Seems a sensible description.
Droplets pressed into sand
- see my paper

AN INTEGRATED PHYSICAL MODEL OF THE H.B.C. FUSE ARCING PROCESS

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S u m m a r y. Paper gives a phenomenological description of the whole arcing process which has take place in a fuse with single notched fuse-element, but particularly the fuse element burn-back and arc-channel physics. All considerations are based upon existing literature and own extensive short-circuit experiments in the range 3-30 kA(RMS) 550 V, 50 Hz. Three stages are considered: arc-ignition, arc-burning, post-arc recovery withstand.

1. Introduction

The paper deals with the arcing phenomena in high breaking capacity fuses (h.b.c.) during short-circuit current interruption. The arcing under consideration takes place in a fuse within multi-notched single strip fuse-element. In such a case known approaches do assume several simplifications about the arcing physics to facilitate the calculations. In this respect usually two arc aspects are considered: the arc-elongation due to fuse-element burn-back and secondly,- the arc-column conditions in time. Both make possible the arc-voltage calculation, hence the analytical prediction of h.b.c. fuse behaviour in a given electric circuit is possible.

Meanwhile the whole arcing process contains 3 following stages: arc-ignition, arc-burning, post-arc recovery strenght. The existing literature concentrates mainly on the second stage. So one aim of the paper is to give an integrated approach which includes mentioned 3 stages. Not less important is another aim, to show an improved look onto the burn-back process and arc-column behaviour during the second stage.

2. Arc-ignition

Two groups of parameters are responsible for arc ignition in the notches: first,- for a given fuse-element material, the fuse-element geometry, but particularly so-called the "constriction ratio"; second,- the short-circuit parameters amongwhich the most important is the prospective current. Under "constriction ratio" one has understand the ratio of the fuse-element shoulder cross-section to the notch cross-section. If by a given constriction ratio the short-circuit current is of the magnitude, which can lead to the multiple arcing, such case is excluded from considerations.

The arc-ignition voltages u_i in a notch one can calculate using a number of the Hibner's empirical relations. The newest one for round notches is given in a paper for this ICEFA [1]. Earlier 8 Hibner's publications on this subject one can trace using "Digests"[2]. The general form of all those relations is

$$u_i = c i_o^a S^{-b} \tag{1}$$

where: c - some constant; i_o- cut-off current S - notch cross-sectional area; a, b - constants (e.g. a=0.5, b=-0.2). Besides, there is a number of consecutive approaches to the arc-ignition physics [3-5]. The newest one is given in a paper for this ICEFA [6].

During the arc-ignition appears the pressure exploding componenet [7]. A clear record of such a componenet is shown in Fig.1.

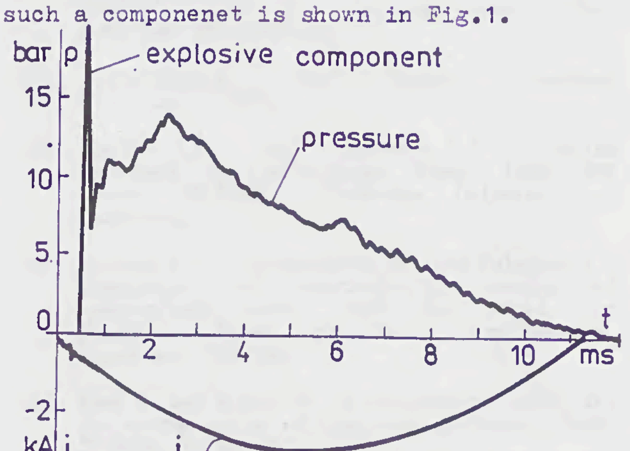

Fig. 1 Record during arc-ignition and burning in ice tube 10 mm dia, 150 mm long

Although the record referres to the ablative arc investigations [8] , but the arc was ignited by 0.1 mm Cu wire in 150 mm long ice hole. The Figure was not shown in the paper [8], but belong to the same series of tests as described in that paper(by courtesy of Prof.A.D. Stokes). The physics ruling the wire explosion and the arc ignition in notches is nearly analogous. As a result of notch-explosion X-ray photography after current interruption shows typical explosion region (encircled in Fig.2) . The region

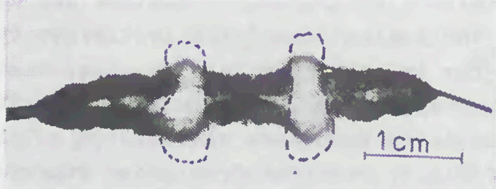

Fig. 2 X-ray picture of a fulgurite, side view, Cu-strip 6x0.2 mm^2, 2 constrictions 1.2x0.2 mm^2, 12 mm apart, 3.1kA

shows complete lack of the metal particles. Moreover the cavity after explosion indicates the largest cross-setion. As it will be demonstrated farther, the encircled region is one of the major componenet of the post-arc gap to withstand the recovery voltage.

2. Arc-burning

2.1 Burn-back process

One of the most advanced approach to the burn-back process is done by [9] which exploits very much the results of a basic work [10]. Repeated after [9] Fig.3 shows phases distributed along the element-end during the burn-back process. At the arcing front x=xl the liquid silver is overheated up to abt 1700 K, whereas in the case Cu-strip the liquid reaches T_{drop}= abt melting poit, i.e. 1356 K 10 .

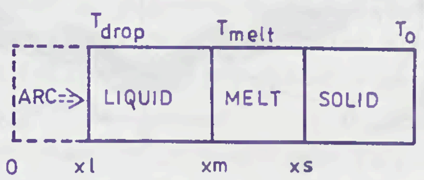

Fig. 3 Phases within fuse-element during burn-back process [9]

To verify the model taken in calculations [9, 10] a number of tests were carried out, described in detailes in [11] using strip Cu-elements, 6x0.2 mm^2 with notches 1.2x0.2 mm^2 (constriction ratio 5). The number of notches 1 to 5 within distances up to 15 mm.

Standard fuse quartz sand of 0.2-0.5 mm sieve dimension was packed into the tested DIN dimension 500 V fuse-links by a standard procedure. The active fuse-element length was 56 mm. Tests were performed within 3.1, 9.99 and 32 kA (RMS) , p.f.=024 and 550 V, 50 Hz. After every shot the test voltage was maintained 15 sec between fuse-terminals.

From the literature are well known descriptions of the fulgurites after short-circuit interruption (e.g. [10, 12]). But our inspection of more than hundred fulgurites after above tests shows some new detailes essential for the burn-back process. Several of them only one can deduce from the Figs 2 and 4. One can distinguish yet not described two processes: droplet formation and acceleration and droplet penetration into the sand. The energy needed to get both processes shall be drawn from the heat of overheated element-end (at arcing front xl in the Fig.3) . That is why suggested in [10] for copper the droplet formation temperature 1356 K shall be higher, otherwise the droplets penetration into the sand is impossible.

In the literature the droplets formation and acceleration processes are described for arc cathode root on contact switches only [13,14]. In this case the surface in touch with the root is prctically unlimited in comparison with the cathode-spot dimensions. Whereas in fuses the element-end area at the arcing front xl (Fig.3) is restricted, for example in our experiments up to 1.2 mm^2. So in both cases the droplet process can show some differences. But qualitatively it seems is similar one to that demonstrated in the Fig.5.

Fig. 4 Cross-section of fulgurite cut along the arc-channel axis, Cu-strip 6x0.2 mm^2, 2 constrictions 1.2x0.2 mm^2, 1 mm apart, 3.1 kA, 1 - bright dots on the rim are Cu droplets

From the fulgurite inspection remarkably is that the droplets diffusion into the sand the very element-end shows nearly ideal symmetry, i.e. half of the strip metal is removing in one and second half in opposite direction, both perpendicular to the strip flat surface.

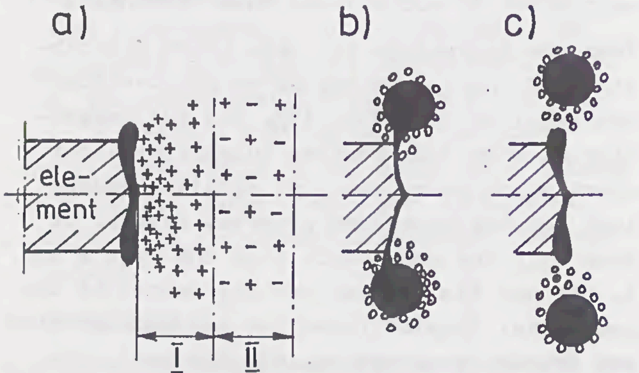

Fig. 5 Consecutive pictures showing droplets ejection from the cathode-element-end a - melting and deformation of liquid b - droplets ejection, c - heating and vaporization of droplets, I - space charge zone, II - ionization zone Note: Zones I and II in Figs b and c are not shown.

The droplet penetration into the sand shall depend first of all upon:

- the kinetic energy of droplets in the instant of the clashing into the sand wall,
- the dynamic viscosity and mass density of droplets,
- the sand wall porosity,
- the dynamic pressure of the arc-column,
- the pressure distribution in direction z (Fig.4).

The hydrodynamics of that penetration can be formulated as follows [15]

$$-\frac{dp}{dz}=\alpha\mu G+\beta v G^2 \qquad (2)$$

where: left hand side means the local pressure gradient in z direction, α- dynamic coefficient of resistance between sand and droplets due to adhesion, β - resistance of sand due to inertia, μ - dynamic coefficient of viscosity, v - specific volume of metal. Unfortunately all the right hand side parameters are not known quantitatively.

During the droplets filtering through sand their temperature is decaying eventually up to the metal solidification, unless immediately after a heat wave from the arc-column will overtake the termal conditions of already dispersed metal.

Two velocities are deciding on the dynamic shape of the droplet layer dispersed into sand in the vicinity of the element-end, viz.: one is the burn-back velocity, which is axial, and second,- the initial velocity of droplet penetration into sand, eventually perpendicular to the axis (Fig.6) . The burn-back velocity one can calculate, for example by method demonstrated in [9] , whereas the droplet velocity is not yet possible even evaluate analytically. What we can do now is the evaluation of the last velocity from X-ray images of fulgurites, e.g. taken from our experiments, in a combination with the calculated burn-back velocity [9]. The angle α (Fig.6) received from those experiments is between abt 25° and 65° and relates to the test current and the fuse-element geometry. For mean value 45°, assuming penetration velocity perpendicular to the axis, the penetration velocity shall be equal to the burn-back velocity. By current density range 1 to 4 kA/mm^2 the measured burn-back velocity [10] was between abt 1 and 5 m/s correspondingly. This means the droplet penetration velocity of this same order.

The final point with droplet filtering into sand is on the enthalpy H_{con} increase per unit volume needed to rais the temperature from the initial fuse-element temperature to

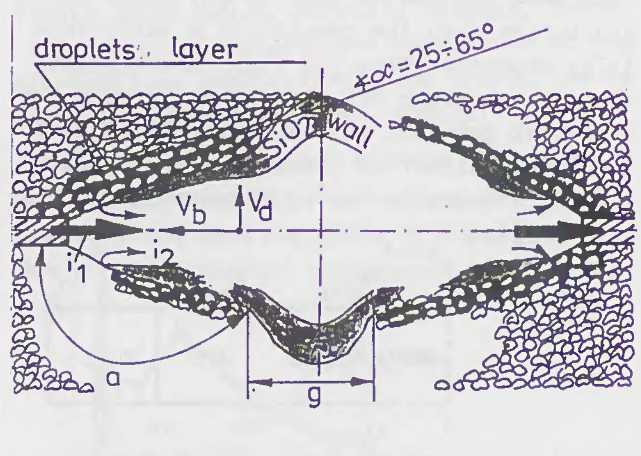

Fig. 6 Image of the arc
i_1- main current path; i_2- partial current path; v_b- burn-back velocity; v_d- droplet velocity; α- angle between droplets layer and axis; g - recovery withstand gap between droplets layers which in fact is the gap after explosion; a - points of connection

T_{drop}. To get reasonably good agrement of voltage and current traces for the calculations based upon method given by [10] and recorded in our experiments we needed to assume H_{con} as a variable depending upon test conditions and the fuse-element geometry. For Cu, for instance, the magnitudes of the H_{con} shall be as in the Tables 1 and 2, shown in our paper [16] . Those magnitudes are between o.7 and 1.18 times 10^9 J/m^3 if the calculating errors of the current have to be not greater than abt 20 %, the voltage 25 % and the final arc length abt 7 %. Moreover similar enthalpy but for sand H_{ag} shall vary between 4.9 and 7 J/m^3 times 10^9. So a remark in [10] that H_{con} shall not necessarily be constant is confirmed by our experiments and calculations.

All said means that also in the Cu case the T_{drop} shall be higher than the melting temperature and the degree of metal overheating shall be different for various short-circuit conditions and the fuse-element geometry. Mentioned earlier the dynamic pressure of the arc-column it seems is responsible for farther pressing into the sand of the liquid metal particles.

Another observation from the fulgurites indicate that the droplets pressed into the sand in the vicinity of the element-end are still in a direct touch with the arc column. In this region is not yet arised any shield made from the molten silica sand, which can isolate the arc-column from dispersed metal. It denotes that some portion of the current i_2 in Fig.6 also flows through dispersed metal in parallel to the current i_1 of the main feeding path. But due to droplets dynamic and their very high temperature the magnitude of current i_2 supposed to be negligible in relation to i_1. As a result also electromagnetical influence on the mobile liquid metal can be omitted.

Next important observation based upon fulgurites inspection shows that the dispersed metal (Fig.4) is in very good galvanic connection with the element-end. Such a connection exists even up to the farthest droplets apart to the element-end. Also a galvanic connection with the element-end demonstrates inner wall of the arc-channel just in the vicinity of the element-end. The connection in this region is likely due to yet lack of the developed tight silica shield, isolating the arc-column from the dispersed metal. Obviously the observations described refer to the fulgutites after completing of interruption. During the arc-burning those galvanic connections could not exist. But, in any case, very close to the final current zero such connections should already become actual due to droplets merging into one connecting layer. From this follows an important behaviour of the fuse during the post-arc recovery withstand stage.

2.2 Arc-column behaviour

It is already well known and is confirmed by Figs.4 and 6 that the arc-column is surrounded by a tight tube made from molten sand which includes chemically bound Cu. Detailed inspections of the inner walls of fulgurites in an arbitrary distance to the element-end does not show any axial draugt traces on those walls. It seems, it witnesses of the lack of considerable axial plasma jets originated in its constricted region in the vicinity of electrode-eneds. In fact a simple calculation shows, for example, that for coditions corresponding to our experiments, the overpressure in the vicinity of the electrode-ends againstarc-column should be abt 0.1 to 0.5 MPa only. That's why the existing approaches which treat the arc as a SiO_2 wall stabilized one, of course, are correct. Arc is assumed in LTE and characterized by temperature, pressure, cross-sectional area and velocity of the plasma in perpendicular direction to the strip flat surface induced by the column expansion and the opposite abtion process.

3. Post-arc recovery withstand

Coming back to the fulgurite inspection after our experiments (Figs.4, 6) one can came to the conclusions about the post-arc withstand. The processes responsible for recovery withstand are concentrated along two parallel paths . One is the gap between the metal layers diperesed into the sand and golvanically connected to the element-ends. The second is along the molten silica wall. That's why a first step in analytical prediction of that withstand should be the heat transfer calculation from the elongating arc-column to the sand. This heat, first of all, cause the growing of molten wall thickness. But penetrating farher the heat can reach earlier dispersed droplets bringing them eventually to the boiling point. In a result the metal can evaporize giving the elongation of mentioned gap.

Above sketchy description of phenomena associated with the post-arc recovery withstand are crucial for the final arc-extinction and for the time being are awaiting on extensive investigations.

4. Final remarks

We tried to give an integrated physical picture of the arcing in h.b.c. fuses equipped within a notched single strip fuse-element overloaded by a short-circuit current. The picture containes some new aspects, among them: droplets formation, their penetration into the sand, the galvanic contact of those droplets with the element-ends. Moreover a very crucial for the final arc-extinction problem was mentioned, namely the post-arc recovery withstand of the hot fulgurite, which waits for investigations.

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