# THE NUMBER OF ARCS INITIATED DURING STRIATED DISINTEGRATION OF THE UNIFORM STRIP h.b.c. FUSE-ELEMENTS AT a.c.A SHORT-CIRCUIT CURRENT INTERRUPTION

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## PRINCIPAL SYMBOLS

$d$ - fuse-wire diameter, mm
$h_u$ - unduloid disintegration modulus of wire-fuse-element, mm
$h_s$ - striated disintegration modulus of wire fuse-element, mm
$M_f$ - striated disintegration modulus of strip fuse-element, mm
$i_f$ - let-through current limited by fuse, A
$j$ - current densinty in fuse-element, $A \cdot mm^{-2}$
$l$ - fuse element length, mm
$L$ - circuit inductance, H
$n_a$ - number of arcs appearing at striated disintegration
$S$ - fuse-element cross-section area, $mm^2$
$S_s$ - area of smallest short-circuit cross-section of fuse element, $mm^2$
$\varepsilon$ - magnetic field energy pervolume unit required for copper or silver fuse-element at multi-arc disintegration, $Wsmm^{-3}$
$U_p$ - arc overvoltage peak value on all arcs at striated disintegration, V

1. INTRODUCTION. Since a very long time now-attempts have been made to explain the operation of h.b.c. fuses in the short-circuit conditions. The present state of knowledge does not permit a theoretical explanation of all the h.b.c. fuse-element disintegration phases. Only some of the phenomena of the element deformation and disintegration due to the short-circuit current have been explained by a number of theories [1,2,4,7÷10,12]. It is the result of the still incomplete investigations in the mentioned field. This paper gives some supplementary information in this respect.

2. DISINTEGRATION OF FUSE-ELEMENTS. Studies contributed to the establishment of two basically controversial points of view on the course of the phenomena which accompany the operation of h.b.c. fuses. The first one, according to Mayer [9], known for a number of decades, says: the whole fuse-element charges from its solid state into plasma through a liquid state in the result of extensive temperature rise caused by the Joule'an heat. The second one, commenced by Kleen [7],

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does suggest that only some parts of the fuse-element change into plasma whilst the rest of the fuse-elements remains in its solid or liquid state.

2.1. Disintegration of wire fuse-elements. Phenomena relating to the disintegration of wire elements placed in a fine sand have been relatively quite precisely investigated [e.g. 2, 4, 10]: at not very high current densities the cylindrical wire transit into an unduloid shape, during the pre-arcing time, and then over the arcing time it is in form of drops detached by the arcs. The average unduloid modulus was found [10,11] to follow from the action of the surface tension forces and the pinch-forces and is determined by the relation:

$$h_u = 5.3d \quad \text{for} \quad j_{Ag} < 900d^{-0.78} \qquad (1)$$

Extensive study by Nasiłowski [10,11] has shown that at high short-circuit currents wire elements form no unduloids but disintegrate according to the segment mechanism, the so-called striated mechanism. According to it, the striation modulus is constant and is given by

$$h_s = 0.555 + 2.08d \quad \text{for} \quad j_{Cu} \geq 4300d^{-0.68} \qquad (2)$$

After the current interruption remains a fulgurite i.e. the sintered element metal with sand. In the case of streak disintegration the fulgurite involveld has a laminar structure composed of rings streaks of a bright colour - metal rests - and of a dark colour - post - arc rests (see Fig.1).

The possible cause of striation is explained by Nasiłowski by mechanical vibration of the wire, to which the fuse element is subjected at the pre-arcing time. Theoretical studies of this phenomenon have shown, that at a high-density current flow through the wire, mechanical vibration generated by magnetothermoelastic processes causing lateral cuting stresses may appear in that wire [12].

The initial stage of striation recently has been done by X-rayflash studies by Arai [1] at the current-densities more than 14 kA/mm$^2$. The exposition was abt.every 15 $\mu$s. From the Arai's photographs the disintegration shows a segment nature with a determined modulus. In here the wire has in no case any shape that would resemble an unduloid (Fig.1). The very beginning of the wire striation after Arai is caused by the wire thermal buckling. But this buckling was also very clear observed previously and described in [3].

2.2. Disintegration of strip fuse-elements. The plain strip fuse-elements disintegration has been relatively less investigated. But it is known that strip fuse-elements also disintegrate according to the striated mechanism. Now the fulgurites have a similar structure to that from wire fuse-elements. The fulgurite after a strip element has an oval cross section whereas after the wire element a round cross-section (Fig.1).

Before a strip fuse-element undergoes striated disintegration it also gets waved by a thermal shock. The wave length is considerably bigger than the striation modulus and depends not on the width but on the thickness of the fuse-element. The wave amplitude increases with the current-density increasing [5].

The causes of striated disintegration of strip fuse-elements are still more complicated than those of wire fuse-elements. Because of the limited place the author confined to give the results of study of disintegration modulus without ony explanation of the physical causes. The dependence of the striated disintegration modulus on the strip width at constant thickness [6] is only a special case. At present, results will be given with a high degree of generalization for different dimensions of the fuse element.

3. LABORATORY DETERMINATION OF THE DISINTEGRATION MODULUS

3.1. Model fuses. Fuses with a cylindrical 26 mm dia., chamber (Fig.2) were used for the tests. The element active length was 60 mm. The construction makes taking readable X-ray pictures easy.

3.2. Strip fuse-elements. The elements were cut off from a copper band 99.9 % Cu . The fuse elements had a length of 60 mm, a width of 2.5; 5; 7.5; 10; 12.5 and 15 mm and a thickness of 0. 052; 0.1; 0.144; and 0.184 mm. It gives the cross-sectional areas within the range from 0.13 to 2.76 $mm^2$. All the tests were made on elements of the same material as regards its chemical composition, thermal treatment and thickness tolerance. Fuse-elements was selected within similar width of tolerance of ±2 % .

3.3. Preparation of the fuse-elements. After putting the fuse-elements in their place the fuses were filled with fine quartz sand 99.24 % $SiO_2$ having a granulation of 0.4 to 0.6 mm and a massdensity of the grain material equal to 2.85 $g/cm^3$ or 1.64 $g/cm^2$ of the loose sand. In one corner of the cover there was an opening closeable by means of a nut for filling the fuse with sand. The package of the sand was carried out in a shock shaker having a pitch of 20 mm and a cycle of 48 shocks per minute. The shaking process lasted 5 minutes. The fuse shaking method applied in the tests ensured reliable and repeatable filling of them with sand as confirmed by the fact that the increase in weight amounted to abt. 20 to 22 % in comparison with the weight before the shaking operation.

3.4. Test circuit. The tests were carried on in a.c. circuit with prospective currents from 3.8 to 37,4 kA at a voltage of 230 V, 50 Hz and $\cos\varphi = 0.2$. Three dry transformers of special construction having a power of 500 kVA and a primery voltage of 15 kV and a secondary voltage of 220 V were applied. In order to avoid any considerable differences in the disintegration current for fuse-elements with the same dimensions the tests were carried out at symmetrical short-circuit current at the first sine half-wave.

Measurement of the let-through (disintegration) current was taken by a loop record with a non-inductive shunt of resistances 1 or 5 mΩ. Measurement of the voltage at fuse-element were taken by a cathodic oscillograph with RC potential divider.

4. TEST RESULTS. All 20 varieties of fuse-elements were subjected to the tests and 10 tests on each type of element were made. The disintegration current density amounted to from 6 to 18 kA/mm$^2$, and the disintegration time from 10 to 120 µs. After each test an X-ray picture was taken of the fuses at a scale of 1:1. Then, the X-ray pictures served for determining the disintegration modulus for the strips(Fig.3). In some cases (at small cross-sectional area of the strips) the structure of the fulgurite involved was highly brittle and there was no possibility of taking it out of the fuse without breaking into pieces.

Similarily as it was the case with wire fuse-elements the fulgurite along the longitudinal axis represented a tube with a characteristic laminar structure having an oval opening, being composed alternately of bright-metalic streaks and dark ones where the arc burned. The distance between the bright and dark streaks was taken as the disintegration modulus. The average modulus was established on the basis of the number of streaks at an element length of a rythmic, regular, disintegration with a disintegration modulus close to average.

It is to be stressed that a probable number of streaks was assumed for the calculations, and not the true number of them which may appear in the first moment of a sudden disintegration of the element. It is possible that their number may be different at the arc ignition moment than that at the arc quenching instant because of the fact that some of the arcs could get connected and show longer arc breaks in the X-ray pictures. That is why only strip lengths with regular disintegration were taken into consideration.

Tests, during which the disintegration process was limited by shunting the fuse with a switch at the moment when the voltage peak value appeared at it, may be considered as a verification of the above problem to some extent. The disintegration modulus calculated in such case was the same as in the case of a fuse after breaking the current - without shunting.

The modulus as calculated on the basic of the X-ray pictures were subjected to statistical elaboration and the confidence interval for the average value of the modulus at a confidence level of 0.95. Fig.4 shows the range as determined by the confidence regions of the worked-out data collection.

5. DETERMINATION OF THE GENERAL DISINTEGRATION MODULUS DEPENDENCE. Whilst taking readings of the disintegration modulus of various elements it has been found that strips of the same

cross-sectional area in spite of their different widths and thicknesses have the same modulus from the statistical point of view.

This means that it is only the cross-sectional area of the fuse-element that can be taken as a parameter for characterizing the disintegration modulus, and the width and thickness of the strip merely effects the volume of the fulgurite.

The below given dependence (3) has been obtained for the collection of the disintegration modulus mean values in dependence on the cross-section of the strip by the method of least squares:

$$\overline{M}_f = AS^B = 3.07\ S^{0.256} \qquad (3)$$

The A and B parameters may change within the following limits $A = 2.78$ to $3.19\ mm^{1-B}$ and $B = 0.2101$ to $0.3015$ in order that the dependence (3) has its course still on the determined range of average values.

In the case of strip fuse-elements of a small width of less than 1 mm the disintegration modulus should be close to the wire elements disintegration modulus according to formula (2) - Fig.4, curve 2. This condition may be fulfilled by the dependence (3) but with a slightly different exponent B, namely:

$$\overline{M}_f = 3.07\ S^{0.3} \qquad (4)$$

The above formula is one of the permissible deviations from the least squares curve (3), but it is of a more general character.

Whilst investigating the dependence of the modulus on the disintegration current density no logical dependence has been found. It may be stated only that in order to get a regular disintegration with a probable average modulus according to formula (4) it is required that the current density shall satisfy the following inequality:

$$j \geqslant 4660\ S^{-0.29} \qquad (5)$$

This condition requires the fuse-element to attain a high temperature in a shorter time than 5 ms.

Further tests show that the magnitude of available energy per element unit volume for rapid and regular disintegration at the whole length of the element shall correspond to the following relation.

$$\varepsilon = Li_f^2 : 2Sl \geqslant 25\ Ws.mm^{-3} \qquad (6)$$

It should be added that the conditions (5) and (6) must be complied with simultaneously in order that the formula (4) gives good results. If only the condition (5) is fulfilled, the element may not disintegrate into streaks, but undergo common melting as it was found to take place e.g. in a circuit with a voltage of 24 V and $L \approx 0$ [6].

On the other hand fulfillment of the condition (6) only also leads to a different disintegration than the regular striated one. In such case a non-modulus disintegration of the strip may take place (Fig.5).

6. NUMBER OF ARCS APPEARING AT STRIATED DISINTEGRATION.
When the disintegration module is known according to formula (4) it is possible to determine the number of arcs burning at the fuse-element length following from that modulus.

$$n_a = l : M_f \qquad (7)$$

The number of arcs calculated on the basis of formula (7) may have a deviation of ±1 depending on the fuse-element length and distribution of the interruptions along strip. The formula (7) may also find application for fuse-element with long narrow strip parts of uniform cross-section area $S_s$, but only when the following condition is fulfilled:

$$S_s < 0.65\ S \qquad (8)$$

Condition (8) ensures that it is only the narrow portions of the strip will undergo streak disintegration, as it is shown in the Figure 6.

A comparison of the results based on calculation with those on the measurement of the number of arcs burning at striated disintegration in the carried out tests has proved a conformity of the calculation with a statistical deviation of up to 20 %.

7. CONCLUSIONS
1) In the case of fuses with strip elements of an uniform cross-sectional area the calculated on the basis of the formula (7) number of arcs appearing at the element disintegration is compatable with the results of experiment, provided that the conditions (5) and (6) are complied with.

2) The disintegration module as well as the number of arcs can be calculated with a good result for strip fuse-elements with constrictions in the strip of a uniform cross-section area. In this case, however, the condition (8) must be also satisfied in addition to conditions (5) and (6).

3) Fuse-element strips of a relatively large width of more than 12 mm may disintegrate according to a non-modulus mechanism, if the condition (5)in not satisfied - Fig. 5.

4) Taking into account the maximum statistical errors, it may be assumed that the wire disintegration modulus as given by Nasiłowski according to formula (2) may also find application for the disintegration of strips. In such case the calculated module will be slightly shorter than that in reality (Fig.4).

5) Knowledge of the number of striated disintegration arcs makes calculation possible of the arc ignition voltage at a single streak in the process of over-voltage generation. But

it is necessary to know the peak voltage at the disintegrating strip fuse-element. This voltage one can calculate on the basis of the following formula [6]:

$$U_p = \rho_o \, l \sqrt{\frac{i_f}{S_s}} = \rho_o \, l \sqrt{j}$$

where: $\rho_o$ - fuse-element disintegration resistivity at peak voltage and let-through current instant, $\rho_{ow} = 0.5 \Omega A^{0.5}$ - for wire element, $\rho_{os} = 0.4 \Omega A^{0.5}$ - for strip element.
As proved by the author in his numerous papers the above formula gives good results at conditions (5) and (6) satisfied in comparison with measurements, the maximum statical error being up to ±15 %.

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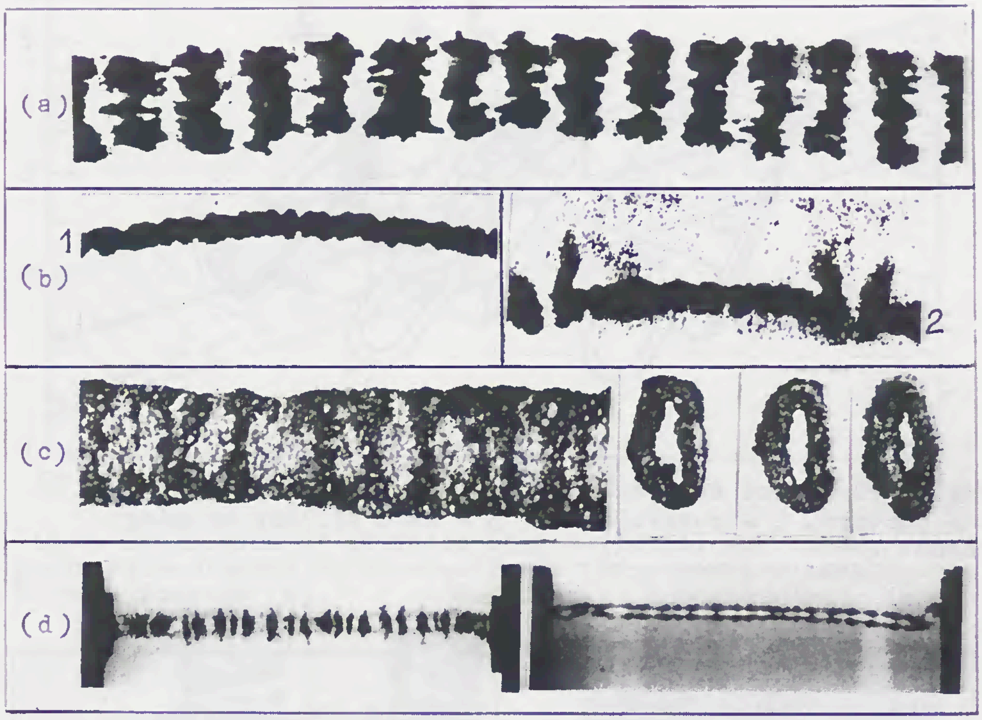


Fig.1. Fulgurities remaning in the h.b.c. fuse after multiple arcing quenching (a) typical X-ray photograph ( section ) of the disintegration modulus ( Ag wire, d = 0.3 mm, $j_f$ = 3 kA $mm^{-2}$ [10],(b) X-ray flash photographs of deformations and disruption of Ag wire ( d = 0.5 mm, $j_f$ = 4.14 kA $mm^{-2}$), 1 - $t_x$ = 38 µs, 2 - $t_x$ = 68 µs, $t_x$ - the time from the point 0 on the voltage wave on the oscillograph to the instand the photograph was taken, (c) photograph( section ) of the striated( modulus ) fulgurite ( Cu strip fuse-element with uniform cross-sectional dimension 5 mm x 0.1 mm, $j_f$ = 8 kA $mm^{-2}$), ( d) X-ray photograph of the disintegration modulus ( Cu strip, 5 mm x 0.1 mm, $j_f$ = 8 kA·$mm^{-2}$).

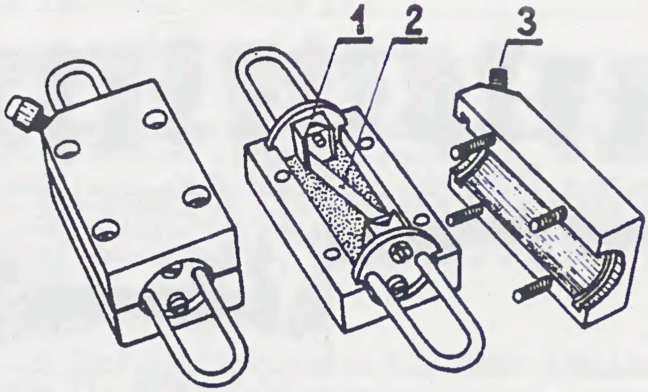


Fig.2. Fuse-link as used in test.
1 - contact, 2 - fuse-element, 3 - sand filling opening channel.

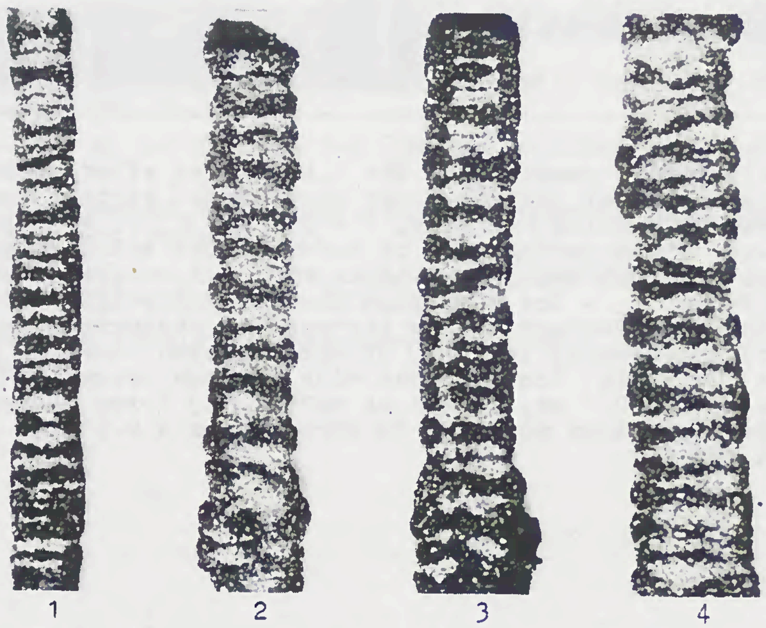


Fig.3. Fulgurities remaining in the h.b.c. fuse after multiple arcing quenching (Cu strip fuse-element with uniform cross-sectional dimensions: 1 - 2.5 x 0.18 $mm^2$, 2 - 5 x 0.1 $mm^2$, 3 - 5 x 0.14 $mm^2$, 4 - 10 x 0.1 $mm^2$).

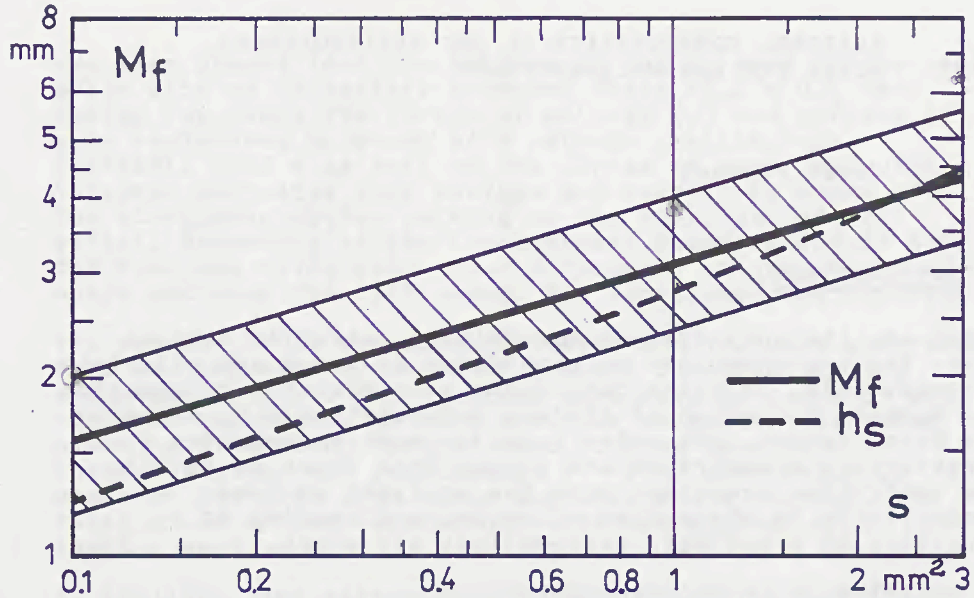


Fig.4. Dependence of striated disintegration modulus $M_f$ of strip fuse-element on short-circuit cross-section area $S_s$. $M_f$ - on formula (4), $h_s$ - on formula (2).

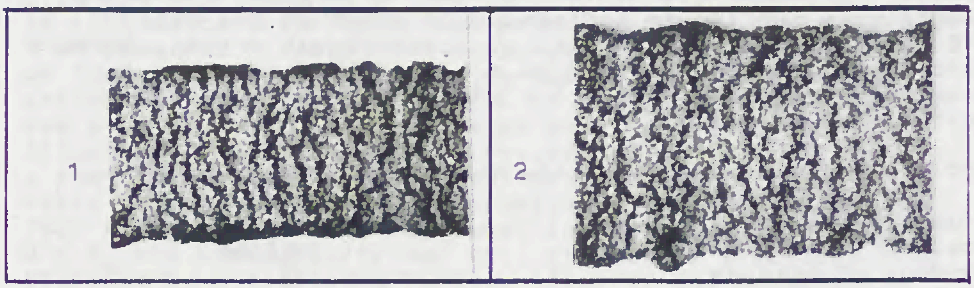


Fig.5. Photograph section of the disintegration fulgurite non-modulus( Cu strip fuse-element with uniform cross-sectional dimension: 1 - 5 = 15 x 0.05 mm$^2$, 2 - 5 = 20 x 0.05 mm$^2$, 1 = 60 mm). U = 260 V, 50 Hz, $j_f$ = 5 kA·mm$^{-2}$

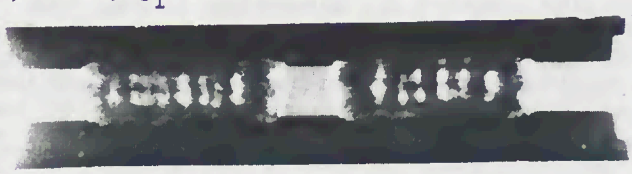

Fig.6. X-ray photographs of disintegration of copper strip fuse-element. U = 260 V, 50 Hz, $j_f$ = 7 kA·mm$^{-2}$, S = 5 x 0.1 mm$^2$ $S_s$ = 2.5 x 0.1 mm$^2$, 1 = 60 mm, $l_s$ = 15 mm x 2.