefore brighter. After 100 ns, the conductor increases in diameter with the formation of instabilities [11] and both polished and rough parts of the conductor begin almost simultaneously to behave in the same way. For excluding possible effects of the roughness location on the result, we made the cathode part of the load rough to a depth of 100 μm and polished its anode part such that its surface roughness was no greater than 2 μm . Figure 3 shows an image of a thus treated stainless steel conductor of diameter 2 mm at $t = 0$ and images of its surface glow in $t = 90$, 130, and 170 ns after the onset of current flow.

It is seen that at $t = 90$ ns, the near-cathode part of the conductor with higher surface roughness glows brighter than the polished near-anode part. However, at $t = 85$ and 105 ns in figure 2, it is also the near-cathode part, though polished, which glows brighter. After about 120 ns, the glow intensities of both conductor parts have leveled off. The same behavior is found for St3 steel conductors of diameter 2 mm and stainless steel conductors of diameter 3 mm.

At later points in time, instabilities were observed being more pronounced and expanding with higher rates at rougher load parts.

3. Conclusion

Reasoning from the foregoing it can be concluded that the pattern of plasma formation at the conductor surface in a skin explosion depends weakly on the quality of surface finish in the roughness range 1–100 μm . It can be stated that turning of electrodes to a surface finish class of 6.3 for operation at magnetic fields of up to 400 T is quite sufficient and their finer surface treatment is not required.

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