

Pulsed Current Static Electrical Contact Experiment

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Abstract-- Railguns involve both static and sliding electrical contacts, which must transmit the large transient electrical currents necessary to impart high forces onto a projectile for acceleration to hypervelocity. Static electrical contacts between metals initially take place through small asperities, or "a-spots", distributed over the contact area. The voltage developed across the interface is directly related to the contact temperature and pressure, the number of a-spots, the thermophysical and mechanical properties of the contacting materials, the current history, and any interfacial materials that may be present. To physically simulate some of the conditions attained within a railgun, a pulsed current static electrical contact experimental facility has been developed at the Naval Research Laboratory. This facility employs a 500 kN capacity servohydraulic load frame equipped with an electrically insulated load train to establish a contact pressure on interfaces between metals through which a pulsed current is transmitted. The time dependent evolutions of the voltage drops across the interfaces, as detected by probes pushed into the contacting materials, are recorded during a 40 kA peak current pulse having a 300 μ s rise time with peak current densities on the order of 50 kA/cm². The interface stack is assembled from a 12 mm outside diameter annular disk of metal with a 6.3 mm hole which is compressed between two hollow pedestals of a second metal. The evolution of the voltage drop across an interface during a pulse will be described as a function of initial contact pressures, current density, and polarity for dissimilar (Al/Cu) metal contacts. Thermal effects on the surfaces, including localized melting of the interface materials, were also investigated.

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I. INTRODUCTION

The behavior of electrical contacts between metals has been an intensively studied area due to their existence in all electrical machinery and power transmission systems. As a result, nearly all research has focussed on industrially important problems such as sliding contacts, intermittent contacts, and the long-term behavior of static contacts at moderate current densities [1]. The electrical contacts within electromagnetic launchers, in contrast, whether static or sliding, must function at much higher current densities than normally encountered, typically on the order of 40 kA/cm^2 . These currents are transient, with rapid rise times leading to skin effects within conductors and the contacts between them. At the beginning of a launch within a railgun the electrical contact between the rails and the armature is static until sufficient force has been built up to overcome the static coefficient of friction. It is during this early stage of the launch that the performance of the static electrical contact is critical, as run away arcing or freezing in place of the armature can cause adverse effects on the bore of the gun or the containment structure. To physically simulate this situation a static electrical contact experiment has been designed to measure the effects of both high contact pressures (up to 550 MPa) and high current densities (50 kA/cm^2) on the interface between dissimilar metals encountered within railguns. Unlike most studies on electrical contacts, where a steady state current is normally used, this experiment employs a pulsed electrical current obtained from the discharge of a capacitor bank. We report here the design and construction of an experimental apparatus that can reproduce these conditions. The results of some exploratory experiments involving static contacts of dissimilar metals (Al/Cu) are also discussed.

II. EXPERIMENTAL APPARATUS

In order to reproduce the conditions encountered by static electrical contacts within a railgun sufficient force must be applied to the contacting surfaces to attain the pressures that are developed during the early stages of the launch. Additionally, both the magnitude of the peak current density and its temporal characteristics, such as the short rise time up to the peak, need to be duplicated. To achieve these conditions, a 500 kN servohydraulic load frame was equipped with an insulated load train attached to a 300 kA capacity pulsed current power supply by means of flexible cables. An overall view of the load frame is shown in Fig. 1 with the major components indicated.

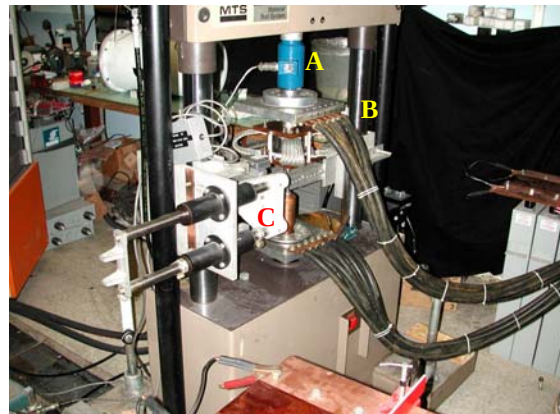


Fig. 1. Overall view of load frame showing the load cell, "A", load train insulator, "B", and interface voltage drop probe carrier, "C".

This load frame was used to apply force to and send a pulsed current

through an interface stack assembled from the components shown in Fig. 2. The interface stack consists of a 2.5 mm thick annular disk of metal having an outside diameter of 12 mm and an inside diameter of 6.3 mm which is compressed between two hollow pedestals of a second metal. This design allows the use of a nonconducting pin inserted through the center of the disk to provide axial alignment during assembly of the stack in the load frame. Also, polarity effects on the transmission of electrical current across dissimilar metal interfaces can be captured in one experiment. The contact area is nominally 0.81 cm², which allows high current densities to be developed with moderate currents. The contacting surfaces are finished with a 600 grit silicon carbide metallographic paper on a glass plate to produce a flat geometry with a consistent surface roughness, Ra 0.05 µm. After this finishing operation the parts are cleaned with acetone and ethyl alcohol to remove grinding debris and oils remaining from machining or handling.

The pedestals are mounted on copper platens using threaded studs. These are firmly tightened to produce a static contact in which the two contacting surfaces wipe against each other as the pedestal is torqued. This feature produces an initial contact pressure between the pedestal and the compression platen that is independent of the load on the annular disk in order to avoid the possibility of arcing and damage to this surface.

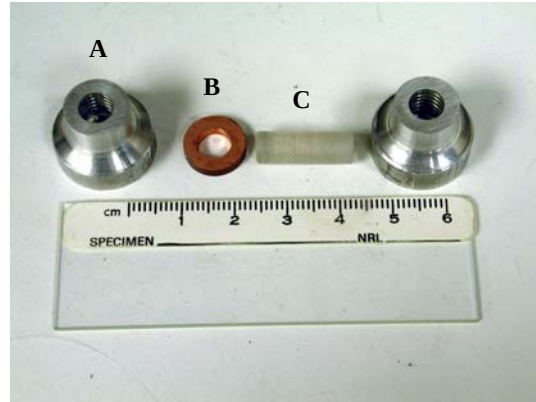


Fig. 2. Components of the interface stack, "A", hollow pedestal, "B", annular disk, and "C", plastic alignment pin.

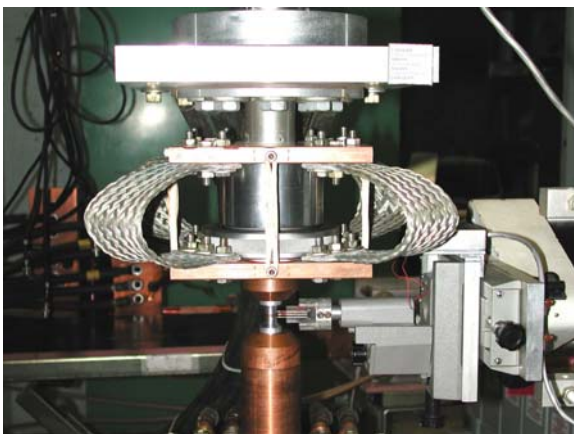


Fig. 3. Spherical joint compression platen with compliant shunts between two copper plates which are used to protect the spherical contacting surfaces from arching. Also shown is the probe for detecting the voltage drop across the interfaces and the translation table for fine adjustments of the probe contact point location.

When compressing surfaces together to develop a contact pressure an important consideration is to insure that the pressure is evenly distributed. This requires a number of design features in the load train that applies force to the interface stack. Both angular and translational adjustments of one of the compression platens are needed to minimize uneven loading on the interface. The load train developed to accommodate the small adjustments needed to insure an evenly distributed contact pressure is shown in Fig. 3. It consists of a spherical joint compression platen around which compliant shunts are attached to two copper plates. This allows passage of the electrical current to the upper platen without damage to

the spherical joint contacting surfaces. The lower copper plate is insulated from the spherical joint compression platen by a sheet of Mylar film and is suspended on rubber bands. Four pins with plastic sleeves hold the lower platen in a nominally centered position, but with sufficient clearance to accommodate small in-plane displacements relative to the load train axis.

To detect the voltage drop across the interfaces during a current pulse, a probe was developed that contacted the interface stack from the side as shown in Figs. 3 and 4. This probe consists of three steel pins inserted into holes drilled into a plastic block spaced by 2.5 mm intervals. The pins slide within the holes and their ends bear against a rubber pad inside the block. This gives each pin an elastic compliance independent of the others when pushed against the stack. To minimize the inductive effects on the signal during a pulse a twisted pair of wires is spot-welded as close as possible to the pin contact points to minimize the loop area as shown in Fig. 4. This feature is different from commercially available pin probes, where the wire attachment is at the other end of the pin, making them unsuitable for this application. The voltage drops across the interfaces are carried to a battery powered 200 MHz digital oscilloscope with the filter set to 20

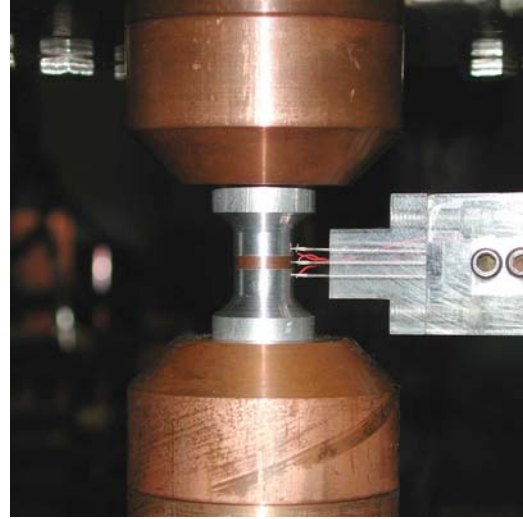


Fig. 4. Photograph showing details of the voltage drop probe head pressed into the side of the interface stack. The contact pedestals are mounted on the copper platens using threaded studs. Note that the signal wires are attached near the pin contact points to minimize the loop area.

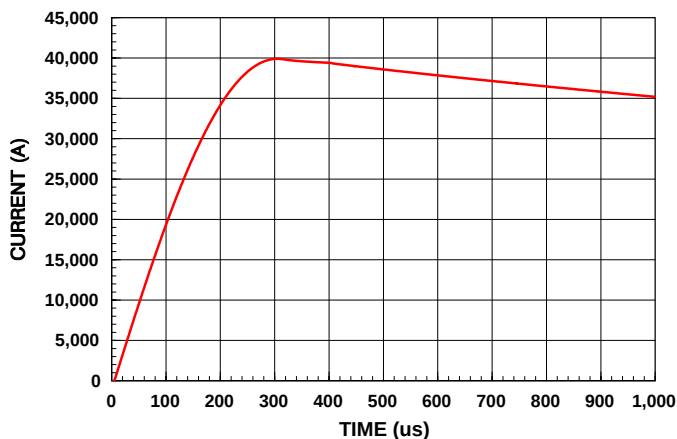


Fig. 5. Pulsed current characteristics. The peak current of 40 kA occurs 300 μ s after the start of the discharge of the capacitor bank, and the initial rise rate is 2.4×10^8 A/s. After the peak the current decay rate is -7.08×10^6 A/s. The inductive effect of this decay rate has no measurable effect on the voltage drop measurement.

MHz via twisted pair cables. The probe head assembly, consisting of the probe head and a three-axis translation table, are mounted on a carrier using linear bearings for movement into the side of the interface stack and for retraction after an experiment. The translation table is used for fine adjustments of the pin contact location relative to the interfaces.

Several effects generate the voltages sensed by the probe. Since the current is pulsed, an induced voltage results from the magnetic induction interacting with the small loop area defined

by the end of the twisted pair and the short leads to the pin ends. This induced voltage is

unavoidable, and needs to be known in order to extract the voltage drop due to contact resistance from the signal recorded during a pulse. To measure the magnitude of the inductive effects that might be encountered during an experiment a shunt was fabricated from aluminum that duplicated the over all geometry of the interface stack. An insulated piece of copper foil was applied to this shunt and the voltage drop probes were applied to the foil. When a 40 kA peak current pulse, having the temporal characteristics shown in Fig. 5, passed through the shunt the resulting signals shown in Fig. 6 were recorded. The peak inductive pickup at the probe was on the order of 140 mV and matched the derivative of the current history.

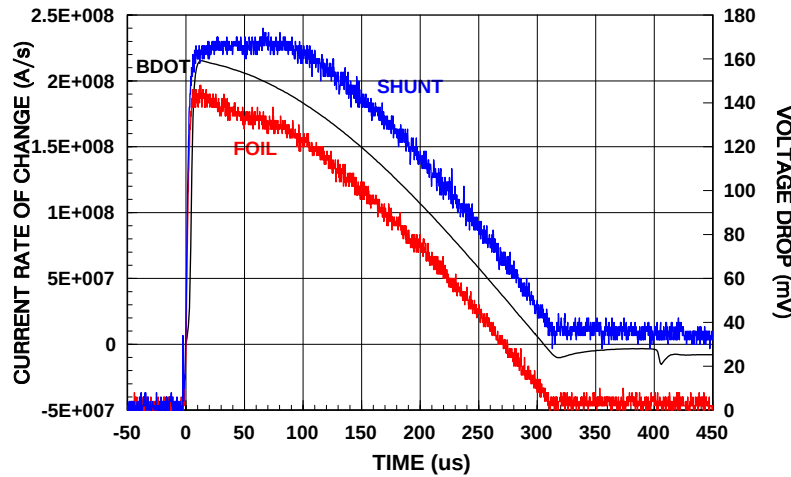


Fig. 6. Results of both the foil and shunt shot experiments. The “FOIL” curve shows the inductive pickup of the probe. The “SHUNT” curve shows both inductive and resistive effects on the probe signal. The “BDOT” curve is generated by the coils used to sense the discharge rate of the capacitors and is integrated to produce the current history shown in Fig. 5. The skin effect in the “SHUNT” shot is a small effect.

Another experiment was conducted in which the foil was removed and the probes contacted the shunt directly. The signal now reflected the combination of both the resistive voltage drop between the probe contact points and the inductive effects. After the peak current was attained at 300 μ s the inductive component of the signal changes sign, and becomes very small relative to the resistive component. The 38 mV voltage drop at this point corresponds to the calculated voltage drop across a 2.5 mm length of the 6061-T6 aluminum shunt for 40 kA of current indicating that after the peak inductive effects are minimal. The ratio of the decay rate after the peak to the initial current rise rate is 3×10^{-2} , which indicates that inductive effects are over two orders of magnitude smaller after the peak and cannot be resolved with the instrumentation used.

III. EXPERIMENTAL PROCEDURE

For assembly of the interface stack within the load frame the pedestals are first installed on the copper platens. The plastic alignment pin is inserted into the annular disk and then mounted on the lower pedestal. The load frame is powered up in stroke control mode and the hydraulic ram positioned to within about 20 mm of upper platen. At this point the controller is switched to load control and the ram movement is induced by manually pulling or pushing on the load cell. This allows the ram to drift slowly until the upper pedestal engages the alignment pin. It is during this part of the load up routine that the self-alignment features of the upper platen are used. Once the surfaces have contacted the required load is set on the controller. The voltage drop probe is then deployed against the interface stack and positioned so that the middle pin contacts the midpoint of the annular disk. The digital oscilloscope is then armed and the capacitor bank charged. The signal used to activate the discharge of the capacitor bank is used to trigger the oscilloscope. After the discharge the probe head is withdrawn from the interface stack and the data down loaded from the oscilloscope. The ram is lowered and the interface stack is removed for examination of the contacting surfaces.

IV. PRELIMINARY RESULTS

An example of the voltage drops observed across interfaces between 6061-T6 aluminum and copper (Glidcop AL-25) during a 40 kA current pulse for two different force levels is shown in Fig. 7. For the 0.445 kN load, corresponding to an initial contact stress of 6.3 MPa and a peak current density of 56 kA/cm², the voltage drop peaks at 648 mV at the very beginning of the pulse where the current is low. However, only about 140 mV of the signal is due to inductive effects, the balance, 508 mV, being developed primarily as the result of the initial contact resistance. The remaining voltage drop is due mostly to contact resistance, with IR drop in the material between the pins accounting for only 10.3 mV at 50 μ s. A portion of the 0.445 kN upper interface voltage record on Fig. 7, starting at 50 μ s, has been compensated for inductive effects, and the calculated evolution of the contact resistance during the current rise time is also shown to demonstrate the rapid change.

Interface resistance during a pulse is not constant due to the heating of the contacting asperities within the interface. The calculated evolutions of the contact resistances for the two loads used in the experiments are compared in Fig. 8. For the 0.445 kN force level the contact resistance decreases rapidly from 49.8 to 6.7 $\mu\Omega$ over the 50 to 1000 μ s time interval, with most of the decrease occurring during the 300 μ s rise time. In contrast, for the 2.23 kN force level, the contact resistance drops from 7.8 to 2.3 $\mu\Omega$ at 300 μ s, and then slowly increases to 2.9 $\mu\Omega$ at 1000 μ s. The calculated contact resistances do not take into account the increase in resistivity resulting from Joule heating of the materials encompassed by the probes, but this effect is small during the 300 μ s rise time. Additional contributions to the measured voltage drop may include thermoelectric effects, such as the Seebeck effect, where temperature gradients on either side of the

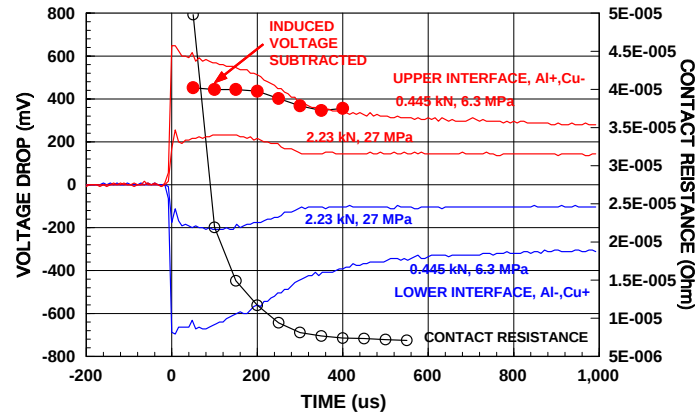


Fig. 7. Voltages developed across Al-Cu interfaces during a 40 kA pulse for two force levels. Current densities are 56 kA/cm² and 48 kA/cm² for the 0.445 kN and 2.23 kN experiments respectively. Part of the upper interface 0.445 kN curve has been compensated for inductive effects. For this portion of the voltage record the evolution of the contact resistance is also calculated showing the rapid decrease.

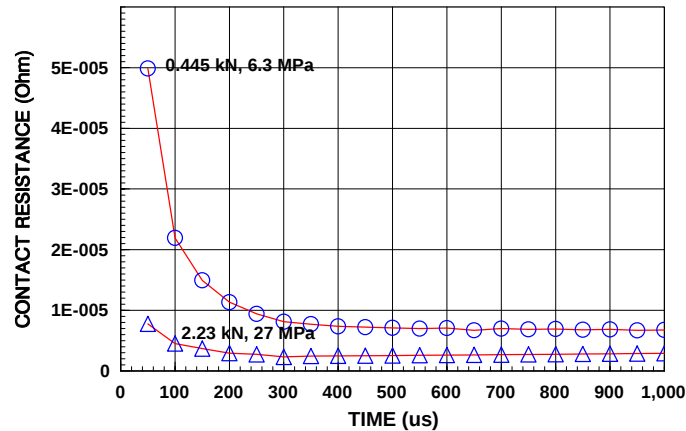


Fig. 8. Comparison of contact resistance histories for the 0.445 and 2.23 kN force levels. For both force levels the contact resistance decreases as the current (Fig. 5) increases to 40 kA at 300 μ s. The change in contact resistance is much greater for the lower contact force. After the peak current is attained the contact resistance becomes virtually constant.

interface generate a potential. However, the magnitude of these effects is thought to be small relative to the voltage drop due to contact resistance since the differences between the measured voltage drops for both interfaces (Al+, Cu- vs. Al-, Cu+) are small.

The load on the contact interfaces during the pulse is not constant during the pulse due to a number of effects. The response of the servovalve to the inductive effects on the load cell, cabling, and controller is not thought to be a factor during the 300 μ s rise time because of its limited frequency response when operated at 10 MPa system pressure, which is half the normal pressure of 21 MPa. The pulse occurs under essentially "fixed grip" conditions where only the elastic stiffness of the load frame and load train can have any effect. Thermal expansion of the load train will increase the load on the interface during the pulse. It is observed that there is some oscillation of the load after the current pulse decays completely over its 13 ms total duration. Blow-off forces within the interfaces can be significant at the currents used, on the order of 0.7 kN at 40 kA peak current [2]. This exceeds the initial force level for the 0.445 kN experiment, but there is no indication based on the voltage drop record that the interfaces separated significantly to cause an increase in contact resistance.

Even though the temperature is increasing rapidly within the interfaces, which would normally increase the contact resistance, the voltage drop does not increase in a manner consistent with the current history. This effect is initially due to the plastic deformation of the rapidly heated contact points, or "a-spots", which increases the effective contact area and possibly alters the electrical conductivity properties in the contact during the early part of the pulse [3]. In the 0.445 kN case the melt voltage for aluminum, 0.3 V, is exceeded very early in the current pulse which would indicate that liquid metal contact also occurred. A similar effect is observed at the 2.23 kN load, where the peak current density was 48 kA/cm², but the initial voltage drop is much lower due to the higher initial contact force. Here, the voltage drop never exceeds the melt voltage for aluminum, and the primary interaction affecting the contact resistance involves the rapid heating elevated temperature plasticity of the contacting materials [4].

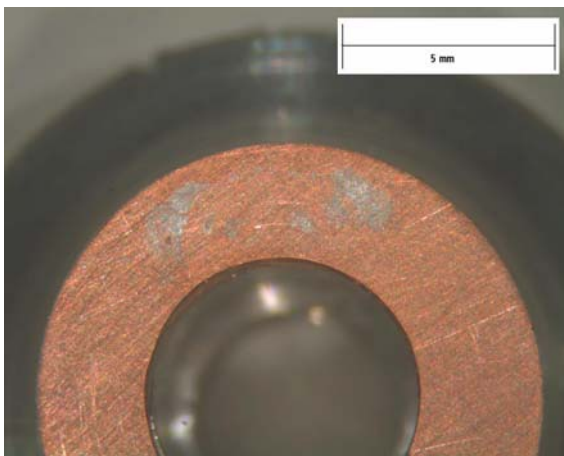


Fig. 9. Aluminum transfer onto the negative surface of the copper disk from the 0.445 kN experiment.

Examination of the contacting surfaces after an exposure to a current pulse provides further insight into the processes occurring in the interface. Examples of this are shown in Figs. 9-11. For the lower force of 0.445 kN there is evidence of aluminum melting and transfer to the copper disk as shown in Fig 9. This is confirmed by SEM examination as shown in Fig. 10, where clear evidence of melting is found in the aluminum deposit. This is expected from the observed 0.5 V voltage drop, which exceeds the melt voltages of both of the contacting

materials (Al 0.3 V, Cu 0.43V). At 2.23 kN, however, this is not observed, as shown in Fig.11. This reflects the lower heat generation within the interface resulting from the higher initial contact load, and the observation that the melt voltage of the contacting materials is never exceeded.

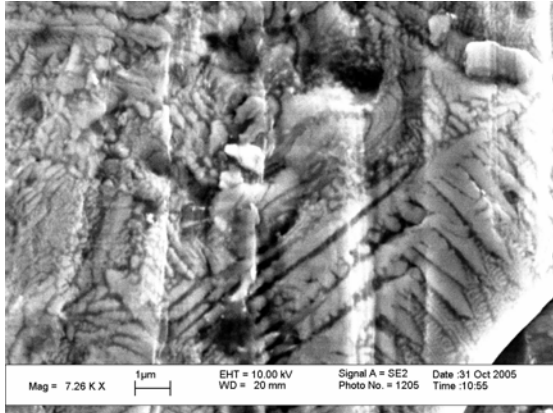


Fig. 10. SEM photomicrograph of aluminum deposit showing dendritic solidification pattern indicating that the melting had occurred within the contact interface.



Fig. 11. Absence of visual aluminum transfer onto the negative surface of the copper disk from the 2.23 kN experiment.

V. CONCLUSION

The results from the preliminary trials with the pulsed current static electrical contact experiment indicate that the contact resistance decreases rapidly during the initial part of the pulse. The rapid heating of the contacting asperities causes them to plastically deform or melt which rapidly increases the effective contact area very early during the pulse, as well as altering the electrical conductivity of the contacting materials. During the current pulse rise time of 300 μ s heating within the interfaces is virtually adiabatic. As a result, the material on either side of the interface contains very steep temperature gradients. Thus, despite the increase in resistivity of the contact due to heating, the dominant factor affecting the evolution of the contact resistance is the mechanical behavior of the contacting materials undergoing rapid heating.

Acknowledgment

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