ELECTROTHERMAL FUSE-ELEMENT DISINTEGRATING MECHANISM BY SHORT-CIRCUIT CURRENTS

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Summary

The paper gives a new hypothesis of the striated disintegration of the fuse-elements. The hypothesis name is electrothermal mechanism of the striated disintegration. From general assumptions of the synergetics is shown a possibility of generating of the electrothermal instabilities by means of the relation of dispersions. For a simplified model by a numerical analyses are determined the conditions of the arising of those instabilities.

1. Introduction

During short-circuit interruption a uniform fuse-element of h.b.c. fuses disintegrates in form of the stration. Such a multiple arc-ignition shows also the shoulders (thicker parts) of notched fuse-element if those shoulders length, between notches is sufficient and the prospective current is large enough. Criteria of striation appearance for uniform wire elements, in form of a relation: the wire diameter versus the current density, are given by Nasiłowski[8]. Experimental formulae for averange modulus h_w of striation for Cu and Ag wires is

$$h_w \doteq 0.555 + 2.08 \cdot d \qquad (1)$$

where: d - wire diameter, h_w and d in mm. But for uniform strip Cu and Ag elements that modulus h_s in mm, also established experimentally by Hibner[5] is

$$h_s = k_c \cdot S^{0.3} \qquad (2)$$

in which: k_c= const. = 3.1 $mm^{0.4}$, S - strip cross-sectional area in mm^2. A defined minimal current density and a minimal energy stored in the circuit at the instant of disintergation shall be fulfilled to get stration.

In the literature there is a number of the hypothesis given on the striation origin in the frames of discussion on the wire explosion. The major are:

a) magneto-thermo-elastic vibrations, Liebiediew[7],
b) magneto-hydrodynamic vibrations, Liebiediew[7],
c) wire vibrations, Nasiłowski[8],
d) nonuniform wire heating, Liebiediew[7].

In the case a) and b) the disintegration is due to local deviation of the wire from the straight line or local deviation of the outer wire surface from cylinder. In the case c) the vibration starts immediately after first arc-ignition, whereas in the case d) some geometrical or structural inhomogenities generate the disintegration. According to up to date opinion (e.g. Liebiediew[7]), which shares also author of this paper, the pinch-effect in an exploding wire in h.b.c. fuses can be neglected as a cause of disintegration suggested by hypothesis a) and b). However, the last one still have lot of followers hypothesis b). X-ray pictures showed, Arai[1,2], that the arc ignites only after the wire disintegration, which is in contradiction to the hypothesis c). Author is of opinion that hypothesis d) is the most adequate to reality, however, it explains the initiation of stration only.

The paper gives an attempt of extention of this hypothesis, which brought practically a new one, called farther the electrothermal mechanism.

Outgoing from the general assumptions of the synergetics, Wasiliew[9], has been shown a possibility of appearance of the electrothermal instability by means of dispersion relations. For a simplified model by the numerical approach the conditions of that instability arising havebeen defined.

2. Striated disintegration as a dissipative structure

Dissipative structures are one of forms of the selforganization of the active systems, Wasiliew[9]. These structures are leading to distortion of the uniformities of non-equlibrized thermodynamical systems. Such structures show very often the periodical distribution in the space. The active systems are described by the nonlinear equa-tions of diffusion. So our exploding wire, as an active system is described by the equation of the electromagnetic field diffusion

$$\frac{\partial j}{\partial t} = \frac{1}{\mu_0} [-\nabla (\nabla \cdot \frac{j}{\sigma}) + \nabla^2 (\frac{j}{\sigma})] \qquad (3)$$

and the transient heat conduction equation

$$\frac{\partial T}{\partial t} = \frac{j^2}{\rho \cdot c_p \cdot \sigma} + \frac{1}{\rho \cdot c_p} \nabla \cdot (\lambda \nabla T) \qquad (4)$$

where: ρ, c_p - mass density and specific heat,

σ, λ - electrical and thermal conductcvities respectively, whichare functins of the temperature,

T - tewmperature,

j- vector of density currents.

In active systems described by (3) and (4) can arise dissipative structures, Wasiliew[9], - i.e. stration.

3. Conditions of arising of the electrothermal instabilities

During fast heating up by Joule'an heat some geometrical and structural nonuniformities of a conductor cause small local overheating. Because the time-constant of diffusion in equation (3) for Cu and Ag is 2 order smaller than the time-constant of equation (4), Jakubiuk[6], so according to equation (3) will be overheated nearly adiabatic a number of cross-section perpendicular to the current direction. But over a it can not be overheated. This observation striation for the wire diameter above certain magnitude, Nasiłowski[8]. So one can assume that the temperature distribution along a wire, being already in melted state, is stochastical one.

In electrothermal analysis we get the temperature distribution in the form

$$T(z,t) = T_o(t) + \sum_{k=1}^{\infty} T_k(t)\, e^{ikz} \qquad (5)$$

where: $k = \frac{2\pi}{\lambda_k}$ - wave number, $i = \sqrt{-1}$,

λ_k - wave length,

$T_o(t)$ - constant temperature component along wire axis,

$T_k(t)$ - amplitude of k-waves of temperature.

Assuming $\rho \cdot c_p$ = const., λ = const. and

$$\sigma = \frac{\sigma_{oo}}{1 + \alpha \cdot \Delta T} \qquad (6)$$

in which: σ_{oo} - electrical conductivity in the temperature T_{oo}, $\Delta T = T - T_{oo}$,

T_o - one can get the relation

$$\frac{dT}{dt} = \frac{j^2}{\rho \cdot c_p \cdot \sigma_{oo}} (1 + \alpha \cdot \Delta T) \qquad (7)$$

But the amplitude T_k of k-temperature wave fulfils the equation

$$\frac{1}{T_k} \frac{dT_k}{dt} = \frac{1}{\rho \cdot c_p} \cdot (\frac{j^2}{\sigma_{oo}} \cdot \alpha - \lambda \cdot k^2) \qquad (8)$$

From (8) is seen that short wave temperature distortions will be damped whereas long wave ones will grow. The boundry wave expresses the relationship

$$\lambda_{kb} = \frac{2\pi}{j} (\frac{\sigma_{oo} \cdot \lambda}{\alpha})^{0.5} \qquad (9)$$

Because in a wire arise mainly short-wave distortions it shell be expected appearance of the waves $\lambda_k \geq \lambda_{kb}$. For example for Cu wire and $j = 5\ kA \cdot mm^{-2}$ - $\lambda_{kb} = 2.95$ mm. From this the modulus is $h_g = 0.5 \cdot \lambda_{kb} = 1.47$ mm, i.e. after (1) it gives the wire diameter 0.44 mm. The results, despite simplified analysis, are close to the experimental results.

4. Investigations of the development of electrothermal instabilities

Electrothermal instabilities can arise if the fuse-element is in liquid dynamic overheated state above the boiling point. In such conditions the conductivity depends on the temperature and the mass density by means of exponent γ ($\gamma>1$) in the relation

$$\sigma = \sigma_{o1} \cdot \left(\frac{T_{o1}}{T} \right)^{\gamma} \quad (10)$$

In calculations the temperature was taken as

$$T(z,t) = T_o(t) + T_1(z,t) \quad (11)$$

where the component T_o fulfils the equation

$$\frac{dT_o}{dt} = \frac{j^2}{\rho \cdot c_p \cdot \sigma_{o1}} \cdot \left(\frac{T_o}{T_{o1}} \right)^{\gamma} \quad (12)$$

wheras T_1 the equation

$$\frac{\partial T_1}{\partial t} = \frac{j^2}{\rho c_p \sigma_{o1}} \left[\left(\frac{T_o+T_1}{T_{o1}} \right)^{\gamma} - \left(\frac{T_o}{T_{o1}} \right)^{\gamma} \right] - \frac{\lambda_{o1}}{\rho c_p} \frac{\partial^2 T_1}{\partial z^2} \quad (13)$$

where: $\sigma_{o1}, \lambda_{o1}$ - values in temperature T_{o1}. Introducing non-dimensioned variables

$$\vartheta = \frac{T}{T_{o1}}, \quad \vartheta_o = \frac{T_o}{T_{o1}}, \quad \vartheta_1 = \frac{T_1}{T_{o1}}, \quad (14)$$

$$\eta = \frac{z}{l_o}, \quad \tau = \frac{t}{\rho \cdot c_p \cdot \lambda_{o1}^{-1} \cdot l_o^2}$$

in which: l_o - characteristic linear parameter,

and taking the non-dimensional constant

$$D = \frac{j^2 \cdot l_o^2}{\sigma_{o1} \cdot \lambda_{o1} \cdot T_{o1}} \quad (15)$$

the equations (12) and (13) are reducing to the form

$$\frac{d\vartheta_o}{d\tau} = D \cdot \vartheta_o^{\gamma} \quad (16)$$

and

$$\frac{\partial \vartheta_1}{\partial \tau} = D \cdot \left[(\vartheta_o + \vartheta_1)^{\gamma} - \vartheta_o^{\gamma} \right] + \frac{\partial^2 \vartheta_1}{\partial \eta^2} \quad (17)$$

Equation (16) is to be integrated analytically. By $\gamma>1$ and initial condition $\vartheta_o(\tau=0) = 1$ the solution is done by

$$\vartheta_o = [1 - (\gamma - 1) \cdot D \cdot \tau]^{1/(\gamma-1)} \quad (18)$$

From (18) outcomes, that in a finite time span the temperature will reach the infinity, what is possible in a non-linear relation only.

The solution of equation (17) was done numerically for the initial conditions given in the Fig.1 and boundry conditions

$$\left. \frac{\partial \vartheta_1}{\partial \eta} \right|_{\eta=0} = \left. \frac{\partial \vartheta_1}{\partial \eta} \right|_{\eta=1} = 0 \quad (19)$$

which denote thermal isolation of the wire section.

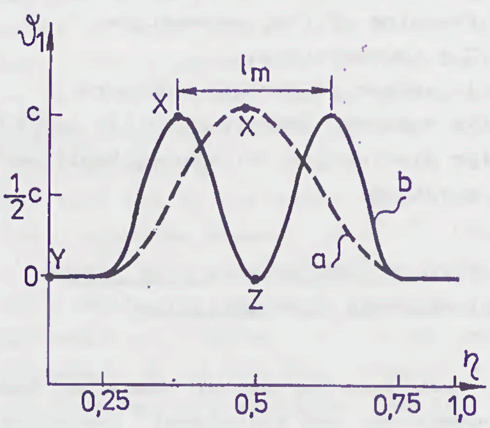

Fig. 1 Initial conditions for equation (17) X,Y,Z - points for which the temperature profiles are given in Fig.2. l_m - distance between overheated regions.

The calculations are made for different magnitudes γ, D and initial amplitudes of the distortion c (Fig.1). Exemplary results of the calculations are given in Fig.2. To enable comparison the profiles are given as the function of $D \cdot \tau$. The diagrams show the temperature profiles of ϑ_o and ϑ_1 in different wire points (Fig.1). Moreover for a

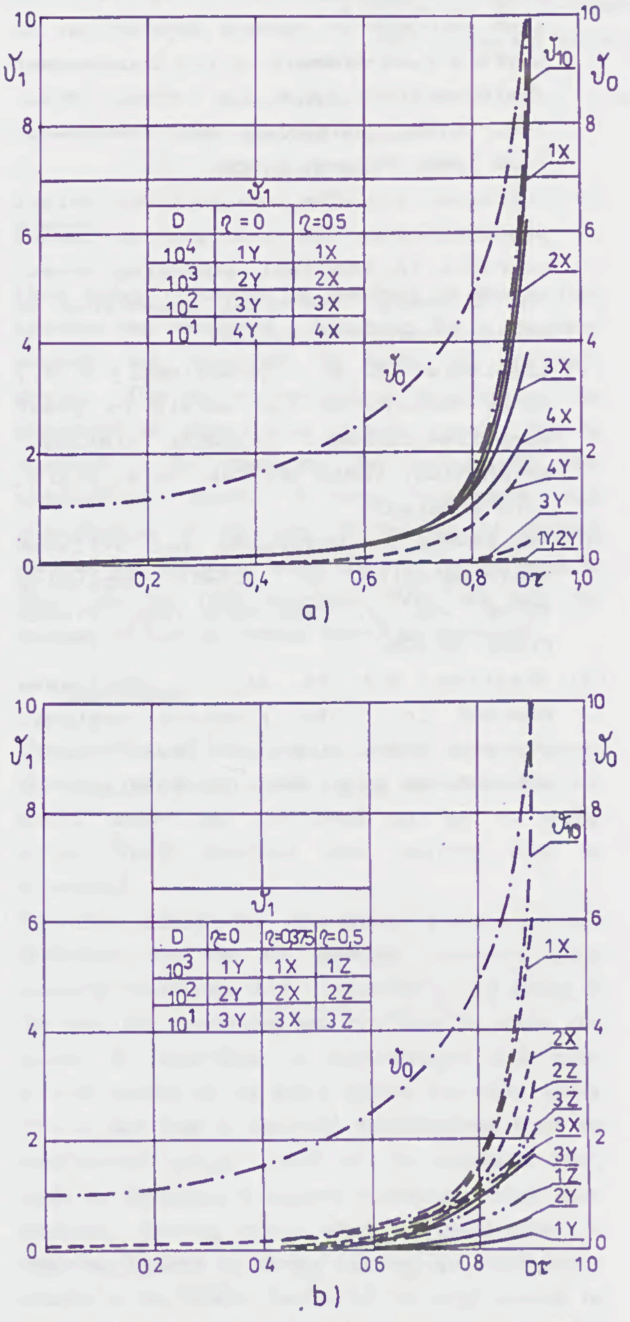

Fig.2 Temperature ϑ_o, ϑ_1, ϑ_{10} profiles in the points indicated in Fig.1 as function of time $D\cdot\tau$ for $\gamma = 2$ and $c = 0.05$

a) initial condition a (Fig.1)

b) initial condition b (Fig.1)

comparison the difference of the temperatures ϑ_{10} between points X and Y is shown, but the thermal conductivity was neglected. It gives the maximal possible difference temperature in the wire.

From Fig. 2a and some results, not enclosed to this paper, a conclusion is, that for every magnitudes of the exponent $\gamma>1$ exist a defined boundry value of the constant $D = D_b$ above which the thermal conductivity is not able to equlibrize of the non-uniform temperature distribution.

As a criteria of D_b selection by a convention was taken non-changeable temperature difference $\vartheta = \vartheta_o + \vartheta_1$ in the points X and Y at the initial instant and in the instant when $\vartheta_o = 10$.

The following results are obtained:

for $\gamma = 1.2$ - $D_b = 50$; for $\gamma = 1.5$ - $D_b = 20$;
for $\gamma = 2.0$ - $D_b = 10$; for $\gamma = 3.0$ - $D_b = 5$.

For Cu and Ag wires ane can take approximatively $\gamma = 2.0$. Obtained results D_b make possible, for given magnitude j and material data at the melting point T_m ($T_{o1} = T_m$), to determine after (15) at which dimensions those temperature non-uniformities can be equalized. For example, at $j = 5\ kA\cdot mm^{-2}$, $\gamma = 2.0$ and Cu wire the non-uniformities $l_o < 0.88$ mm should give the temperature equalization.

From Fig.2b and results not shown in this paper, can define boundry value of the constant $D = D_w$ that two regions with distance l_m apart will join together due to the heat transfer. It would correspond to the short wave damping of length l_m and shorter. As a criterion to define D_w for given γ we took connection in one two regions heated up when $\vartheta = \vartheta_o + \vartheta_1 = 10$. In this way we get:

for $\gamma = 1.5$ - $D_w = 100$; for $\gamma = 2.0$ - $D_w = 80$.

The paramerter D_w enables approximative calculation of the disintegrating modulus after the formulae

$$l_m \le \frac{(D_w \cdot \sigma_{o1} \cdot T_{o1} \cdot \lambda_{o1})^{0.5}}{4\cdot j} \qquad (20)$$

Comparison of the results of experiments and after the formulae (14) are given in the Table 1.

The conclusion from the Table 1 is that for current-density actual in fuses the formulae (20) gives a satisfactory agreement. But for higher current-density, typical for so-called fast explosions the differences are great. Possibly it is due to considerable overheating of the liquid metal for fast explosions and changes of the material parameters.

Table 1 Juxtapposition of exerimental and analytical results

Mate-rial	Dia-meter (mm)	j (kA·mm^{-2})	Modul. exper. (mm)	Modul. calcul (mm)	Sour-ce
Ag	0.3	8.2	0.31	0.39	[2]
Ag	0.5	6.0	0.36	0.54	[2]
Ag	0.5	12.0	0.24	0.27	[1]
Cu	0.625	170.0	0.23	0.018	[4]
Cu	0.625	260.0	0.20	0.020	[3]

v.high. expl. wire.

5. Conclusions

The paper pointed out, that the striated disintegration of a fuse-element, or more wide, of an exploding wire can arise due to development of the electrothermal instabilities, which are appearing with the non-linear volumetric heat sources taking into account the heat transfer. An analysis of a simplified model we got a formulae to determine the striation modulus. The calculating results are in agreement with the experiments for fuses, but are in disagreement for the exploding wires. This problem now is under further investigations.

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