EFFECT OF FUSE ELEMENT CONFINEMENT ON THE RATE OF RISE OF FUSE ARC IGNITION VOLTAGE

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Abstract The effect of confinement on fuse arc ignition voltage is discussed. It has been demonstrated that consecutive disruptions in the fuse element differ due to the increase in metal temperature. Two factors are responsible for the course of arc ignition voltage: pressure and deformation of segments. Disrupts in nylon confinement with long modulus point to insufficient knowledge on the fuse element rupturing.

I. Introduction

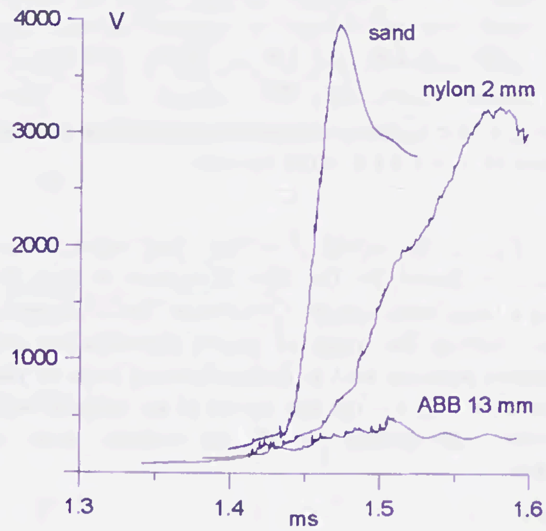

Fig. 1 Fuse arc ignition voltage I_p = 2.2 kA, copper fuse element 0.36 mm ∅ in various confinements.

Discussion on mechanisms of fuse element rupturing and arc ignition voltage generation cannot be yet concluded, for all presented ideas still show many imperfections. There is no doubt that fuse elements rupture at sufficiently high currents in accordance with a certain modulus defined experimentally many years ago by Nasilowski [1]. However, even the latest theories [2] are unable to prove rationally the dynamics of rupturing, initial geometry of breaks, the energy envolved in the proces, or the arc development in disruptions. In spite of difficulties in explanation of differences in the rate of rise of the fuse arc ignition voltage under various conditions, when the consideration of effect of the fuse element surroundings is neglected, a temptation of the application of a slightly modified old Baxters theory [3], describing the arc ignition voltage as a simple product of the number of disruptions and the arc root voltage, is still alive [4].

The fact that fuse arc ignition voltages measured for similar fuse elements in different enclosures differ substantially, Fig. 1, can be matched with the only possible conclusion: the voltage per gap must depend on fuse element confinement. However, the maximum number of created ruptures should not be questioned. It is difficult to relate this number to anything else than the energy comprised in the fuse element, thus influence of the surroundings is doubtful. In spite of such strong confirmation of the belief in the present knowledge on the fuse arc ignition rupturing, anxiety should be expressed, based on some experiments of the author presented below, demonstrating that the observations used for the recognised theories could be incomplete. In fact, the foundations of actual theories are static. Even the last report of Gomez [4] only provides static X-ray photographs of fulgurites. But are the disrupts always created randomly or maybe in a special order?

II. Current commutation fuses

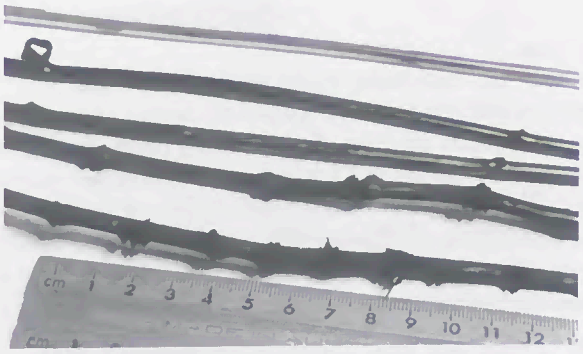

Fig. 2 Double nylon tube confinement of copper fuse elements 0,36 mm ∅ after current commutation I_p = 2,2 kA.

Above, in Fig. 2, photographs of nylon tubes applied as confinements of thin copper fuse elements of a current commutating fuse, after the fuse operation, and current take-over by the parallel varistor, are presented. Clearly visible regular breaks in the tubes can be noticed. The modulus of rupturing is of approximately 17 mm. The fuse elements were 0.36 mm in diameter, and the prospective current was of 2.2 kA giving the cut-off current density approximately of 12 kA/mm^2. The presented confinement consisted in two layers: the outer tube, 5 mm in the external diameter, which contained well fitted inside another nylon tube, 2 mm in the internal diameter. The confinement length varied from 0.15 m to about 1 m.

The modulus of confinement rupturing is completely different from that defined for the fuse element striation, which for the diameter of the applied wire, followed Nasiłowski [1], should be as short as about 1.3 mm. Even if creation of unduloids was supposed, when the modulus of rupturing was longer, the pictures could not match. Hence a question should be raised: does the observed pattern of confinement rupturing reflect that of the fuse element breaking by the moment of current commutation, ie, all the breaks created before commutation? If so, why these disrupts are created followed special pitch of 17 mm and not in aleatory points? Moreover, current commutation occurred at the voltage exceeding half of the arc ignition peak voltage. This means that the average distance between breaks should be shorter than double modulus of Nasiłowski [1].

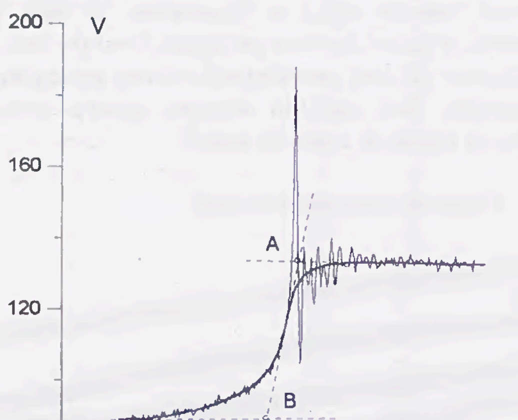

Fig. 3. Arc voltage of the first disruption in copper fuse element 0.36-mm ∅, I_p = 1.5 kA, ABB carrier

Other observations are also difficult to explain: damages in the breaks shown in Fig. 2 are very similar, suggesting that their "age" is comparable. Moreover, intermediate points in the enclosure, "ready" to disrupt in course of the rupturing process are missing. However, for lower currents a smaller number of disruptions is noticed.

At present it is difficult to answer these questions. They have been raised just to show that the knowledge on fuse arc ignition and the role of enclosure during that process are still unsatisfactory. Perhaps, such a state is due to the concentration of research on sand-filled fuses and exploding wires.

III. Characteristic of typical disruptions

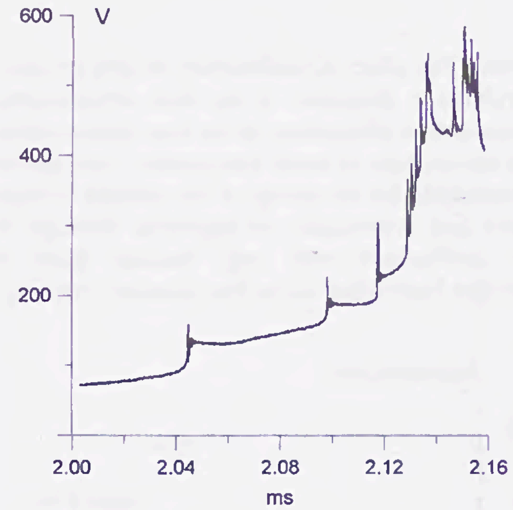

Fig. 4. Arc ignition voltage for copper fuse element 0.36-mm ∅, I_p = 1.5 kA, ABB carrier

In Fig. 3, the record of voltage drop between fuse terminals is shown, for the first disruption of fuse element in a large confinement. Continuous line of approximation, filtering the ripple of record digitalisation and the ignition peak, as well as broken lines of rates of rise are added. In Fig. 4, - the full record of arc ignition with consecutive disruptions up to the voltage peak is presented.

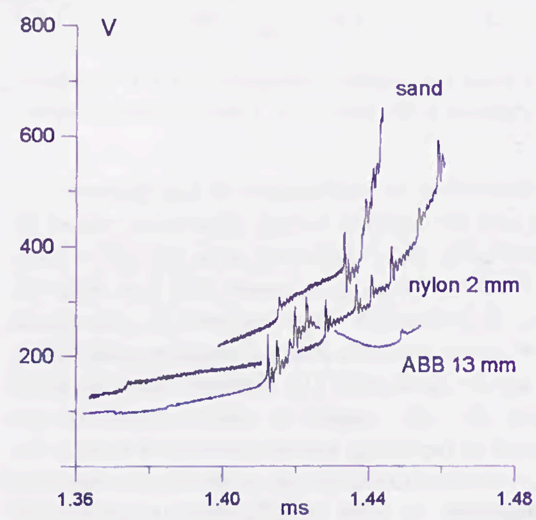

Fig. 5. Beginning of voltage traces presented in Fig. 1, I_p = 2.2 kA, copper fuse element 0.36-mm ∅

The first disruption can be considered typical for practically all confinements, since the first step on the voltage trace after zooming looks similarly for all confinements presented in Fig. 5. The time of the break creation, measured between points A and B is only 1 μs, and quasi stabilisation of disruption voltage take approximately less than 2 μs. Hence, assumed the process of stabilisation follows exponential curve, the time constant of this process is only about 0.5 μs.

It is worth noticing that the voltage across the gap rises monotonously, after a very narrow voltage impulse, Fig. 3. This impulse does not play any practical role in the arc ignition voltage build-up. Its width is dependent on the effect of compensation of plasma heating in the gap by the increase of plasma pressure or gap extension.

It is interesting that such a picture is observed in the beginning of rupturing process, when the temperature of the liquefied fuse element is relatively low. The voltage traces of following disruptions show larger and larger ignition impulses, Fig. 5. Assumed, the voltage impulse is due to a low electrical conductivity of plasma in the new-born gap, the width of the impulse reflects the energy needed for heating up the gap plasma.

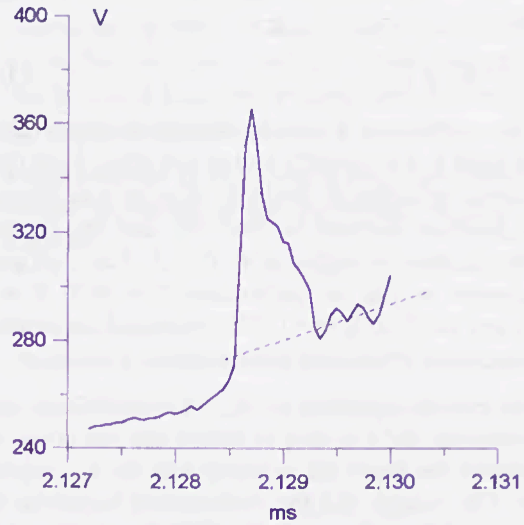

Fig. 6. Arc voltage of the fourth disruption in copper fuse element 0.36-mm ∅, I_p = 1.5 kA, ABB carrier

This energy rises as temperature or volume. The plasma volume in gap is defined by the gap itself, and the initial dimensions of gaps created in the process of rupturing is practically unknown. Most photographs, like those famous of Arai [5] deal with the fuse element frozen at a stage of fuse arc ignition process, which implies that a time has to pass from the instant of gap creation by the moment of recording. The value of approximately 0.1÷0.2 mm, reported many years ago by Kul'gavchuk and Novoskol'tseva [6], observed in exploding wires, can be understood as very rough. There is no proof that gaps of consecutive rupturings are equal in the moment of their creation.

A reliable information on plasma temperature in the moment of gap creation is missing. However, it would be difficult to assume that this temperature should significantly differ between consecutive rupturings. Therefore, a possible explanation of the temporal widening of voltage impulses related to rupturing of fuse element, can be founded upon the fact, that in time, the temperature of liquefied fuse element rises, and viscosity of a hotter metal reduces, which can lead to enhanced deformation of necks in the process of rupturing, i.e., more fuse element material can be transformed into plasma.

The voltage step between points A and B in Fig. 3 is of 44.7 V, which is higher than the arc root voltage, and higher than that suggested by Gomez [4] for sand fuses. The rate of voltage rise between points A and B is 41.4 V/μs, and for the voltage impuls 254 V/μs.

The frequency of rupturing is not constant, at least in the beginning of the process, Fig 4. For modest current densities two quite distinct time steps can be noticed, Fig. 6. In the beginning of the process the time between consecutive rupturings is reducing in each act of disruption, and finally stabilises at a value several times shorter than the initial one. This fact can be due to variation as time of the viscosity of liquid metal, or even presence of a thin hard core at the very beginning of rupturing process. It is true that the latter possibility was strongly criticised a time ago, nevertheless the sudden change of pace in the rupturing process requires a change of conditions, and only state of material can influence significantly properties of the fuse element.

IV. Large confinement

A large confinement plays practically the role of fuse element carrier. In such a case one can assume that the arc is ignited just in the air, and the plasma in gap between segments of the ruptured fuse element is marginally affected by confinement walls. The position of fuse element segments in the confinement is determined by the balance of forces due to the plasma pressure and inertia, since no support of the surroundings can be expected.

ABB expulsion fuse carriers with the internal diameter of about 13 mm were used. The fuse elements were made from a copper wire, 0.36 mm in the diameter, and from 50 mm to 200 mm in the length. Prospective currents were taken from the range of 1.2 kA to 12 kA, which ensured moderate current densities of several kA/mm^2.

The pressure of plasma in gaps pushes the segments of liquefied fuse element axially. This causes deformation of segments and their dislocation. In very fast processes, such as those in exploding wires inertia prevents movement of segments, but when the current density is moderate the rupturing slows down, and dislocation of segments cannot be excluded, especially in the case of large confinements. Extensive deformation of the segmented fuse element in large confinements, affecting the arc ignition voltage can be expected. Probably, irregularities of the voltage curve in Fig. 4 are due to such mechanism.

Therefore, only deformation of fuse element segments may be considered the basic factor affecting arc ignition voltage in large confinements.

In sand fuses and in close confinements the position of fuse element segments is better controlled. Thus, the voltage traces are more regular, Fig. 2.

V. Close confinement

In Fig. 7 traces of arc voltage referring to 2-mm ∅ nylon confinement and 1-mm ∅ PTFE enclosure rise at different rates and acquire different maxima, but the time to maximum is similar. Since the number of voltage steps is approximately conform to the modulus of rupturing of the fuse element, only plasma electrical conductivity in breaks can be responsible for the difference in shapes of voltage curves.

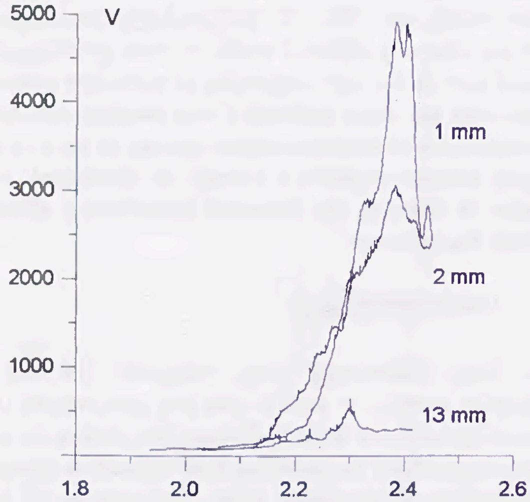

Fig. 7. Arc ignition voltage in close enclosures: PTFE 1-mm ∅, nylon 2-mm ∅ compared to ABB carrier, copper fuse element 0.36-mm ∅, I_p = 1.2 kA.

In first instances the temperature of new-created plasma in gaps is connected with the boiling point of fuse element material, so only pressure can be considered the basic factor affecting electrical conductivity. Pressure in fuses is controlled by the confinement diameter. Thus its effect can be evaluated in a simple way.

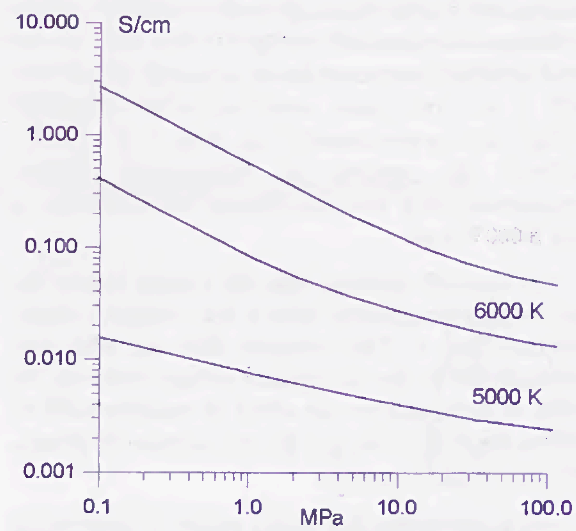

Fig. 8. Electrical conductivity of copper plasma at low temperature and high pressure

Rough characteristics of electrical conductivity σ of copper plasma for relatively low temperature, calculated after Kovitya [7], presented in Fig. 8 indicate very moderate reduction of σ by increase of pressure p. The function $\sigma = f(p)$ may be approximated by a simple formula:

$$\sigma = k \cdot p^{-m} \tag{1}$$

The coefficients $\boldsymbol{k}$ and $\boldsymbol{m}$ depend on temperature. E.g. for 5000 K $\boldsymbol{k}$ = 0.00079, and $\boldsymbol{m}$ = 0.2705. With these coefficients, reduction of conductivity σ by half due to a tenfold pressure increase is observed, and the pressure 100$\boldsymbol{p}$ brings about reduction of σ by 3.5. The coefficient $\boldsymbol{k}$ and power $\boldsymbol{m}$. rise as temperature. For 6000 K $\boldsymbol{m}$ = 0.4877, and for 7000 K $\boldsymbol{m}$ = 0.582. Increased temperature the conductivity σ becomes more sensitive to pressure.

The records presented in Fig. 7 roughly comply with this evaluation, for it is easy to notice that the larger the confinement the lower the pressure and the arc ignition voltage. The voltage and the confinement variations approximately follow formula (1). However it should be underlined that the larger the confinement, the stronger the effect of deformation of fuse element segments, and the voltage curve becomes more and more rugged. Hence the voltage can reduce faster than function (1). Prediction of arc ignition voltage on basis of calculation of pressure in flexible confinements is extremely difficult.

It was shown [8] that ablation of confinement is negligible in the arc ignition process.

One can conclude that mainly pressure is responsible for the arc ignition voltage in close confinements. The effect of deformation of segments is limited.

VI. Sand fuses

In sand fuses the fuse element is practically immobilised, which facilitates prediction of its behaviour in the arc ignition process. but on the other hand, the complicated structure of filler makes difficult evaluation of pressure variation in disruptions. A virtual confinement may be introduced. However its diameter need not be constant. Influence of sand dilatation and condensation of metal vapour should be expected.

The effect of sand filler on fuse arc ignition voltage may be estimated by comparison of the voltage trace with a similar one recorded for a given regular capillary, Fig. 1.Applied of relation (1), and plasma temperature 5000 K, the virtual diameter of sand "confinement" would be comparable with the fuse element diameter, if no enlargement of diameter of the nylon confinement were considered.

VII. Conclusions

- Initial course of fuse element rupturing process in all examined confinements is similar.
- Consecutive voltage steps due to fuse element rupturing differ one another probably because of rising temperature of liquid metal.
- The nature of effect of fuse element confinement on the fuse arc ignition voltage - time characteristics is related to plasma pressure and deformation of fuse element segments.
- Large modulus of rupturing of nylon confinement reveals deficiency of our knowledge on fuse arc ignition.

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