The Effect of Scaling Factors on the Pinch-Induced Transition from a High-Velocity Sliding Contact to the Arc Mode

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Abstract—Dependence of the velocity of a compact projectile slider accelerated in a railtron, reached by the moment of a transition of the high-velocity sliding contact to the high-current arc mode, on the system parameters and the acceleration regime is determined within the framework of a model assuming the magnetohydrodynamic (pinching) instabilities as the main factor responsible for this transition. It is established that the maximum transition velocity is proportional to the system gauge, specific conductivity, and strength of the slider material and is inversely proportional to the average slider density. © 2001 MAIK “Nauka/Interperiodica”.

Introduction. When a solid slider is accelerated in a railtron system, the initial stage of a rather stable operation of the sliding metal–metal contact is followed by the arc formation between the rail and slider surfaces. As a result, the dusty plasma is ejected from the contact gap into the duct to initiate shorting arcs both in front of and behind the slider [1, 2]. As a result, the solid slider operates in a hybrid regime and the acceleration process passes within a few microseconds into a low-efficiency arc mode. This transition is unambiguously indicated by a sharp increase in the voltage drop measured at the duct output (ΔU_{\text{in}} ≥ 30–60 V).

Monitoring and analysis of the above phenomena, together with the study of the surface layers of rails and sliders upon acceleration and stopping, led us to the conclusion that the main factors responsible for the contact transition to the arc mode are the magnetohydrodynamic (MHD) instabilities of the pinch type developed in the contact zone [1, 2], rather than some two-dimensional processes of the velocity skin effect (VSE) type [3, 4]. This discovery allowed us to explain the well-known empirical rule according to which no contact transition to the arc mode takes place provided that the slider is pressed against the rails at a load exceeding a “one gram per ampere” level [5]. Under these conditions, a magnetic field pressure at the contact gap during the slider acceleration within a nearly standard regime does not exceed the slider pressure on the rails and the slider material strength, so that no pinching can take place in the contact zone. Determining the key role of the MHD phenomena at the contact interface revealed the inadequacy of the boundary conditions conventionally formulated assuming the ideal contact between slider and rails.

Within the framework of the VSE model [3, 4], the main parameter characterizing the contact transition to the arc mode during the slider acceleration is the critical velocity \( V_c \) at which the fusion wave arising at the back edge of the slider contact surface (where the skinned electric current concentrates) reaches the front edge of the contact zone. For a preset linear current density in the 2D approximation, the \( V_c \) value is a function of only the electric and thermodynamic (ETD) parameters of the rail and slider materials [3, 4].

However, in a real 3D experiment it is necessary to take into account, at least, the possibility of the current protruding forward by the side faces of both rail and slider. This implies dependence of the VSE manifestations on the system geometry, in particular, on the system gauge. An attempt at the theoretical analysis of the effect of scaling factors on the \( V_c \) value based on the experimental data was undertaken by James [6, 7]. Performed within the framework of the VSE model, this analysis showed that, in the general case, \( V_c \) must decrease with increasing system gauge.

It should be noted that the problem of the acceleration process scaling in a railtron, considered as a generalized electromechanical system, has been repeatedly studied, for example, in [8, 9]. An analysis of the general equations showed that a \( K \)-fold change in the system gauge, provided conservation of the current shape and a linear dependence of the current strength on \( K \), the time scale increases as \( K^2 \) and the accelerator length and the accelerated body mass—as \( K^5 \). The sliding velocity grows in proportion to \( K \), the acceleration is proportional to \( K^{-1} \), whereas the output kinetic energy of the projectile device is proportional to \( K^5 \).

Below we will attempt to elucidate, based on the new physical model of the slider–rail contact transition to the arc mode, how the resultant transition velocity \( V_c \) depends on the system gauge and other typical acceleration regime parameters. This will make possible a targeted search for the conditions ensuring the maximum possible \( V_c \) value, for the optimum accelerator design, and for the arcless system operation regime.
Main assumptions. In order to follow the major trends, we will ultimately simplify the problem making the following assumptions.

(i) We consider a monolithic slider (cube, cylinder, etc.) with a mass obeying the relationship \( m = \rho_{a} d_{0}^{3} \), where \( d_{0} \) is the railtron gauge (m) and \( \rho_{a} \) is the average slider density (below we use \( \rho_{a} = 2700 \text{ kg/m}^{3} \)).

(ii) We assume that the sliding contact transition to the arc mode is due to a pinching constriction of the slider by the magnetic field pressure \( p_{B} \) in the zone of the slider–rail contact. In this zone, the material strength is decreased by the lack of shear resistance, whereby the transition onset corresponds to

\[
p_{B} = \frac{B^{2}}{2\mu_{0}} > s_{y}, \tag{1}
\]

where \( \mu_{0} = 4\pi \times 10^{-7} \text{ H/m} \) is the permeability of the vacuum and \( s_{y} \) is the ultimate strength of the slider material (for Al-based alloys, \( s_{y} = 400 \text{ MPa} \)). Since the magnetic field strength \( B \) depends on the current \( I \) as \( B = \mu_{0} I / 2\pi r \), the pressure \( p_{B} \) at \( I = \text{const} \) increases with decreasing pinch constriction radius \( r \) \((r \leq d_{0}/2)\). Under condition (1), this leads to a collapse of the constricted region, followed by a thermal explosion and the appearance of an electric arc.

(iii) We assume that the skin layer thickness on the side faces of the slider increase with time \( t \) as \( l = (t/\mu_{0} \sigma)^{1/2} \), where \( \sigma \) is the specific conductivity of the slider material (for Al, \( \sigma = 10^{7} \text{ S/m} \)).

(iv) We consider the case when the current passing through the slider is constant \((I = \text{const})\).

(v) We assume that the main current flows in the substance under the skin layer, since the \( \sigma \) value within this layer drops with increasing temperature in the course of Joule’s heating. This assumption is corroborated by more rigorous calculations performed for an analogous situation considered previously (see Figs. 1a and 2a in [10]).

(vi) We believe that the material strength within the heated skin layer is significantly lower than the strength of the cold material body.

(vii) We assume that the slider, accelerated by the force \( F = L' I^{2} / 2 \) during the time \( t \), acquires the velocity

\[
V = \frac{L' I^{2}}{2d_{0}^{3} \rho_{a}} t, \tag{2}
\]

where \( L' \) is the linear inductance of the rails (typically, \( L' \approx 0.3 \mu\text{H/m} \)).

We will neglect a certain decrease in the slider mass related to a loss of the low-strength material caused by the TED effects [10]. Finally, we assume that the initial force pressing the slider to the rails is considerably lower than the ultimate strength of the slider material.

The critical velocity of the transition to the arc mode as a function of the acceleration regime. Taking into account the above assumptions (v) and (vi), we conclude that the effective constriction radius is \( r = (d_{0}/2) - l \) and the pinching onset condition (1) in the region of slider–rail contact can be written as

\[
\frac{B^{2}}{2\mu_{0}} = \frac{\mu_{0} I^{2}}{2\pi^{2}(d_{0} - 2l)^{2}} \geq \frac{\mu_{0} I^{2}}{2\pi^{2} d_{0}^{2}} \left[1 - \frac{2}{d_{0} \rho_{a} \sigma} \right]^{1/2} \geq s_{y}. \tag{3}
\]

Excluding the current \( I \) from Eqs. (2) and (3), we obtain the following expression for a critical velocity corresponding to the contact pinching:

\[
V(t) = \pi L' s_{y} d_{0} / \mu_{0} \rho_{a} \left[1 - \frac{2}{d_{0} \rho_{a} \sigma} \right]^{1/2}. \tag{4}
\]

Depending on the acceleration regime and the characteristics of the slider (more precisely, of the entire projectile structure), including the values of \( I, \rho_{a}, \sigma \), the contact crisis onset may take place at any velocity given by formula (4). The maximum value of \( V(t) = V_{c} \) is reached when the term in the square brackets equals 1/2, that is, when \( t = \tau_{0}/4 = \mu_{0} \rho_{a} d_{0}^{2} / 16 \). In this case,

\[
V_{c} = \gamma L' s_{y} d_{0} / \mu_{0} \rho_{a}, \tag{5}
\]

where \( \gamma = (\pi^{2}/256 \text{ for the above assumptions}) \) is the normalization factor. Thus, the critical transition velocity for a compact slider is proportional to the system gauge. With the numerical values indicated above for an aluminum slider, we obtain \( V_{c} = 68.5d_{0} \text{ km/s} \). In order to reach this velocity, it is necessary to maintain (over a time period \( \tau_{0}/4 \)) the current at

\[
I = \pi d_{0} / (s_{y}/2\mu_{0})^{1/2}, \tag{6}
\]

which corresponds to the transverse linear current density \( I/d_{0} \approx 40 \text{ MA/m} \). This result implies that the scaling relationships are consistent with the aforementioned general scaling laws for electromechanical systems.

Discussion and conclusions. It is obvious that the obtained relationship between \( V_{c} \), the slider characteristics, and the overall system parameters is a rough approximation, which can be employed only for estimating the character of the influence of various factors on the acceleration process. More precise particular relationships can be obtained by refining the assumptions and making allowance for some additional factors.

Nevertheless, we can already draw the following obvious conclusions.

First, the critical velocity has proved to depend on the properties of the slider material. In this respect, the combined parameter \( \sigma s_{y}/\rho_{a} \) is the best for beryllium- and aluminum-based alloys. Thus, the variants selected...