Material Effect on Glowing Contact Properties

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***Abstract*—Properties of glowing connections for a variety of electrically conductive materials are presented. The properties investigated include voltage waveforms, rms voltage with current, and the propensity to initiate glowing. This was done using materials that may be used in residential electrical wiring. The materials and combinations of materials investigated were copper, brass, phosphorous bronze, steel, and stainless steel. It is found that material type has a pronounced effect on the voltage wave-shape of the glowing contact and the associated rms voltage. It is also shown that the number of make/break operations to get the connection glowing is greatly influenced by the material with steel materials being the easiest to initiate glowing. Waveforms and voltage values over a current range of $0.5\,A_{rms}$ to $11\,A_{rms}$ are presented, and there is discussion on the influence of oxide resistivity and material parameters on glow voltage.**

***Index Terms*—Arc discharges, arc heating, conductivity, electric breakdown, glowing, glowing contact, oxidation, resistance.**

I. Introduction

GLOWING connections can occur in virtually any type of electrical circuit, including residential $115\,V_{ac}$ wiring, dc automotive applications, aerospace applications, and so on [1]–[5]. Factors controlling glow initiation and sustainability depend on many factors, including current, wire interface shape, wire diameter, dc or ac, and wire material [4]–[7]. Glowing connections have been created with currents as low as $0.25\,A_{rms}$ [4]–[7].

Glowing contacts have previously been studied for copper conductors, but there are other materials that may be present in electrical wiring that can glow. The metals chosen for this investigation were chosen because of their potential use in various types of electrical products with copper being the most common. Alloys of copper, brass, and phosphorous bronze are used in wall outlets and electrical switches. Steels can be found in the screws that secure the wires in wall outlet receptacles. Sometimes, the steel screws are brass plated for identification purposes, but, if arcing occurs, the plating can be removed exposing the base metal.

This research was done to show how the type of material affects the characteristics of a glowing connection. Properties of the voltage wave-shape were determined for materials and for combinations of materials along with the rms glow voltage over a current range of $0.5\,A_{rms}$ up to $11\,A_{rms}$. In addition, the approximate number of make/break operations necessary to start a glowing connection, for each material, is tabulated. The physical phenomena regarding semi-conductive temperature dependent oxide properties and other physical parameters are discussed to explain the glowing property differences between various materials. This type of information is useful not only for understanding the association between glowing connection formation and properties of these materials, but can be used for practical information in choosing a material that is more resistant to the creation of glowing connections.

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II. Background

Glowing connections can form at the interface of an electrical connection and are characterized by an incandescent orange glow of molten oxide at an electrical joint [4]–[7]. Frequently, this glow would be the unintended result of a loose connection that arcs under load current. Depending on the material, it may take thousands of make/break cycles or vibration in which arcing occurs and just the proper alignment of the wires to make the glow occur. In other cases, especially with steel materials, the glow can occur with only a few or as little as one make/break arcing operation, making it relatively easy to initiate a glowing connection as opposed to copper wire which can take longer to initiate a glow and more easily disrupted. The make/break teasing action of a loose connection is especially vulnerable to the initiation of a glowing connection because the arcing creates a metal oxide between the connections that can overheat the interface. It is suspected that the repeated make break action draws a thin strand of metal/metal oxide that is heated to high temperatures because of the high current density created by the thin strand. With sufficient oxide present on the surface of the interface, the glow will be initiated and sustained due to the negative temperature coefficient of resistance that the oxide materials possess. The material type and current level also determine the physical shape of the glowing area and the stability of the glow.

Vibration can quickly accelerate the conditions needed for glowing due to the repeated oscillatory action. One practical example is the repeated action of plugging and unplugging an appliance in an outlet with loose wires. This can provide enough motion that over time can cause a glowing condition [2], [6].

The glow is characterized by a relatively high contact voltage drop as compared to a resistive joint. A glowing connection is not to be confused with a high resistance

TABLE I
WIRE MATERIALS COMBINATIONS AND OUTCOMES

Material Type	Extinction Current (A_{rms})	Outcome	Possible Oxide Products	Ease to Initiate Glow
Copper–copper	1.0	Breeding	Cu_2O, CuO	Hard
Brass–brass	1.0	Slow growth	Cu_2O, CuO, ZnO	Hard
Steel–steel	1.0	Slow growth	FeO, Fe_2O_3, Fe_3O_4	Very easy
Stainless steel–stainless steel	0.5	Slow growth	Cr_2O_3, NiO, FeO, Fe_2O_3, Fe_3O_4	Very easy
Phosphor bronze–phosphor bronze	0.5	Breeding	Cu_2O, CuO, SnO_2, Sn_2O_4	Very hard
Copper–brass	1.0	Breeding	Cu_2O, CuO, ZnO	Hard
Copper–phosphor bronze	1.0	Breeding	Cu_2O, CuO, SnO_2, Sn_2O_4	Very hard
Copper–steel	1.0	Slow growth	Cu_2O, CuO, FeO, Fe_2O_3, Fe_3O_4	Easy
Copper–stainless steel	0.5	Slow growth	Cu_2O, CuO, FeO, Fe_2O_3, Fe_3O_4, Cr_2O_3, NiO	Easy

All wires 1.0 mm diameter. Degree of ease to initiate glow scale: very easy = 1 to 2, easy = 2 to 10, hard = hundreds, very hard = hundreds to thousands of make/break operations.

connection. Simply having a loose joint with a high resistance may result in a voltage drop on the order of hundreds of mV's or less. Rather, glowing, associated with molten metal oxides at temperatures on the order of 1200 °C, has voltage drops on the order of 1 to 10 V, depending on current, geometry, and material [4]–[7]. It is not known if oxidation and fretting without arcing can lead to glowing.

Japanese researchers have shown that a glowing connection can be created from various types of conductor materials, but have not documented the associated waveforms or experimental details [8], [9].

III. EXPERIMENTAL SETUP

This section details the experimental setup used to create glowing connections and to acquire the waveforms and images. An ac resistive circuit was used for all testing.

Glowing contacts, using wire material pairs shown in Table I, were produced using the setup shown in Fig. 1. The moving electrode was spring loaded with about 1 N of spring force. The make/break action was obtained by manually turning the micrometer with light force until current flowed. Initially, the make/break action was performed rapidly (~3 Hz) in order to condition the wire surface. When a glowing condition began to form, as detected by an increased voltage V_{glow} and visual detection of a corresponding orange glow, the motion of the moving wire was slowed to draw the oxide across the gap. At this point, the micrometer was slowly turned out to extend the glowing bridge to as long a length as possible without breakage and arcing. Typically, the bridge would break and had to be reformed by subsequent make/break action. Frequently, due to the insulating nature of copper oxide bridge, it was not possible to remake current flow unless the oxide was removed. The iron materials did not form an insulating layer and thus could be easily restarted. The current was controlled by adjusting the variac and the resistive load.

IV. RESULTS

Nine material combinations based on five materials were investigated. In the first set of tests, the current was set at 1.6 A_{rms}. Copper was used as one electrode for five of the trials where the other electrode material varied as seen in the

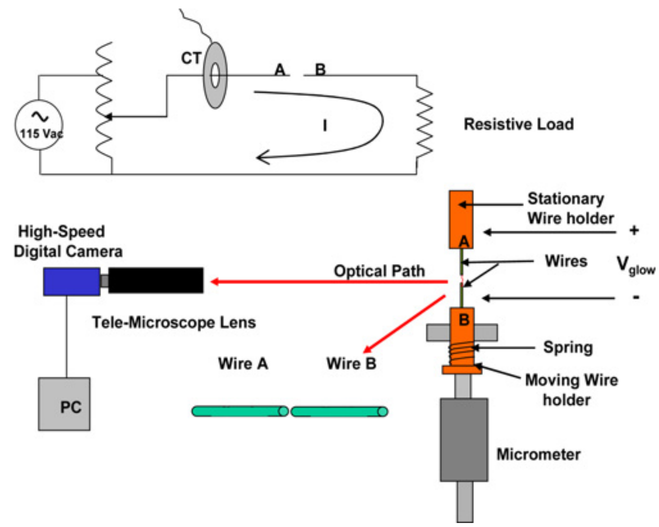

Fig. 1. Setup used to produce, image, and record glowing contact properties.

left-hand column of the results shown in Fig. 2. A new wire was used for each trial. Fig. 3 shows how the glowing contact resistance changed dynamically for copper wires. The glowing temperature was modulated by the current so subsequently, at the current zero crossings, the glowing temperature was at its lowest point. The consequence was increased oxide resistivity resulting in increased resistance as shown near the zero crossings. At higher currents (e.g., > about 5 A_{rms}), the temperature drop was not low enough to cause a sharp increase in oxide resistivity, but rather displayed only a slight increase. Thus, the voltage waveform (Fig. 4) does not have as sharp a spike, at current zero, as in the voltage waveform from Fig. 2.

The second set of tests was obtained at a current level of 5 A_{rms}, and the waveforms are shown in Fig. 4. Comparing the voltage waveforms in Figs. 2 and 4 shows how the wave-shape is affected by current level, especially for the copper-to-copper wire pair. The spike in the voltage disappears at higher currents for copper wire. It will also be observed that whenever either wire is an iron based material, the wave-shape is smooth and sinusoidal with minimal distortion. Also, as seen in Table I, it was very easy to initiate glowing at any current with the iron based materials. These materials produced a

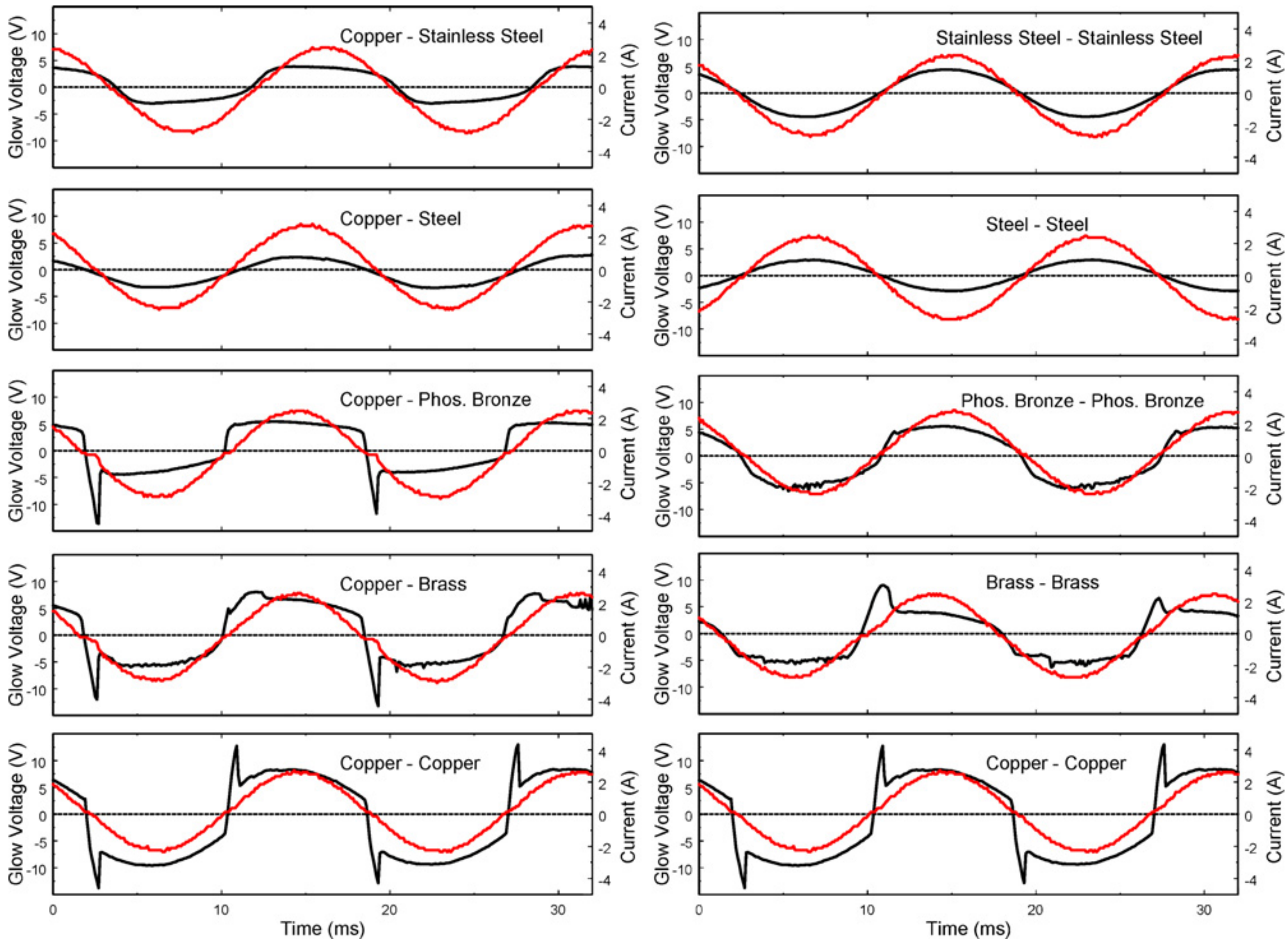

Fig. 2. Current and voltage waveforms for the various material combinations all at 1.6 A_{rms}. All wires were 1.0 mm in diameter. Current shown in red.

uniform glowing region, as seen in the images of Fig. 5. By comparison the copper wires produced a glowing filament that meandered around the oxide surface. This also occurred for alloys of copper materials tested (brass and bronze). The voltage waveforms had non-sinusoidal shapes unlike the wires containing iron (steel and stainless steel) which had smooth sinusoidal voltage waveshapes.

The extinction current, in Table I, shows the minimum current for easy existence of the glow in a steady state, but was not the absolute lowest current that could support a glow. The minimum current to sustain glowing is considered to be about 0.25 A_{rms} for all the materials tested. The extinction current was measured by reducing the current level until the glowing ceased and recording the current as seen in Table I.

The outcome of glowing was the growth of the oxide. Breeding means that the oxide grows actively and consumes the wire length. Slow growth, as in iron based wires, indicates more of a glowing volume rather than a molten filament on the oxide surface as in the copper-to-copper case of Fig. 5.

Fig. 6 illustrates how the glowing voltage, measured with a Fluke 85 True rms multimeter, decreases with increasing current for the various wire material combinations. Copper based materials (i.e., copper, brass, bronze) had higher glowing voltages than iron based materials, especially at low currents. This was also true even if one of the wires was copper based.

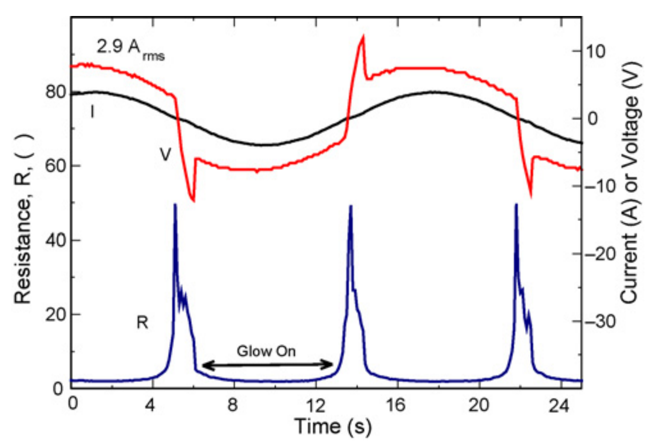

Fig. 3. Dynamic resistance of glowing contact (2.9 A_{rms}, 1 mm diameter copper) shows large increase in resistance near current zero for copper-to-copper [7].

Fig. 7 shows the power dissipated in the wire pair interface for each combination tested as calculated from the results from Fig. 6. The power dissipated increases with current.

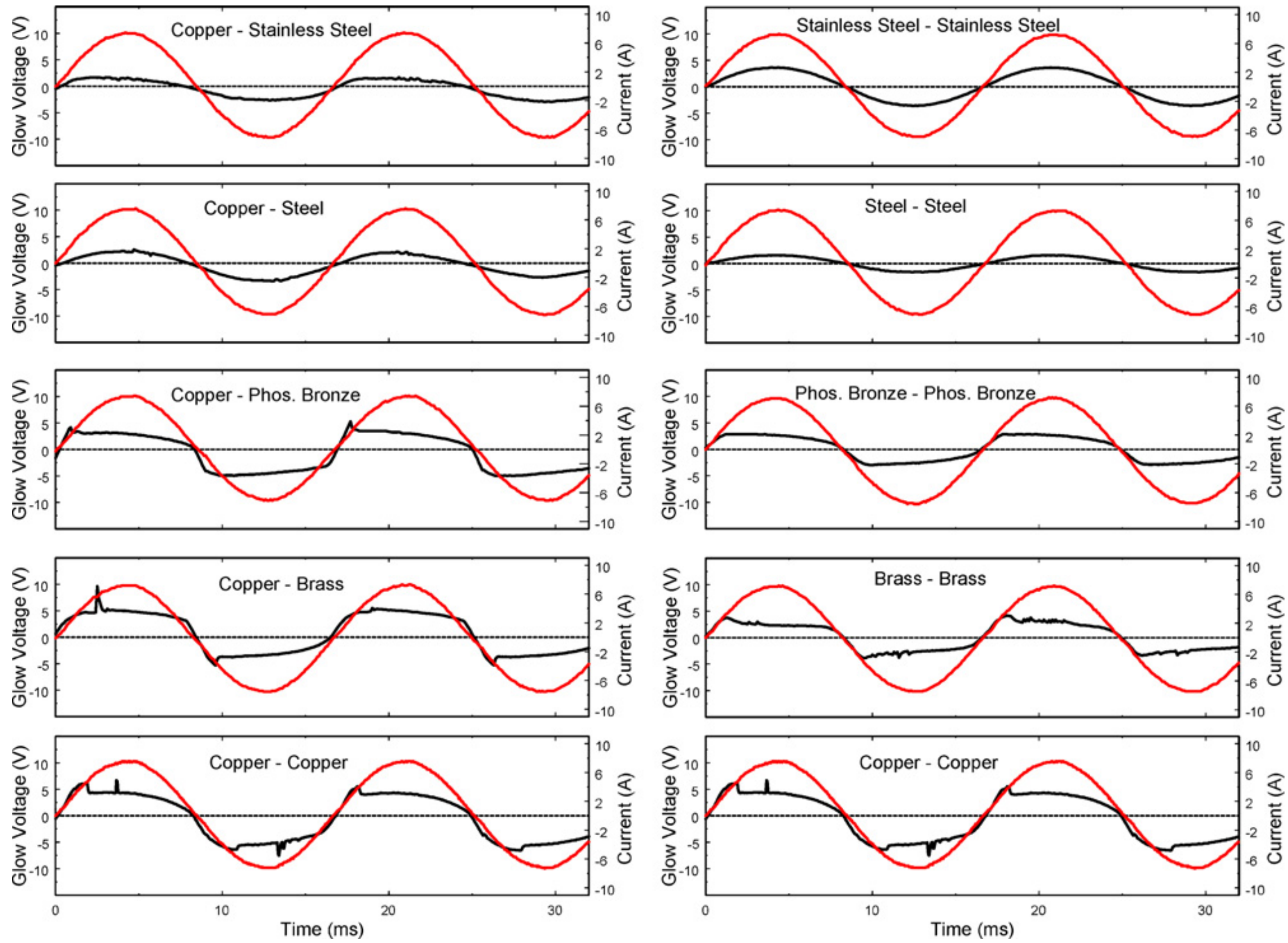

Fig. 4. Current and voltage waveforms for the various material combinations all at 5 A_{rms}. All wires were 1.0 mm in diameter. Current shown in red.

V. Discussion

There appear to be two different glow mechanisms. For copper based materials, the oxide growth is rapid and along the length of the wires whereas with iron based wires, the oxide growth is minimal and the layer is thin as seen in Fig. 5. It would also appear that since the glow voltage remains relatively unchanged, even when the oxide length increases over time, that the oxide resistivity must drop by the amount the length increases in order to maintain a fairly constant voltage. This is particularly true for the case of copper wires.

The oxide resistivity decreases with increasing current because the oxides have a negative temperature coefficient of resistivity. In the case of the copper wires, the glowing filament is in parallel with the solid copper oxide. It is anticipated that a combination of two parallel resistances determines the glowing voltage, the solid oxide, and the molten oxide/plasma vapor of the filament. By contrast, the iron based wires do not have a filament but rather a glowing zone even at low currents. Here, it is anticipated that the glowing voltage is determined solely by a thin layer of iron oxide. With these assumptions, a plot of measured resistance (obtained from the I–V data in Fig. 6) can be compared to a resistance obtained from experimentally measured oxide resistivity available in the literature. This graph can then be used to determine, in the copper oxide case, the amount of contribution to the glowing resistance that comes from the molten filament. In the case of iron oxide, it can be used to determine the oxide thickness.

From Fig. 6, the stainless-steel wire has nearly the identical I–V curve as the non-stainless-steel wires. Thus, the oxides in common (FeO, Fe_2O_3, Fe_3O_4) are likely the dominating factor in determining the glowing properties. This implies that the oxides not in common (i.e., NiO, Cr_2O_3) did not have any effect on the results.

Available temperature versus conductivity curves for two oxide classes, copper oxides (CuO and Cu_2O) and iron oxides (FeO, Fe_2O_3, Fe_3O_4), have been used to calculate resistance versus oxide temperature. Previous paper has shown CuO as the oxide that forms between the copper wires [7]. From the literature, the experimentally measured oxide conductivity as a function of temperature can be found and fit to the following equation:

$$\sigma = \sigma_0 e^{-E_g/2kT} \tag{1}$$

where E_g is the band gap or activation energy, $k = 1.38 \times 10^{-23}$ J/K, and T is temperature in degrees kelvin. The slope of the straight line obtained from plotting the log of conductivity against $1000/T$ gives the band gap energy, E_g, for the oxide and so the intercept. For CuO $E_g = 1.6$ eV and $\sigma_0 = 2075$ S/cm [7], and for Fe_2O_3 $E_g = 2.2$ eV and $\sigma_0 = 3350$ S/cm for

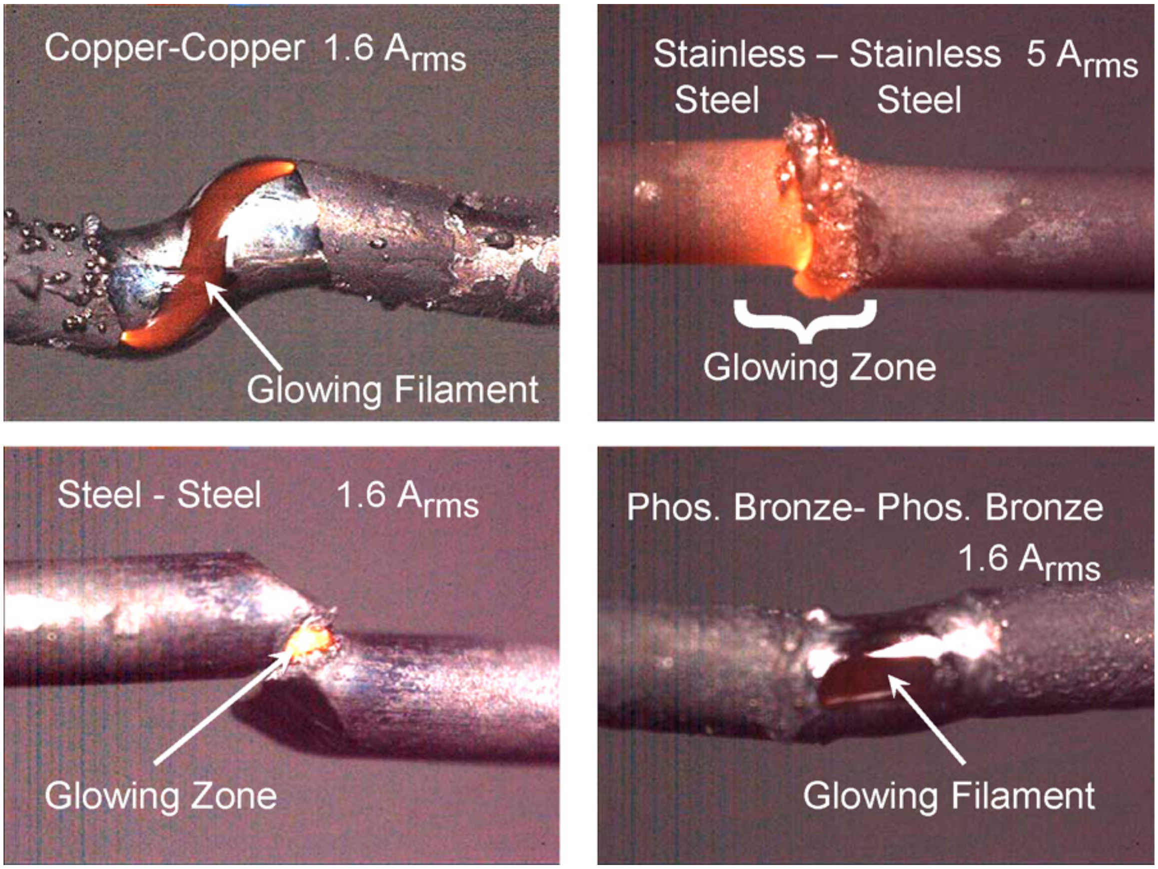

Fig. 5. Images of glowing connection for various wires and currents. Copper based materials produced a glowing filament where steels produced a uniform glow.

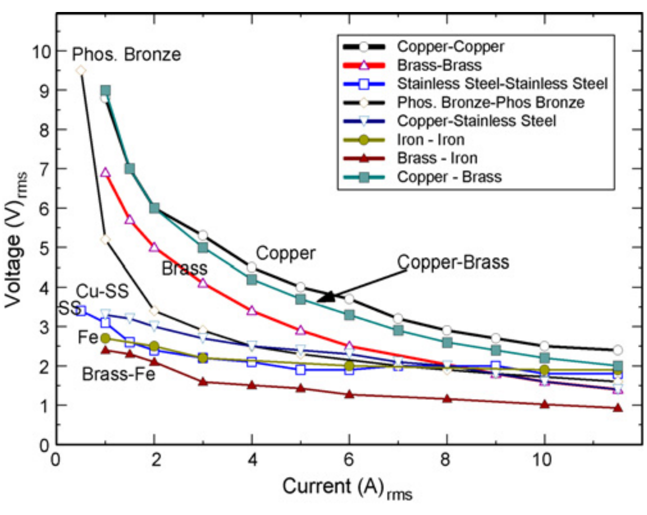

Fig. 6. True rms voltage as a function of current for the various combinations of wire materials. Except for the iron based wires, there is an exponential decrease in voltage with current increase.

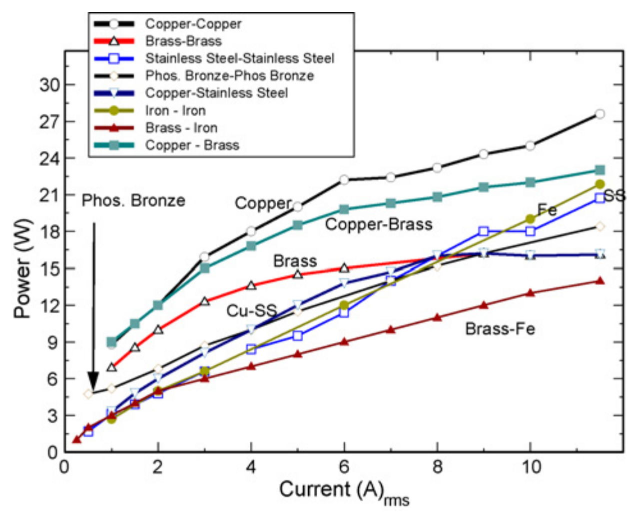

Fig. 7. Power dissipated as a function of current for the various combinations of wire materials.

temperatures between 1300 K and 1600 K and $E_g = 0.5$ eV and $\sigma_0 = 15$ S/cm for temperatures above 1700 K [12].

The conductivities for FeO and Fe_3O_4 are not readily available over a wide temperature range and the limited data available appear to be out of the range for the resistance measured during glowing of the iron based materials. Thus, only Fe_2O_3 oxide data have been used. Using these band gap energies along with either a range of reasonable oxide length estimates, L, for steel, and 0.18 cm for copper as can be estimated using Fig. 5. The resistance can be calculated from

$$R = \rho(T)L/A \tag{2}$$

where $\rho(T)$ is oxide resistivity which is a function of temperature, L is the oxide bridge length, and A is the cross-sectional

TABLE II
WIRE MATERIAL PROPERTIES

Material Type	Composition (wt%)	Metal MP (°C)	Metal Thermal σ λ (W/mK) at 20 °C	MP of Various Stable Oxides (°C)
Copper	Cu (99.999)	1083	400	1235 (Cu_2O) 1326 (CuO)
Brass 260	Cu/Zn (70/30)	915–955	109	1975 (ZnO)
Steel 1006 (FeO)	Fe/C (99.5/0.06)	1535 (Fe)	46	1457 (Fe_2O_3), 1597 (Fe_3O_4), 1360–1424
Stainless steel 302	Fe/Cr/Ni/Mn (71./18/8/2)	1400–1420	16	2400 (Cr_2O_3), 1984 (NiO)
Phosphor bronze 510	Cu/Sn/P(94.8/5.0/0.2)	975–1060	84	540 (SnO_2) 1100 d.(Sn_2O_4)

All wires 1.0 mm diameter. λ at 20 °C. Steel 1006 Fe/C/Mn/P/S (99.5/0.06/0.35/0.04/0.05). Stainless steel 302 Fe/Cr/Ni/Mn/Si/C/P/S(71./18/8/2/0.75/0.15/0.04/0.03). MP: melting point. The MP of oxides lists only new oxides rather than repeating oxides previously listed. Potential intermetallic oxides are not listed. Values from www.webelements.com and www.matweb.com.

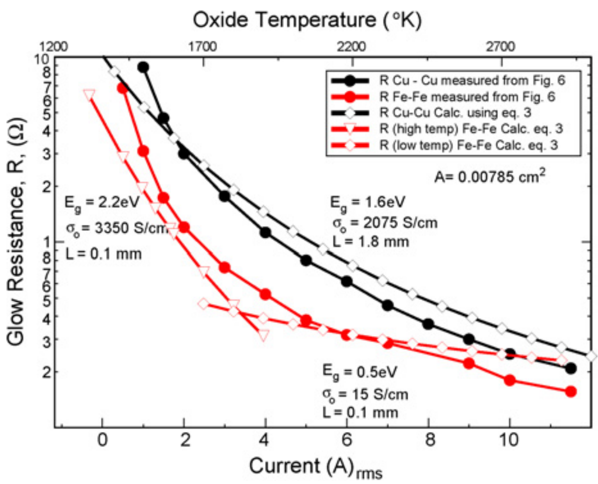

Fig. 8. Current versus measured glow resistance (V_{glow}/current) from Fig. 6 and oxide temperature versus calculated resistance (3).

area of the oxide (assumed equal to the wire area). Equation (1) can be substituted into (2) to obtain the following:

$$R = L/(A\sigma_0 \exp(-E_g/2kT)). \quad (3)$$

Using the values for E_g and σ_0 for each material, the resistance versus temperature is plotted along with the measured resistance of the glowing wires in Fig. 8. The oxide temperature scale was obtained by visually matching the slope of the resistance, obtained from (3) for 2.2 eV, to the slope of the measured resistance as a function of current below 4 A_{rms} for Fe. Similarly, the lower part of the Fe resistance curve, using 0.5 eV in (3), was visually fit to match the slope of the measured resistance at currents above 4 A_{rms}. Two different energy values were used based on prior results [7]. Doing this provides a crude estimate of the oxide temperature for comparison to measured values with an attempt to connect theory with experimental results. In this analysis, the current path through the filament was not considered even though it is expected that a portion of the current flows through the filament.

The iron oxide resistance was curve fit with two equations because the activation energy was a function of oxide temperature. Also note that since Fe_2O_3 decomposes above 1850 K, then above this temperature either another iron oxide (FeO) with a decomposition temperature of 3700 K forms, or FeO is the oxide formed for the entire temperature range [13].

Small additives such as phosphorous can have a dramatic effect on the difficulty of glow initiation, possibly due to the prevention of copper oxide formation.

There is a dramatic difference in the glow voltage waveshape between steel and copper materials. One possible explanation is due to the differences between the oxide melting and vaporization points compared to their respective metal melting points. Copper melts at 1083 °C about 250 °C below the melting point of CuO and Cu_2O (1325 °C). However, steel has a MP of 1400–1535 °C with the iron oxides melting in this range or even lower at 1360 °C to 1500 °C (see Table II). This may explain why the copper breeds rapidly with the formation of a molten pool of metal/metal oxide whereas the steel produces a glowing zone and slow oxide growth since the steel is not melted away as readily as copper. Also, the instabilities at higher currents for copper wires may be attributed to the vaporization temperature of copper oxide (1800 °C). When this temperature is exceeded the glow will tend to extinguish. The stability of the glow when using steel, even at currents higher than the upper limit when using copper, may be attributed to the high vaporization temperature of FeO (3414 °C) [13].

The shape of the copper glowing filament depended on current level. A thin filament at low currents widens and covers the entire oxide surface as the current increases. At currents above about 5 A_{rms} the filament becomes more globular and less stable (i.e., more likely to become an open circuit). This may be caused by the dramatic drop in thermal conductivity of copper from 357 W/(m · K) at 1000 °C to 167 W/(m · K) at 1400 °C [11]. Steel wires and copper both glow brighter with increasing current, but the steel does not create a filament but rather a glowing zone.

The measured temperature of the liquid metal glow was around the melting point of CuO, 1326 °C [7], [10]. With the current increased to 7.5 A_{rms}, the glowing filament temperature increased to 1730 °C [7]. This supports the theory that with higher currents, the glowing filament temperature approaches the CuO vaporization temperature, 1800 °C, and becomes unstable. Exceeding this temperature would lead to an unstable liquid/vapor /ionized interface that would arc. This could explain why it is more difficult to sustain a glow for any long period of time at higher current levels for copper.

VI. Conclusion

Waveform and optical measurements have shown the differences in glowing contact phenomena in various metals that are commonly used for electrical connections.

Results suggest that the copper based materials (copper, brass, bronze) behave similarly and can be grouped together with some minor differences in glowing voltage. This means that the voltage across the contact has a similar shape and magnitude for copper based materials. However, iron based materials (steel and stainless steel) produced dramatically different voltage waveforms and magnitudes compared to copper based materials. The iron based materials can also be grouped together. In comparison to iron wires, it was much more difficult to initiate glowing using copper-based wires, requiring many more make/break cycles of arcing. And, copper materials formed a molten glow that acts as a filament at low currents, and appears to cover the solid-oxide surface at currents above 5 A_{rms} Also, it is unknown as to the percentage of current divided between the solid-oxide and the glowing filament. By comparison, the iron based materials formed a glow with only a few make/break operations but produced a glowing zone rather than a filament. Finally, the copper based materials produced a relatively fast growing oxide bridge between the wires as opposed to the iron which produced no significant oxide bridge over time. It is also noted that the glowing temperature increases with increasing current and that the oxides formed between the wires decrease in resistivity with increasing current. While glowing can occur for copper based conductors, any iron-base material in the current path that can become loose and oxidize could have a very high probability of overheating at currents above which glowing initiates.

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