INVITED PAPER Special Section on Recent Development of Electro-Mechanical Devices (Selected Papers from IS-EMD2009)

Opening Electrical Contacts: The Transition from the Molten Metal Bridge to the Electric Arc

Paul G. SLADE[†a)], ***Nonmember***

SUMMARY This paper presents a comprehensive explanation of the formation of the electric arc between opening contacts in a current carrying electric circuit. As the contacts begin to open a molten metal bridge forms between them. The rupture of this bridge and the initial formation of the electric arc are studied in both atmospheric air and vacuum using experiments to determine the direction of metal transfer between the contacts as a function of time after the rupture of the molten metal bridge. High speed streak photography is also used to show the rupture of the molten metal bridge and the initial formation of the electric arc. Analysis of these data show that a very high-pressure, high-temperature metal vapor zone exists between the contacts after the rupture of the molten metal bridge. Under this condition a pseudo-arc forms where current is carried by metal ions and an anomalous, high net transfer of metal to the cathodic contact occurs. The pressure in this region decreases rapidly and there is a transition to the usual electric arc, which still operates in the metal vapor. In this arc the current is now mostly carried by electrons. The data shows that there is still a net transfer of metal to the cathode, but now its volume is a function of the arcing time.

key words: *opening contacts, molten metal bridge, bridge rupture, high pressure, pseudo arc, arc formation, air arc, vacuum arc*

1. Introduction

When electrical contacts open in circuits with currents greater than a few tens of milliamperes [1] and with driving voltages greater than a few volts [2] an arc is formed. During the initial stages of contact parting, before the development of the arc, molten metal bridges the contact gap in all ambients including vacuum [3]–[11]. It is only after the rupture of the molten metal bridge that the arc forms [3], [7], [10]–[12]. When the arc first forms, it initially operates in the metal vapor that results from the rupture of the molten metal bridge. As the contacts continue to part, it then operates as a columnar arc in the metal vapor evaporated from the closely spaced contacts by the arc roots [10], [13]–[15]. In an ambient gas, as the contact gap increases and the percentage of metal vapor in the arc decreases, this metal phase arc eventually gives way to an arc operating in the ambient gaseous medium. In vacuum, as the contacts move further apart, the usual forms of vacuum arc are established [16]. The voltage across the contacts during the transition from the molten metal bridge to the metal phase arc is always a few 10's of volts even for currents as high as 5000 A. This paper uses experimental data on contact erosion and high-speed photography to examine the time period just after the rupture of the molten metal bridge and before the formation of the metal phase arc in both ambient air and in vacuum.

Manuscript received January 30, 2010.
Manuscript revised June 15, 2010.
[†]The author is Consultant in the Areas of Circuit Interruption and Electrical Contacts, Ithaca, N.Y., 14850 U.S.A.
a) E-mail: paulgslade@verizon.net
DOI: 10.1587/transele.E93.C.1380

2. Experimental Techniques

2.1 Contact Erosion Measurements Using the Radioactive Tracer Technique

It is possible to control the arcing time by opening contacts in a low voltage dc circuit and then by varying the circuit's inductance [2], [17]–[19]. The arcing time is:

$$t_A = \frac{L}{R} \log_e \left[\frac{U_A - U_B}{U_A - U_C} \right] \quad (1)$$

where L is the circuit inductance, R is the circuit resistance, U_A is the arc voltage, U_B is the voltage at the rupture of the molten metal bridge and U_C is the circuit's EMF with $U_C < U_A$. Thus for a constant R and U_A, $t_A \propto L$ and by making L very small the arcing time can be less than 1 μs [17], [19]. In these experiments U_C = 6 V and R = 0.3 Ω and 0.4 Ω. By using a very low inductance circuit, t_A was made to range from 70 ns–4.3 μs.

Erosion of Au contacts opening in atmospheric air and Ni contacts opening in vacuum (10^{-4} mbar) was measured as a function of the acing time using a radioactive tracer technique [20]. One contact was made radioactive and operated against a non-radioactive contact for 500–750 opening operations. The activity of the non-radioactive contact was measured and the volume of the metal transferred to that contact was calculated. Using this method it was possible to differentiate the transfer of contact material to the cathode contact from the transfer to the anode contact.

2.2 High Speed Photography

A Beckman and Whitley, Super Dynafax (318) streaking camera was used to observe the rupture of the molten metal bridge and the transition to the metal phase arc between the opening contacts [10], [12]. The streaking rate was up to 0.26 mm μs^{-1}. The streak photograph was correlated to the oscilloscope voltage trace. The contacts opened with a 1000 A current. In air three contact materials were used: Ni, Cu and Ag. In vacuum two contact materials Cr and W were observed.

3. Experimental Results

Figures 1 shows a typical voltage traces for Au contacts at

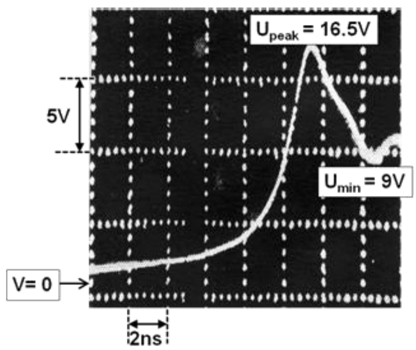

Fig. 1 The initial voltage across Au contacts after the rupture of the molten metal bridge in a 6 V, 20 A dc circuit with an inductance of 0.65 μH [17].

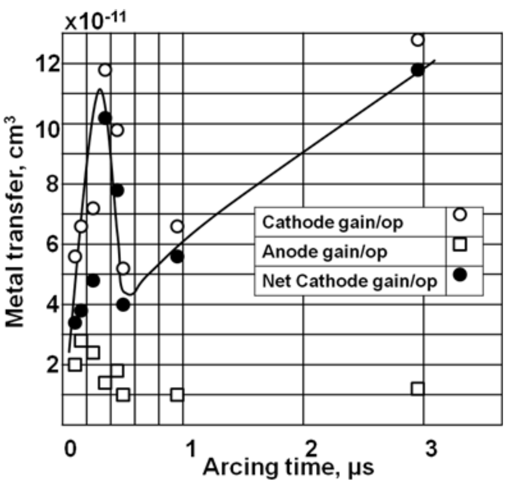

Fig. 2 The metal migration as f(arcing time) for Au contacts in air (6 V, 15 A dc circuit).

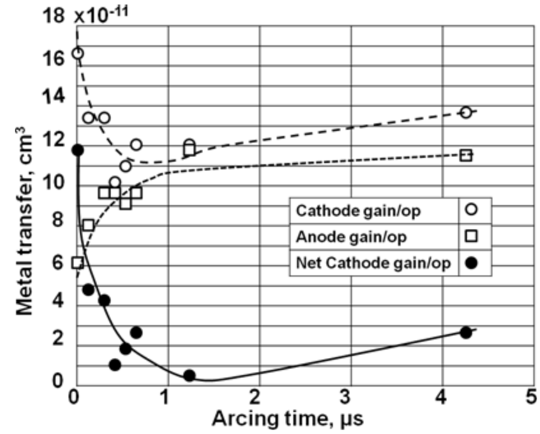

Fig. 3 The metal migration as f(arcing time) for Ni contacts in vacuum (6 V, 20 A dc circuit).

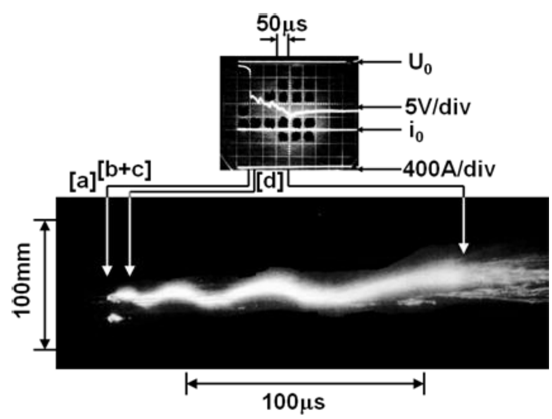

Fig. 4 The initial stages of the arc in vacuum between opening Cr contacts.

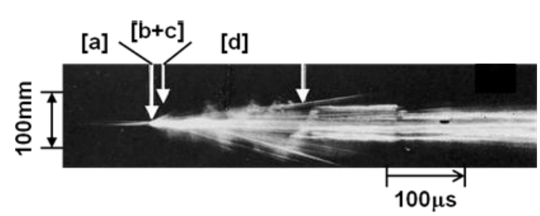

Fig. 5 The initial stages of the arc in vacuum between opening W contacts.

the rupture of the molten metal bridge and during the initiation of the arc for a 20 A current with a circuit inductance of $L = 0.67\,\mu$H. This figure shows that when the molten metal bridge ruptures there is a smooth increase in voltage to a value of ~16.5 V. The rate of rise of voltage during this phase is between 4 and $6{\times}10^9$ $\mathrm{Vs^{-1}}$. This rate of rise is determined by the circuit inductance and the capacitance between the contacts at the position of the molten metal bridge [18]. After the initial voltage peak the voltage drops to a minimum voltage of about 9 V in about 3 ns. The erosion of the Au contacts opening a 15 A circuit as a function of the arcing time is shown in Fig. 2. The cathode shows a rapid gain to a peak value as the arcing time increases to 300 ns. It then drops to a minimum value at 500 ns. After this there is again a gradual increase in cathode gain. The anode also shows an initial gain, which gradually decreases as the arcing time increases. The erosion of the Ni contacts in vacuum opening a 20 A circuit as a function of the arcing time is shown in Fig. 3. Here again there is a large net cathode gain at short arcing times, which also drops to a low value at longer arcing times before gradually increasing again.

Streak photographs for Cr and W contacts opening in vacuum with a 1000 A current are shown in Figs. 4 and 5. Region [a] leads up to the rupture of the molten metal bridge, region [b+c] is a high pressure transition phase and region [c] is where the normal arc is formed. These regions will be explained in Sect. 4. For the Cr contacts at the moment of bridge rupture two high-pressure plasma regions exist where the original, parallel, molten metal bridges resided. Only one of them transitions into the bridge column arc. The other extinguishes after about 7 μs. The W photograph in Fig. 5 clearly shows incandescent metal particles being ejected with velocities in the range 30–150 $\mathrm{ms^{-1}}$. Thus I would expect a similar ejection of particles from the rupturing Cr bridge. At the moment of bridge rupture the

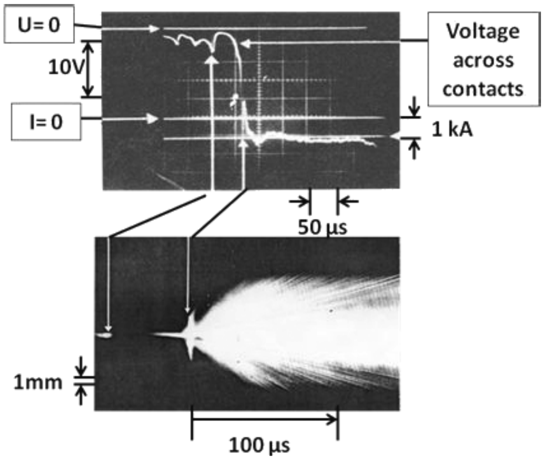

Fig. 6 The rupture of the molten metal bridge and arc formation between opening Ni contacts in air.

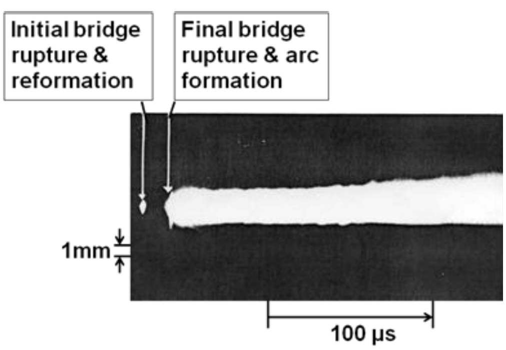

Fig. 7 Streak photograph of the rupture of the molten metal brifge and arc formation between Cu contacts opening 1 kA circuit.

voltage across the contacts for both Cr and W shows similar characteristics as those shown for the 20 A case in Fig. 1. Once the bridge has ruptured there is a rapid dU/dt of about 10^7 Vs^{-1} to a peak value of about 15 V in about 0.5 μs before decreasing to a minimum value of 13 V after 8 μs. The W contacts in Fig. 5 show an incandescent bridge. Both the Cr and W photographs show an expansion of the initial plasma region from the region of the molten metal bridge and the eventual formation of the bridge column arc [16].

Streak photographs for Ni and Cu contacts opening in air with a 1000 A current are shown in Figs. 6 and 7. For the Ni contacts it can be seen that the bridge goes through a period of instability and even becomes incandescent before cooling as more metal enters it. It eventually ruptures about 28 μs later. At the moment of rupture a shock wave is seen which has a velocity of about 350 ms^{-1}. This event finishes after about 6.5 μs. At the moment of bridge rupture incandescent metal particle are ejected with velocities in the range 30–150 ms^{-1}. The voltage across the contacts shows similar characteristics as those shown for the 20 A case in Fig. 1. Once the bridge has ruptured there is a rapid dU/dt of about 10^7 Vs^{-1} to a peak value of about 25 V in about 0.5 μs before decreasing to a minimum value of 19 V after 2 μs. The Cu contacts do not show an incandescent bridge.

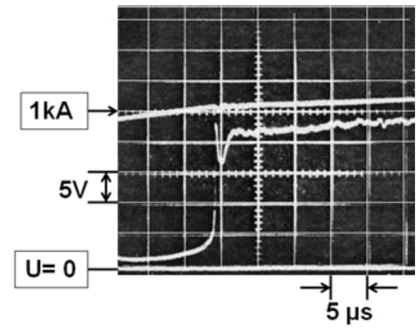

Fig. 8 The voltage across opening Cu contacts at the rupture of the molten metal bridge and formation of the arc.

This is shown by photographs of this 1000 A bridge [6].

Figure 7 does show an initial bridge rupture event, the bridging of the contact gap again and then a final bridge rupture 10 μs later. The shock wave that occurs at the moment of rupture has a similar (within the experimental measurement error) to that shown by the Ni contacts. Figure 8 shows a typical voltage change across the Cu contacts after the rupture of the molten metal bridge in air. Here the dU/dt is about 1×10^9 Vs^{-1}. It increases to a value of 24 V in about 0.1 μs before decreasing to a minimum value of 17 V after 0.5 μs. The data for the Ag contacts is very similar to that shown by the Cu contacts.

4. Discussion of the Arc Formation Process

The formation and rupture of the molten metal bridge between opening contacts occurs for all currents and for all opening accelerations and in all ambients. The causes of the bridge's instability and rupture have previously been discussed in detail [3], [6], [7]. In this paper I am only concerned with the initiation of the electric arc between the contacts once the molten metal bridge has ruptured. It has always seemed remarkable to me that this arc forms so easily. The initial rise in voltage across the opening contacts is shown schematically in Fig. 9. The stages of arc formation are: in region 'a' the molten metal bridge ruptures, in region 'b' the voltages increase rapidly to a peak value (U_{peak}) of a few 10's of volts, and in region 'c' the voltage decreases to a minimum value (U_{min}) before slowly increasing once again, region 'd.' This voltage structure is seen for all currents greater than about 0.5 A, for all practical contact opening speeds in all ambients from vacuum to pressures greater than 1 atmosphere. Figure 9 also shows the radiation observed from opening Cu contacts [7]. A low level of light is seen during the end of the molten metal bridge stage, the intensity of which increases considerably once the voltage reaches the peak value. The CuI spectral lines only become observable once the voltage reaches the peak value. The CuII lines only begin to be seen as the voltage approaches the minimum value. Arc formation occurs although the voltage across the contacts never exceeds a few 10's of volts and it forms within a microsecond or so after the rupture of the molten metal bridge.

During the molten metal bridge stage of contact opening (region 'a' in Fig. 9) for currents in the range of 50 A to 1 kA, the rate of change of voltage is ~2×10^3 Vs^{-1} [3], [6], [7]. When this voltage reaches or exceeds the contact metal's boiling voltage (U_B) the molten metal bridge can no longer exist. The boiling voltage can be calculated:

$$U_B = 2\sqrt{L(T_B^2 + T_0^2)}$$

Where L is the Lorenz constant [21], T_B is the absolute boiling temperature and T_0 is the absolute ambient temperature (For Cu, $U_B \sim 0.91$, for Ni, $U_B \sim 0.97$ V for Cr, $U_B \sim 0.87$ V and for W, $U_B \sim 1.96$ V). Certainly Figs. 4 and 8 show incandescent Ni and W molten metal bridge just before its rupture that indicates a temperature in excess of 2900 K. The Cu and Cr bridges are not seen, because at their boiling temperatures of 2700 K they are not yet incandescent. Once the bridge has ruptured (region 'b' in Fig. 9) the voltage across the contacts rises very rapidly: at 1 kA for Cu, dU/dt $\approx 10^9$ Vs^{-1} [3] and for Ni, dU/dt $\approx 2 \times 10^8$ Vs^{-1}. After the rupture of the molten metal bridge the contacts can be considered to be a capacitor with a very small capacitance [18]. As the circuit inductance prevents a rapid change in the current (see Figs. 4 and 6 and [22]), charge flows from the circuit inductance into the small contact capacitor causing a very rapid voltage rise across the contacts [17], [18], [23]. Without the introduction of charge carriers allowing current to flow between the contacts, this voltage would rise to high values: in excess of a few hundred volts. However, as can be seen, as soon as the voltage reaches a few 10's of volts conduction across the contact gap has been established and the voltage decreases. The voltage continues to decrease until it reaches a minimum value before once again slowly increasing as the contacts continue to open (region 'd' in Fig. 9). The duration of regions 'b' + 'c' for contacts opening in air is a function of current. Figure 10 shows this for Cu contacts and a three orders of magnitude change in current. Here t_{b+c} is $\propto I$ thus as the bridge diameter is $\propto I$ [5], [18], [24], [25], t_{b+c} is $\propto$ bridge diameter. At 1 kA it is also a function of the contact metal: for Cu, $\sim 0.5\,\mu$s and for Ni, $\sim 2\,\mu$s. This also is probably influenced by the diameter of the molten metal bridge at the time of its rupture; e.g. at 1 kA the Cu molten metal bridge has a radius (r_0) of ~ 0.05 mm and a length (ℓ_0) of ~ 0.25 mm, while the Ni molten metal bridge has a radius (r_0) of ~ 0.13 mm and a length (ℓ_0) of ~ 0.25 mm [6].

As Figs. 4, 5, 6, 7 show, the arc is initiated in the region of the molten metal bridge rupture. At the moment of its rupture a very high-pressure region will exist in its vicinity. It is problematical to assess how high this pressure actually is. Potokin et al. [8] assuming that the whole bridge initially forms a dense vapor with a similar volume to that of the bridge calculates a pressure of 9×10^4 atm. As can be seen from Figs. 5 and 6 there is considerable loss of material by particle ejection once the molten metal bridge has ruptured, so the available metal vapor in the bridge region is considerable reduced. One estimate at low currents only gives 5% of the original bridge volume is contained within

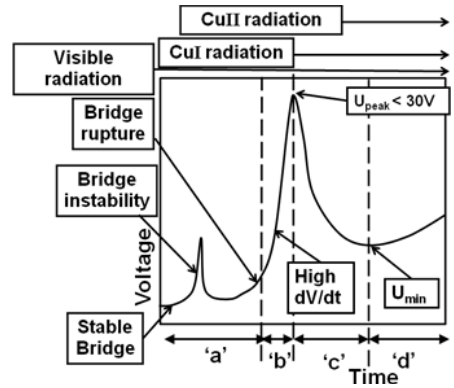

Fig. 9 The voltage across opening Cu contacts at the rupture of the molten metal bridge and formation of the arc showing the Cu radiation [7].

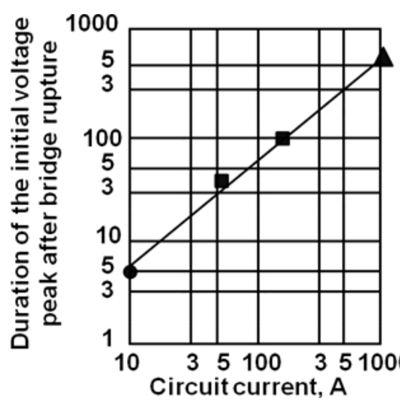

Fig. 10 The duration of the initial voltage peak immediately after the rupture of the molten metal bridge (● [17], ■ [7], ▲ [3]).

the high-pressure region right after the bridge ruptures [26]. In Figs. 6 and 7 the initial stages of the arc formation are obscured by the very bright shock wave. However, in Figs. 4 and 5 when the contacts part in vacuum, there is no shock wave and it can be seen that the arc is initiated in the region of the molten metal bridge rupture. At the moment of its rupture a very high-pressure region will exist in its vicinity. The pressure of the metal vapor can be calculated approximately by considering the self magnetic field on the arc. The average pressure P_a is:

$$P_a = \frac{10^{-7} \times I^2}{\pi r^2}$$

If r is the radius of the plasma in meters (the luminous region in Fig. 4) and I is the current in amperes then P_a is in Nm^{-2}. Figure 11 shows the change in pressure for the first $10\,\mu$s for the plasma region that eventually develops into the bridge column arc for the Cr contacts shown in Fig. 4. The pressure drops from ~ 5 atm. to ~ 2 atm. in the first $10\,\mu$s after the rupture of the molten metal bridge. For the contacts opening in air another way of estimating the initial bridge pressure is to calculate the ratio of the metal density δ_t after time t to the original density δ_0 at the moment of bridge rupture assuming that the metal vapor mass m_R and the bridge length

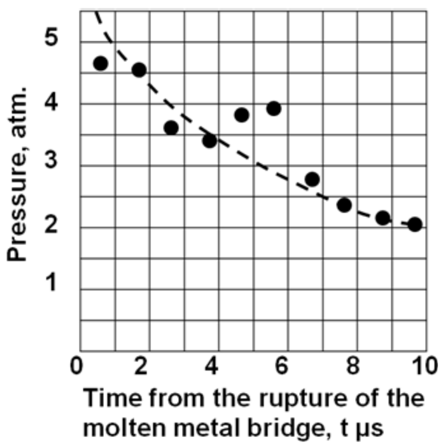

Fig. 11 The initial pressure change for the plasma between the opening Cr contacts.

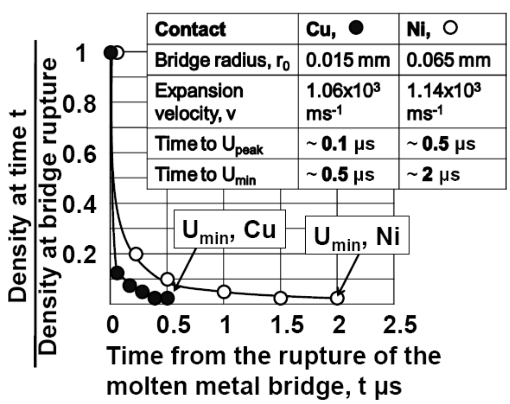

Fig. 12 The ratio of densities at bridge rupture in air and at a later time.

ℓ_B remains essentially constant during the duration of the region 'b' + 'c' in Fig. 9, then:

$$\frac{\sigma_t}{\sigma_0} = \frac{Vol_0}{m_R} \times \frac{m_R}{Vol_t} = \frac{r_0^2}{(r_0 + vt)^2}$$

Where r_0 is the radius of the molten metal bridge just before its rupture (at 1000 A for Cu, $r_0 = 0.05$ mm and for Ni, $r_0 = 0.13$ mm [6]) and v is the velocity of the metal vapor expansion assuming:

$$\frac{1}{2} m_a v^2 = \frac{3}{2} k T_B$$

Where m_a is the atom mass of the metal and k is Boltzmann's constant. At 1 kA the change in time for this ratio for Cu ($v = 1.06 \times 10^3\ \mathrm{ms^{-1}}$) and for Ni ($v = 1.14 \times 10^3\ \mathrm{ms^{-1}}$) is shown in Fig. 12. Interestingly the ratio at the time when the minimum voltage occurs for both metals is ~ 0.015. If we assume that the pressure at this time is between 1–2 atm. Then the initial pressure is between 65 and 135 atm. at the time of bridge rupture and the pressure at the initial voltage peak at the end of region 'b' in Fig. 9 is 3–6 atm. Thus at the beginning of region 'b' in Fig. 9, just after the rupture of the molten metal bridge, the metal vapor between the contacts is at a very high pressure. The voltage in this region increases very rapidly, but at the same time the pressure is decreasing very rapidly as the metal density decreases with the expansion of the confined metal vapor. The voltage at the end of region 'b' reaches value of 10's of volts where the pressure is now 3–6 atm., for both the contacts opening in air and those opening in vacuum. The voltage then decreases to a minimum in region 'c' value where the pressure is now 1–2 atm. The value of pressure given by Fig. 11 for the Cr contacts opening in vacuum is also 3–6 atm. 1–2 μs after the rupture of the molten metal bridge and about 2 atm. after 10 μs.

The data for Ni and Cu contacts in air show that at earlier times (< 100 ns) right after the bridge rupture the pressure is close to 100 atm., but it decays rapidly as the metal vapor expands into the ambient environment. Thus at the beginning of region 'b' in Fig. 9, just after the rupture of the molten metal bridge, the metal vapor between the contacts is at a very high pressure. The voltage in this region increases very rapidly, but at the same time the pressure is decreasing very rapidly as the metal density decreases with the expansion of the inertially confined metal vapor. The voltage at the end of region 'b' reaches value of between 15 and 30 volts where the pressure is now 3–5 atm., before decreasing in region 'c' to a minimum value where the pressure is now about 2 atm. During this initial high-pressure stage the net transfer of contact material is from anode to cathode as shown in Figs. 2 and 3. This has been referred to as an anodic arc [26]–[29] with no real explanation why its exact structure. The interesting study by Puchkarev and Bochkarev [30] gives an important insight into this initial stage of the arc formation. In their experiment they initiate an arc between closely spaces contacts in vacuum and pass current in the high pressure, high density metal vapor that results. They show that this metal vapor after arc initiation comes almost entirely from the anode contact with little or no erosion of the cathode. They show an erosion rate of about 1×10^{-3} g.C^{-1}, which would give an anode loss of about $11.2 \times 10^{-11}\ \mathrm{cm^{-3}}$ for Ni contacts with the 20 A current dropping to zero in 100 ns. The net cathode gain after 100 ns after the rupture of the molten metal bridge in Fig. 3 is $11.5 \times 10^{-11}\ \mathrm{cm^{-3}}$, which shows good agreement with Puchkarov et als' erosion measurement. This hot, high-pressure metal gas initially released into the space between the contacts establishes a condition where a dense, high-pressure, non-ideal plasma/glow discharge can exist. This type of discharge operates in a metal vapor of high density (greater than about $10^{25}\ \mathrm{m^{-3}}$). At high densities/pressures, the Coulomb interaction of the outer bound electrons of the neutral and ionized metal vapor with the surrounding charged particles (the ions and free electrons) leads to a substantial shift in energy levels and a lowering of the electrons' binding energy. The result can be a sharp increase in the ionization state of the plasma; see, for example, Ebeling et al. [31]. The initial plasma can have an ion current density $\sim 10^{10}\ \mathrm{Am^{-2}}$, which will drop to $\sim 10^7\ \mathrm{Am^{-2}}$ as an efficient electron emission mechanism is established at the cathode. During this initial pseudo-arc phase, the electrons from the cathode that are required for current continuity will result from secondary emission caused by ion impact at the cathode. Here only CuI lines are seen between opening Cu contacts [7]. As the metal vapor in this region expands a normal arc will be established, which will have a cathode region generating electrons and the usual neutral plasma between the contacts enabling current to flow between them. At this time CuII lines are seen [7]. Thus conditions are such just after the rupture of the molten metal bridge that ionized plasma forms (pseudo-arc or a high density, low voltage glow discharge) where ions will maintain the flow of current across the contact gap. Assuming that the initial molten metal bridge had equal material from both the cathode and the anode, the flow of ions will result in a net transfer of material from the anode to the cathode. Also by analogy with the work of Germer et al. and Puchkarev et al. continued high anode erosion and migration of anode metal to the cathode would continue until the metal vapor arc is established. As the cathode spot is established there would be a gradual loss of this initially transferred material from the cathode. As the data shows the rapid reduction of the metal vapor's pressure causes the initial pseudo-arc to quickly transition into the usual arc discharge with a voltage impressed across the contacts whose value is about that of the minimum value U_{min} (≈ 10–25 V) for the contact metal. Interestingly Anders et al. also show that for a 100 A discharge in vacuum only anode material is detected during the first 50–100 ns [32]. The anodic arc (i.e. transfer of metal from the anode to the cathode) described by Germer et al. [28], [29] is formed by closely spaced contacts in air with a voltage less than 300 V across them. This is below the Paschen minimum for air at atmospheric pressure and as Slade and Taylor have discussed [33] the breakdown process for small contact gaps in air is similar to the vacuum breakdown in Puchkarov and Buchkarov's experiment. Thus Germer at al's results can also be explained by the high-pressure metal vapor plasma formed immediately after the breakdown of the contact gap.

Thus during the initial stage after the rupture of the molten metal bridge and before charge carriers are established, there is a very high pressure, low conductance, metal vapor region established between the contacts and the voltage across them rises very rapidly. When this voltage reaches a few 10's of volts and the gas pressure has decayed to about 5 atm. a pseudo arc or high pressure glow forms with conduction mainly from ions formed in metal vapor from the anode with the net contact erosion from anode to cathode: the initial anodic arc. As the pressure decreases in this region the cathode region of a normal arc is established which results in a loss of the original material that was initially transferred to the cathode. This arc will establish the normal cathode fall and a plasma region where the current is mostly carried by electrons and its value will be close to but somewhat higher than the minimum arc voltage for the particular contact material. As the contact gap remains very small as this arc forms, it will still operate in the residual metal vapor from the initial bridge rupture and in metal vapor eroded from the contacts by the arc roots. The net transfer of metal remains a net cathode gain [15]. As long as the arc remains mostly a metal vapor arc the net cathode gain will depend upon the arcing time. For an arc operating in a gaseous ambient (in this case air) the arc transitions to a gaseous arc. The net transfer of metal to the cathode will then decrease as has been observed by a number of researchers. Also an arc at currents < 5 kA in vacuum will transition to the usual diffuse vacuum arc with all the contact erosion coming from the cathode [16].

5. Conclusions

(a) Opening contacts in circuits carrying currents greater than a fraction of an ampere will form an arc between them.
(b) The initial phase of opening will produce a molten metal bridge connecting the opening contacts for all currents and in all ambients.
(c) As the contacts continue to open the bridge ruptures at a temperature close to or in excess of its boiling temperature.
(d) A very high-pressure, metal vapor gas (~ 100atm.) is released in a confined space between the contacts. As this gas has few charge carriers to carry the circuit current initially, the voltage across the contacts rises very rapidly.
(e) The pressure in this region decreases rapidly and at a few atmospheres when the voltage reaches a few 10's of volts a pseudo arc forms. In the plasma most of the current is carried by ions and there is rapid erosion of the anode and a transfer of metal to the cathode.
(f) As the metal vapor pressure continues to fall a normal arc forms in metal vapor with a cathode region supplying electrons to carry the current between the contacts.
(g) As the normal arc forms and the usual cathode fall region is established, some of the initial net cathode gain will itself be eroded from the cathode.
(h) There will still be a net transfer of metal to the cathode in this metal phase arc. This will decrease as the contacts continue to open and the arc in the ambient gas is established or the diffuse vacuum arc is formed.

References

[1] N. Ben Jemma and L. Lehfaoui, "Short arc duration laws and distributions at low currents (< 1 A) and voltage (14–42 Vdc)," Proc. 20th International Conference on Electrical Contacts, (SBN 91-7170-585-6), pp.379–394, Stockholm Sweden, June 2000.
[2] P.G. Slade, "An investigation of current interruption in low voltage circuits," IEEE Trans. Parts Hybrids Packag., vol.PHP-5, no.1, pp.56–62, March 1969.
[3] P.P. Koren, M.D. Nahemow, and P.G. Slade, "The molten metal bridge stage of opening contacts," IEEE Trans. Parts Hybrids Packag., vol.PHP-11, no.1, pp.4–10, March 1975.
[4] J.J. Lander and L.H. Germer, "The bridge erosion of electrical contacts, part 1," J. Appl. Phys., vol.19, pp.910–928, Oct. 1948.
[5] T. Utsumi, "Theoretical and experimental investigations of the dynamic molten bridge," IEEE Trans. Parts, Materials and Packaging, vol.PMP-5, no.1, pp.62–68, March 1969.

[6] P.G. Slade and M.D. Nahemow, "Initial separation of electrical contacts carrying high currents," J. Appl. Phys., vol.42, no.9, pp.3290–3297, Aug. 1971.
[7] P. Haug, T. Kouakou, and J. Doremieux, "Phenomena preceding arc ignition between opening contacts: Experimental study and theoretical approach," Proc. International Conference on Electrical Contacts, (IEEE CAT. no.90CH2900-9), pp.543–549, Quebec Canada, Aug. 1990.
[8] V. Potokin and V. Rakhovskii, "Bridge stage in a vacuum switch," Sov. Phys.–Tech. Phys., vol.12, no.2, pp.236–239, Aug. 1967.
[9] V. Potokin, V. Rakhovskii, and V. Tikhonov, "The bridge stage of electrode erosion in switching 1000–5000 A currents in vacuum," Sov. Phys.–Tech. Phys., vol.10, no.10, pp.1424–1427, April 1966.
[10] P.G. Slade and M.F. Hoyaux, "The effect of electrode material on the initial expansion of an arc in vacuum," IEEE Trans. Parts Hybrids Packag., vol.8, no.1, pp.35–47, March 1972.
[11] S.M. Celikatova and I.A. Lukatskaya, "Initial stage of vacuum interrupting arc," Int'l Gas Discharge Conf., pp.370–374, London, 1970.
[12] P.G. Slade and M.D. Nahemow, "A photographic study of the initiation of the drawn arc," Proc. Int'l Conf. on Electrical Contacts, pp.285–288, Munich Germany, May 1970.
[13] P.J. Boddy and T. Utsumi, "Fluctuations of arc potential caused by metal-vapor diffusion arcs in air," J. Appl. Phys., vol.42, no.9, pp.3369–3373, Aug. 1971.
[14] E.W. Gray, "Some spectroscopic observations of the two regions (metallic vapor and gaseous) in break arcs," IEEE Trans. Plasma Sci., vol.PS-1, no.1, pp.30–33, 1973.
[15] Z.-K. Chen, H. Mizukoshi, and K. Sawa, "Contact erosion patterns of Pd material in dc breaking arcs," IEEE Trans. Compon. Packag. Manuf. Technol. A, vol.17, no.1, pp.61–67, 1994.
[16] P.G. Slade, The Vacuum Interrupter: Theory Design and Application, (pub. CRC Press, Nov. 2007), Chapter 2, "The Vacuum Arc," pp.130–172.
[17] M. Hopkins, R. Jones, and J. Evans, "Short time transients in electrical contacts," Proc. Int'l Conf. on Electrical Contacts, pp.270–272, Tokyo, Japan, Aug. 1976.
[18] W.B. Ittner, "Bridge and arc erosion of copper, silver, and palladium contacts on break," J. Appl. Phys., vol.27, no.4, pp.382–388, 1968.
[19] P.G. Slade, "The micro arc between separating contacts electrodes in low voltage circuits," Proc. International Conference on Electrical Contacts, pp.289–292, Munich, Germany, May 1970.
[20] F. Llewellyn-Jones, M.R. Hopkins, and C.R. Jones, "Measurement of metal transfer in electrical contacts by the radioactive isotope method," British J. Appl. Phys., vol.12, no.9, pp.485–489, Sept. 1961.
[21] R. Timsit, "Electrical contact resistance: Fundamental principles," in Electrical Contacts: Principle and Applications, ed. P. Slade, pp.45–56, pub Marcel Dekker, 1999.
[22] M. Hopkins and A. Jenkins, "Transient potentials and currents in a low voltage opening electrical contact," Proc. 5th Int'l Conf. on Electrical Contacts, pp.236–239, Munich, Germany, May 1970.
[23] M. Hopkins, R. Jones, and A. Davis, "Experimental and theoretical study of initial break transients in low voltage electrical contacts," Proc. 7th Int'l Conf. on Electrical Contacts, pp.300–304, Paris, France, June 1974.
[24] M. Price and F. Llewellyn-Jones, "The electrical contact: The properties and rupture of the microscopic molten metal bridge," British J. Applied Physics (J. Physics D), Ser. 2, vol.2, pp.589–596, 1967.
[25] J. Lander and L. Germer, "The bridge erosion of electrical contacts: Part 1," J. Appl. Phys., vol.19, no.10, pp.910–928, Oct. 1948.
[26] M. Cowburn and F. Llewellyn-Jones, "Time-resolved spectroscopy of contact micro plasma," Proc. 8th International Conference on Electrical Contacts, pp.264–268, Tokyo, Japan, Aug. 1976.
[27] W. Rieder, "Low current arc modes," IEEE Trans. Compon. Packag. Manuf. Technol., vol.23, no.2, pp.286–292, June 2000.
[28] L. Germer, "Physical processes in contact erosion," J. Appl. Phys., vol.27, no.7, pp.1076–1082, July 1958.
[29] L. Germer and W. Boyle, "Two distinct types of short arcs," J. Appl. Phys., vol.27, no.1, pp.32–39, Jan. 1957.
[30] V. Puchkarev and M. Bochkarev, "High current density spotless vacuum arc as a glow discharge," IEEE Trans. Plasma Sci., vol.25, no.4, pp.593–597, Aug. 1997.
[31] W. Ebeling, A. Förster, and R. Radtke, Physics of Non-Ideal Plasmas, Pub. Teubner Verlagsgesellschaft, Stuttgart, 1991.
[32] A. Anders, S. Anders, B. Jüttner, W. Bötticher, H. Lück, and G. Schröder, "Pulsed laser diagnostics of vacuum arc cathode spots," IEEE Trans. Plasma Sci., vol.20, no.4, pp.466–472, Aug. 1992.
[33] P.G. Slade and E.D. Taylor, "Electrical breakdown in atmospheric air between closely spaced electrical contacts," IEEE Trans. Compon. Packag. Manuf. Technol., vol.25, no.3, pp.390–396, Sept. 2002.

Paul G. Slade Until his retirement in 2007, he was the Manager of Vacuum Interrupter Technology Department, Eaton Electrical, Horseheads, NY. USA. Currently, he is working as a consultant in the fields of circuit interruption and electrical contacts. He received his Ph.D. degree from the University of Wales, Swansea, U.K. He has over 40 years of research experience covering a wide range of subjects associated with electrical contact research and application, properties of vacuum arcs, vacuum interrupter design, and the application of vacuum interrupters. He received the 1985 Ragnar Holm Scientific Achievement Award. Dr. Slade is a Fellow of IEEE. He edited and is the primary Author for the book: Electrical Contacts published in 1999. He is the author of the book: The Vacuum Interrupter: Theory, Design and Application published November 2007.