

SWITCHES, RELAYS AND SOLENOIDS – PART TWO

What Happens When Contacts Close and Open?

BY BOB THOMAS &
WES GRUENINGER, SR

Switches, solenoids and relays have one important part in common—a set of make-or-break contacts. These contacts are the critical component that controls current flow. They must be able to repeatedly establish and break a loaded electrical connection. That sounds like a simple task ... allowing current to flow only when the contacts are closed and then immediately cease that current flow when the contacts open. But unfortunately, life underneath a solenoid cap is not that simple.

The electrical phenomenon known as “arcing” is the unwanted flow of current which occurs prior to complete contact closure and immediately following the opening of the contacts. Anyone who has ever closely examined a set of worn out solenoid contacts, has seen what repeated arcing can do over time (see Figure 1). This type of wear is to be expected under normal use after many hundreds of on-off cycles. Each arc event transfers some material from one contact to the other—positive to negative. However, severe arcing can destroy a set of contacts rather quickly (see Figure 2)—or even cause them to weld together!

In a starter solenoid, one stationary contact is typically connected directly to the positive side of the battery, while the other contact is connected to a very low resistance path to ground through an at-rest motor. In the case of a diesel engine starter, that ground path can carry a thousand amperes or more. A good battery bank can easily supply that kind of current. A gap of only a few millimeters between the open contacts, electrically separates the battery positive from the battery negative.

An Arc is Formed

While a new set of solenoid contacts may look perfectly smooth to the naked eye, they are microscopically quite rough (see Figure 3). High spots and low spots abound. With each use, the contact surfaces will wear, which will inevitably amplify the roughness. You have probably noticed that contact surface designs can differ greatly between manufacturers. Some have embossed patterns on their mating surfaces. Each design reflects an attempt to minimize arcing.

If you could see inside a solenoid while it is activated and record what takes place with a close-up high-speed camera, you would observe what appears to be a catastrophic event! (see Figure 4) As the contacts begin to close, one tiny spot makes the first point of connection between the two surfaces. In technical terms, that point is known as a constriction, and all available current rushes toward it. The resulting sudden intense flow of electrons creates an extremely hot spot on the contact surface at the constriction. In the case of a diesel starter's solenoid, this is equivalent to forcing hundreds of amperes through the head of a pin.

Though the duration of this condition is only a few nano-seconds, the temperature at the surface of the constriction may reach 8,000 degrees Fahrenheit or more. This extreme heat not only melts the surface of the contacts at the constriction, but it also boils the metal, which can cause it to explode. The air surrounding the hot spot is then super-heated by the explosion



Figure 1 – Used Denso 2.5 kW solenoid contacts, motor terminal (negative) on the left and battery (positive) on the right.



Figure 2 – This 32 volt 40MT starter solenoid was destroyed by severe arcing. Notice that nearly all damage is on the battery contact (left) – positive side.

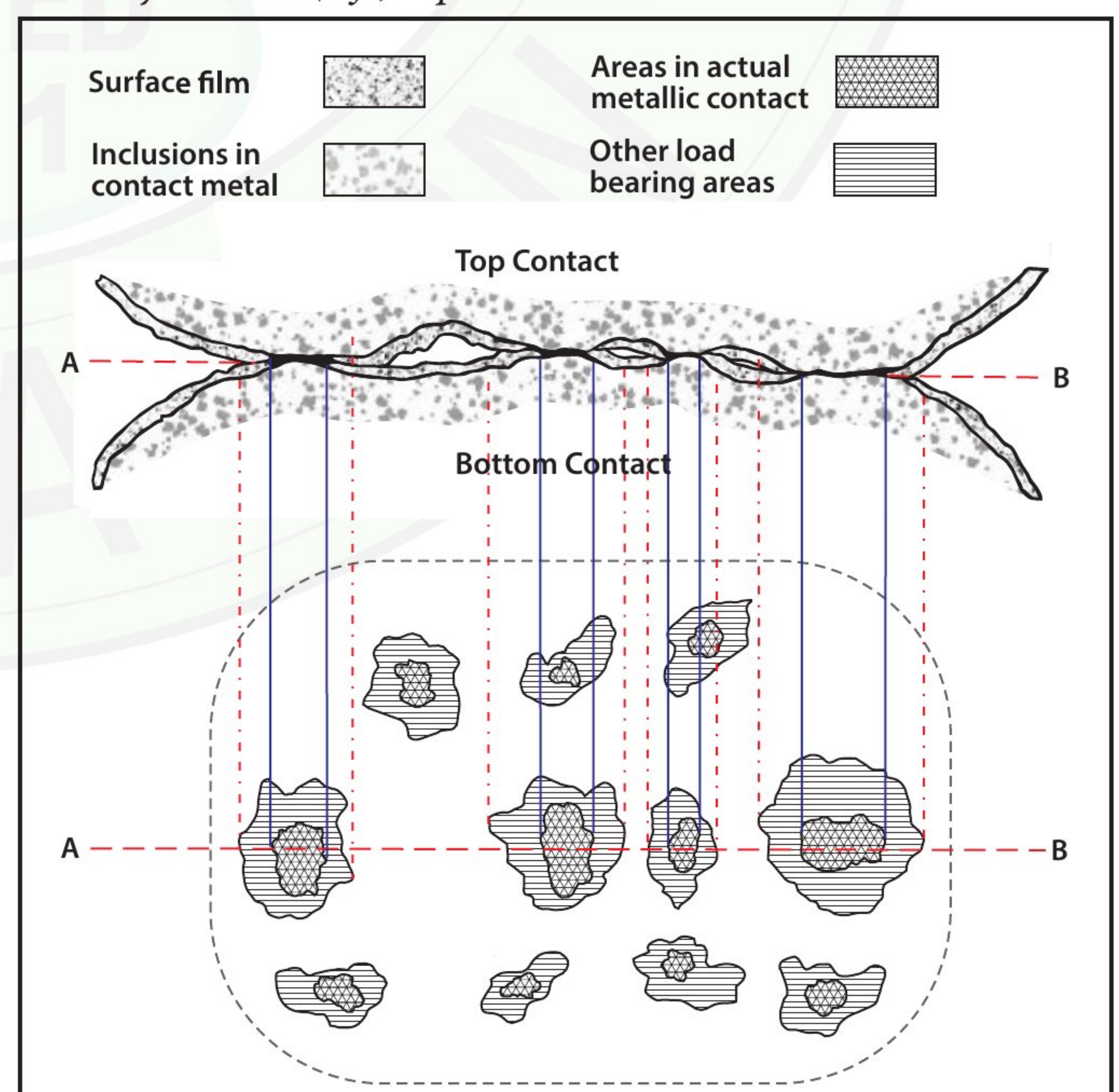


Figure 3 – This diagram shows a microscopic view of the high spots on the surfaces of a set of contacts.

SWITCHES, RELAYS AND SOLENOIDS – PART TWO

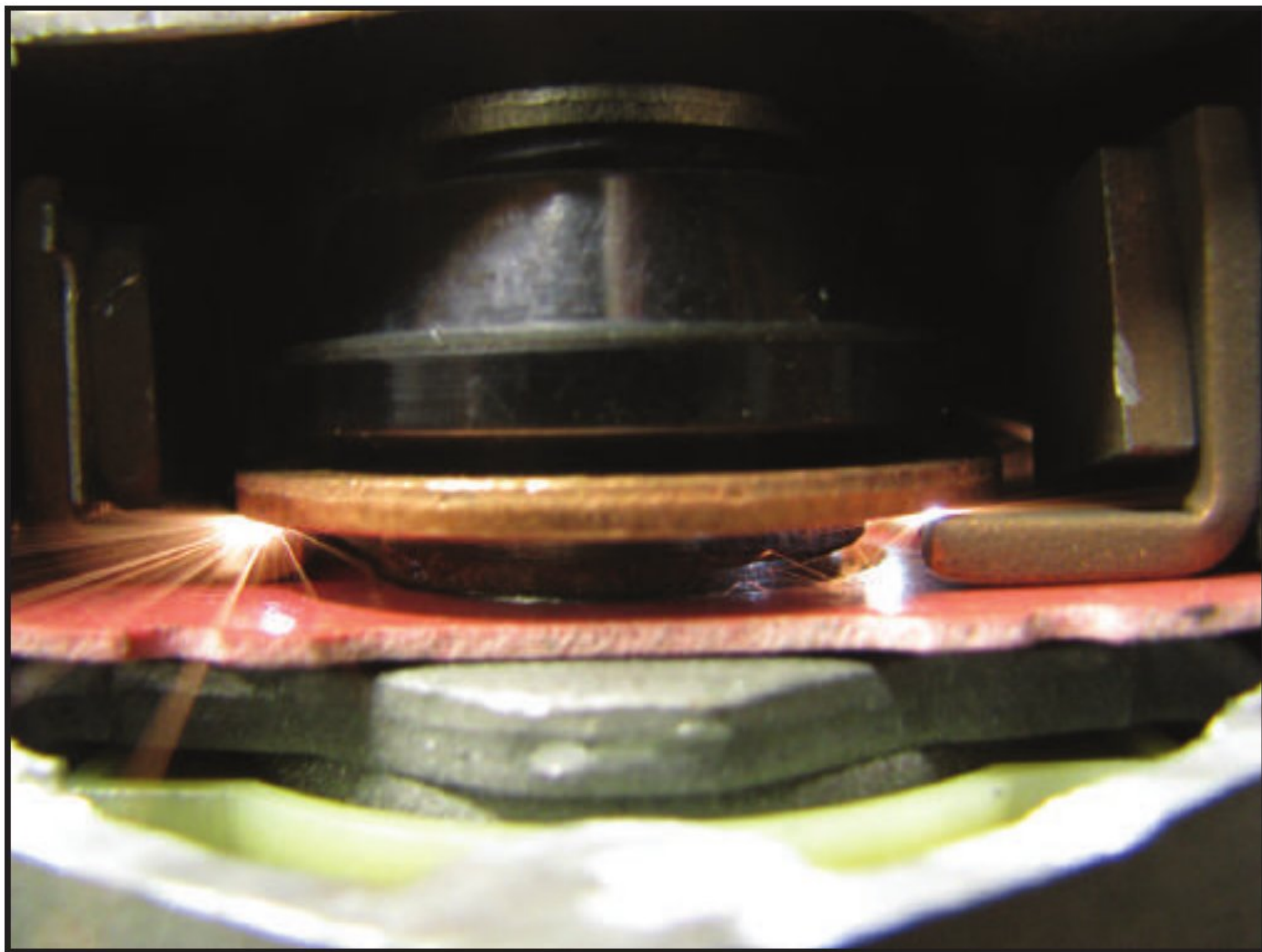


Figure 4 – These are making arcs between the center moving contact and both stationary contacts on a 1.2kW Denso starter during free spin testing.

and is ionized when its electrons are stripped away. At this point, the ionized air (or plasma) itself begins to conduct current. Around the constriction and in the proximity of the explosion, an electrical arc is formed.

That arc, conducted by ionized air, will exist until the next high spot forms another constriction. Then, the previously explained chain of events repeats itself, over and over. As each new arc is established, the previous arc is extinguished. Each arc transfers some contact material. Arcing cascades across the surfaces of the contacts, until the contacts are finally forced tightly together—splattering any remaining melted metal upon impact. This results in the loss of even more contact material (the copper dust you often find inside a used solenoid.)

Once the contacts close completely, the last arc will be extinguished as the current flow is dispersed across the contact surfaces. The extreme temperatures that caused the arcing, begin to dissipate. As the molten metal cools, the contacts actually become fused together in a weak bond while the engine is being cranked. That bond is a “soft weld”, which can be broken by the solenoid’s release spring.

The Grand Finale

When the solenoid is de-energized, the release spring starts to break the contacts apart, with full-load current still flowing. As the contacts begin to move apart, the area of their touching surfaces decreases ... until all flowing current is funneled into the last small area to break. The metal at that point becomes super-heated again and begins to melt. As the contacts move farther apart, a bridge of the molten metal forms between them and is stretched across the gap.

With full-load current still flowing through it, the liquid metal bridge is stretched thinner, until it explodes into a shower of metallic ions (see Figures 5 and 6). As you recall, the

conducting plasma, which was created when the contacts first touched, was made of ionized air. Now, the gap between the breaking contacts is filled with ionized liquid metal, causing an arc of a grander scale to be formed! Since the contacts are now opening, this arc (a breaking-arc) cannot be extinguished in the same way as the arc made when the contacts were closing (a making-arc.) The making-arc was terminated when current flowing through it was ultimately given a path of lower resistance to take (when the contact surfaces came tightly together). The breaking-arc will be sustained as long as there is sufficient energy to supply it—and as long as the arc exists, it will continue to transfer metal.

The making-arcs and breaking-arcs are different in several ways. Making-arcs are numerous and brief, compared to the extended single breaking-arc (or occasional multiple breaking-arcs.) A breaking-arc is much more violent, because it is made up of metallic ions, unlike the making-arc plasma, which is composed of ionized air. In addition, a breaking-arc has no definite ending. But the making-arc does end, when the contacts finally close completely—detouring the current to a path of lower resistance—essentially bypassing the plasma.

The breaking-arc can be extinguished only by opening the circuit at another point (not very practical) or by exceeding the current’s impedance with more distance between the contacts.

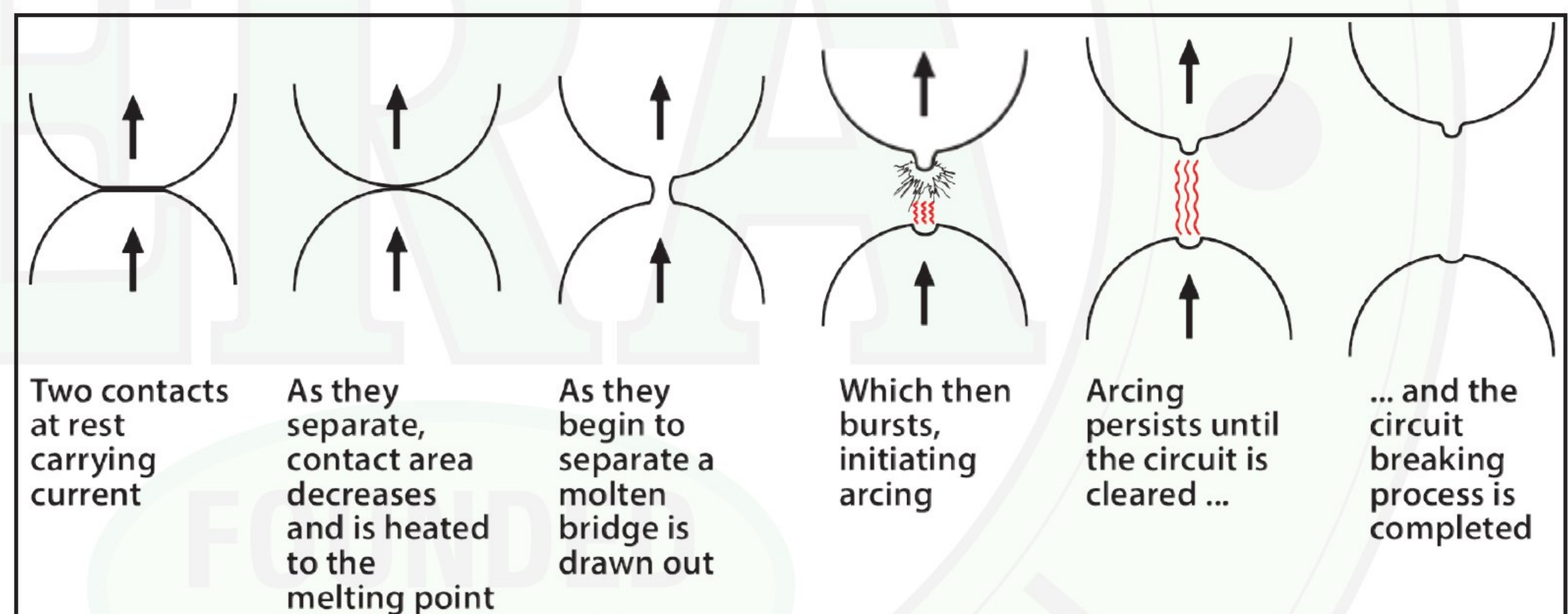


Figure 5 – This sequence of diagrams shows how a breaking arc is formed as a set of contacts open.



Figure 6 – This is an actual breaking arc on the battery side contacts of the same Denso starter during a free spin test.

SWITCHES, RELAYS AND SOLENOIDS – PART TWO

Impedance is the opposition to change in an electric current flow. Once current flow is established, it has resistance to change. As current increases so does impedance. It is directly proportional to the load of the starter's motor.

The at-rest air gap of a solenoid's open contacts must be substantial enough to extinguish a breaking-arc's impedance, based on highest possible load for that application.

Perhaps now, you can better appreciate why solenoid contacts may show signs of damage or wear after just a few starts.

When Things Go Wrong

Under some conditions, a set of solenoid contacts may weld closed during cranking. This can happen in two ways. The first is a dynamic weld (see Figure 7). It is caused when contacts “bounce” during closing—when they “make”, “break” and “make” again in rapid succession. The resulting arcs (both making and breaking) produce molten metal which can partially solidify following a break. During the final “make”, the normally soft weld becomes a hard weld, which the solenoid's release spring is unable to break.

More commonly, starter solenoids fall victim to a static weld (see Figure 8), which is caused by a sudden short burst of extremely high current flowing through closed contacts. This can happen if a starter is over-cranked until it stalls while turning the engine. A stalled starter motor is almost a dead short, causing electrical current to increase significantly. While faulty batteries and cables can contribute to this scenario,

obviously, the operator plays the largest role.

Other Factors at Play

There are other factors involved that can greatly influence arcing between contacts. They are: the composition of the contacts, their design or shape, and the pressures applied in both making and breaking.

Copper has a conductivity rating that is exceeded only by silver. Its low cost makes it the obvious choice for solenoid contacts. However, pure copper is lacking in the mechanical qualities required for solenoids. At temperatures above 320 degrees Fahrenheit, pure copper begins to lose its rigidity. Therefore, solenoid contacts must be manufactured using a copper alloy, with smaller amounts of nickel, zinc, tin, tungsten or silver added to improve its mechanical strength and durability. Cadmium has also been used in manufacturing contacts, but to a lesser extent in recent years. This is because research has shown that long-term exposure to cadmium can lead to serious health issues. The group of metals generally used in solenoid contacts is known as high copper alloys. Each one contains no more than 99.3% copper, but no less than 94%.

In addition to alloys, there are some solenoids in higher voltage applications (24 volts or more) that may utilize a silver alloy inlay on a copper contact (see Figure 9). This type of inlay provides the full durability of a silver contact without its high cost.

Most solenoids incorporate a moving contact with two stationary contacts—one for B+ and one for the load or motor.

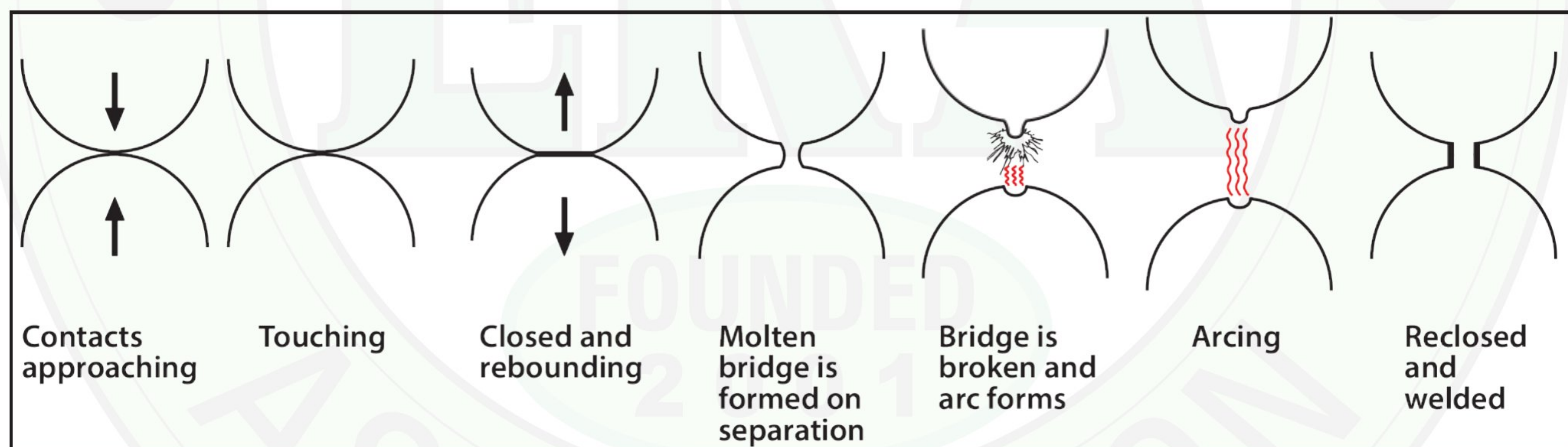


Figure 7 – Here you can see how dynamic welding happens when the moving contact bounces on initial impact.

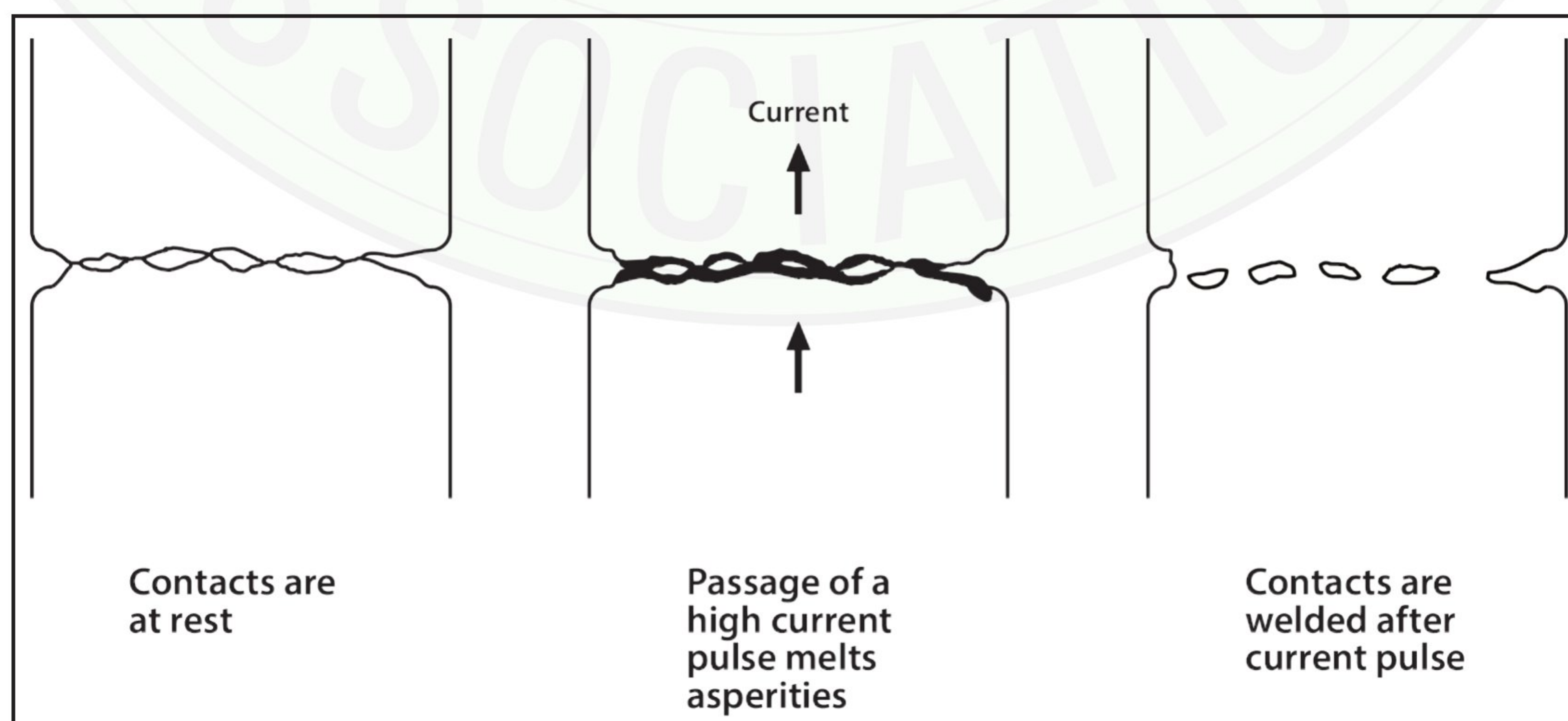


Figure 8 – This diagram shows how static welding occurs when a surge of high current passes briefly through a set of contacts.

SWITCHES, RELAYS AND SOLENOIDS – PART TWO

While many contact surfaces are flat, to increase the area of conduction, some manufacturers have tried other shapes to reduce arcing.

The embossed patterns you see on the contact surfaces in some solenoids are intended to offer sacrificial material across the contact. This helps to create multiple but much smaller breaking-arcs to dissipate the heat—reducing the transfer of material, reducing breaking-arc impedance and extending the life of the contacts. Each pattern attempts to disperse the hot spots across the entire contact mating surface, thus allowing for better heat dissipation. Bosch, Denso, Delco and Mitsuba have all used this method on some applications (see Figures 10, 11 and 12).

The magnetic strength of each solenoid's pull-in coil, affects the time it takes to make a complete contact connection. Increasing that magnetic force would decrease the time it takes to accomplish this and would limit arcing. The high current draw of some diesel starter solenoids (like Delco's 39MT) seems to be aimed at closing the contacts faster. A weaker pull-in coil force increases the closing time, allowing for more arcing to take place.



Figure 9 – This 24 volt Denso contact has a silver inlay to reduce arcing under the higher voltage.

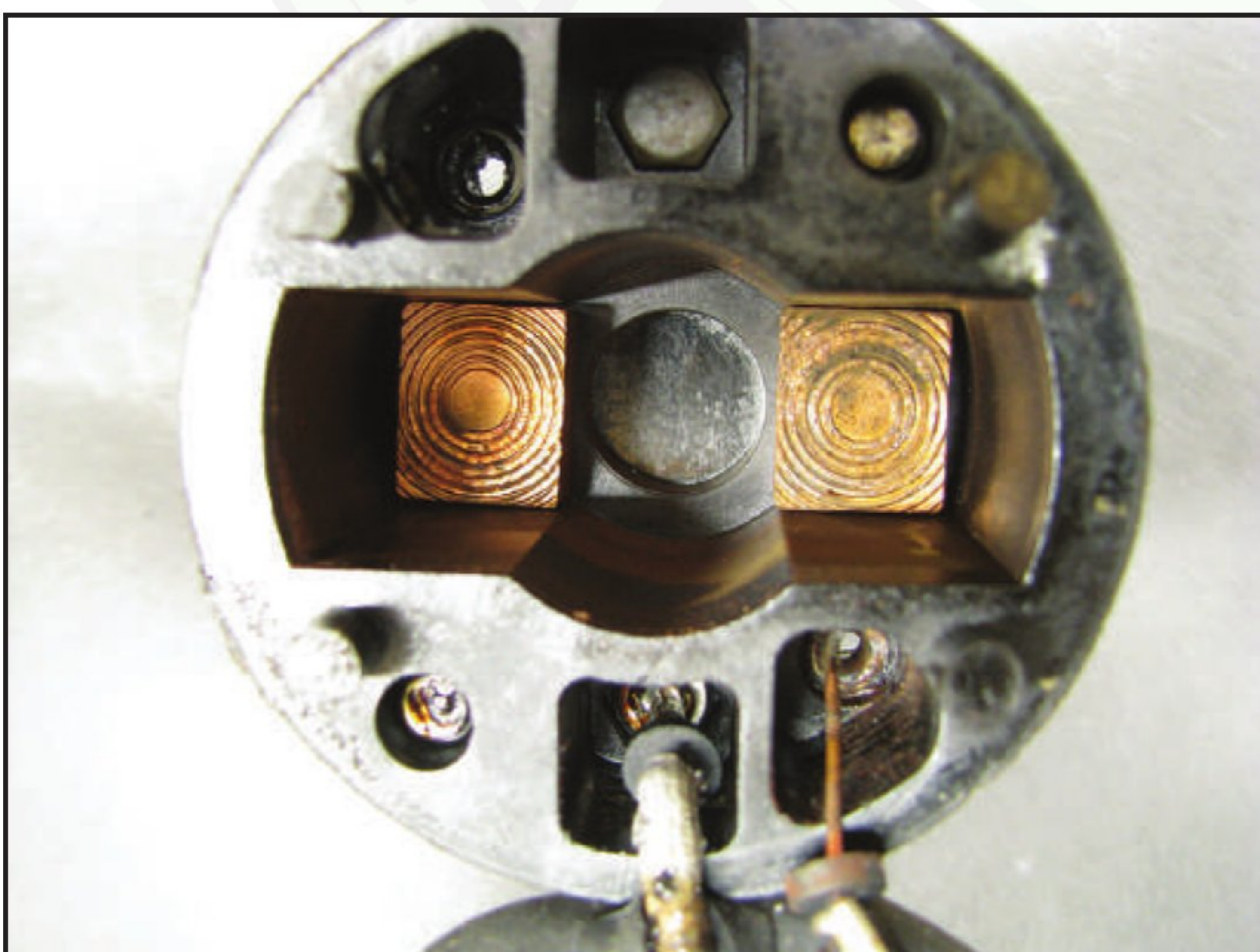


Figure 10 – The contacts of this aftermarket 39MT solenoid are embossed with circular ridges to reduce damage from arcing.



Figure 11 – This Denso PA90S solenoid utilizes straight ridges to limit arcing.

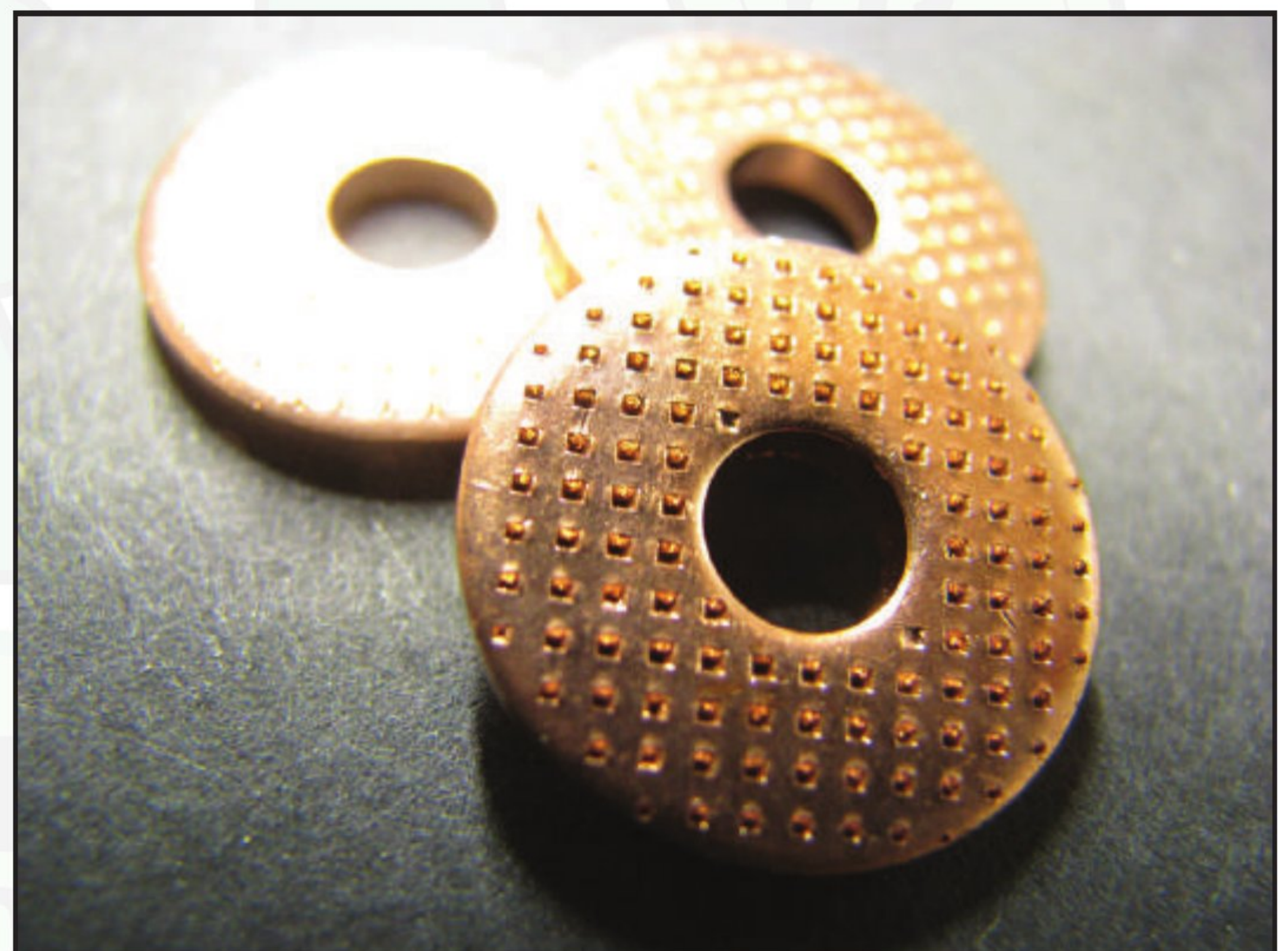


Figure 12 – Mitsuba embossed the moving contact in their SM612 starter to reduce arcing damage.

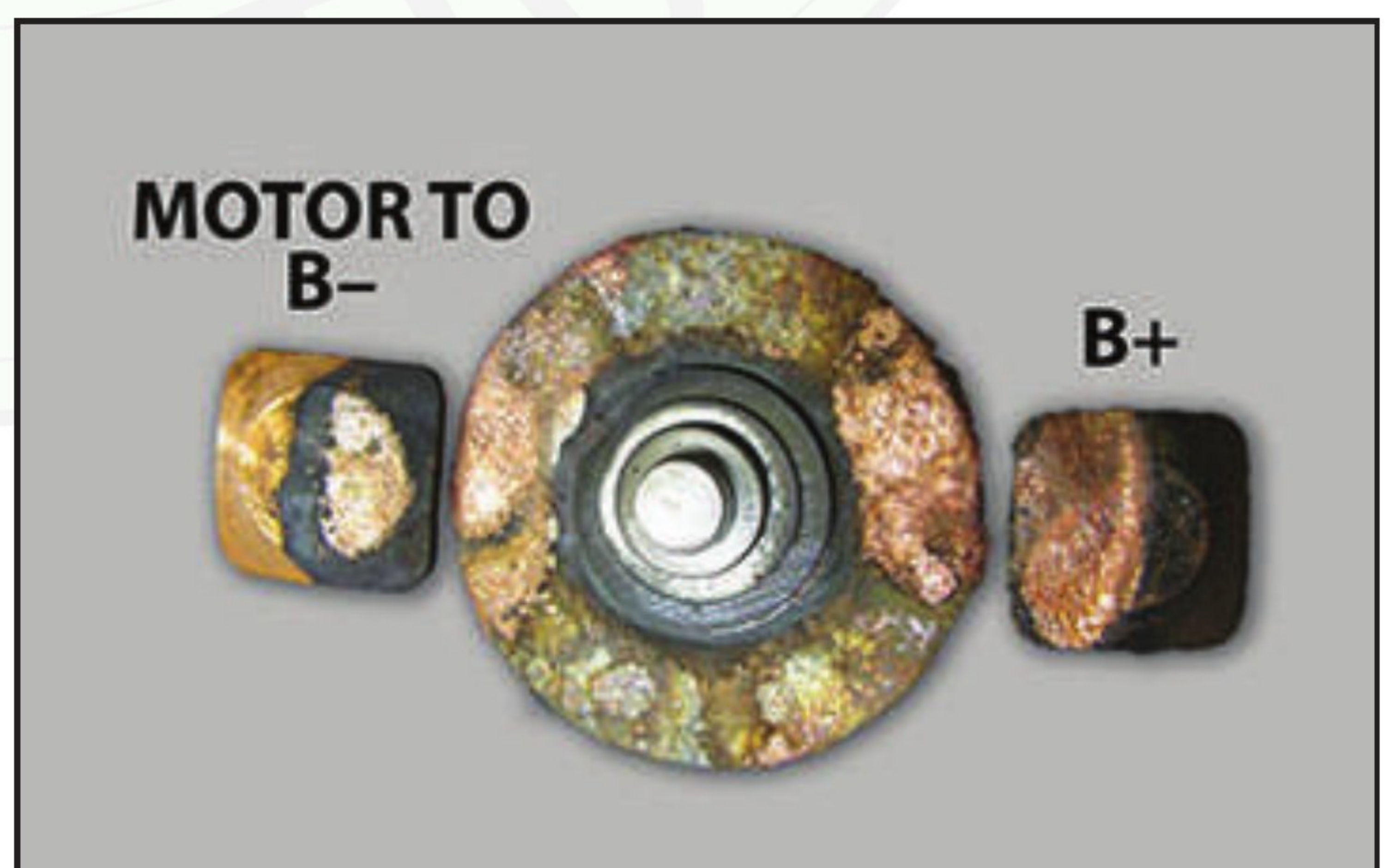


Figure 13 – The battery side (positive) contact from a 42MT solenoid has been damaged by severe arcing.

SWITCHES, RELAYS AND SOLENOIDS – PART TWO

The tension of the contact's release spring must be strong enough to break the contacts. A stronger spring would obviously break them more quickly. But remember that the solenoid's magnetic force must also overcome that spring to force the contacts closed. Also, the hold-in coil must be able to overcome the spring's strength in order to hold the contacts tightly closed. Increasing the strength of the release spring to reduce arcing during "breaking", would require increasing the magnetic field in the hold-in coil to overcome it. Every change or modification comes with a trade-off.

As you can see, a lot of engineering must go into a starter solenoid, as the different forces must interact with each other to limit arcing. (So, when you remanufacture solenoids, be sure that any replacement springs or coils have the same specifications as the original equipment parts.) Hopefully, this understanding of arcing will help you to better serve your customers when a solenoid sticks, or the contacts come back melted. There is a difference between wear and abuse that is not always black and white. It is normal for the positive stationary contact to lose metal as it wears. The motor-side contact will wear significantly less. The moving contact will typically show the least wear of all.

Over-cranking or extended-crank cycles will overheat the contacts to their melting point deep into their surfaces. When this has taken place, the surfaces will be extremely rough (see Figures 13 and 14). When one extended-crank cycle is followed closely by another, the still-molten metal will splatter upon contact-impact and leave signs, such as a deformed positive contact (see Figure 15) and large particles of once-molten copper inside the solenoid (see Figure 16).

In a future article, we will explain how different types of electrical loads affect arcing and contact wear in distinctly unique ways.

The following table provides some basic information on copper alloys used in low-voltage direct-current applications.

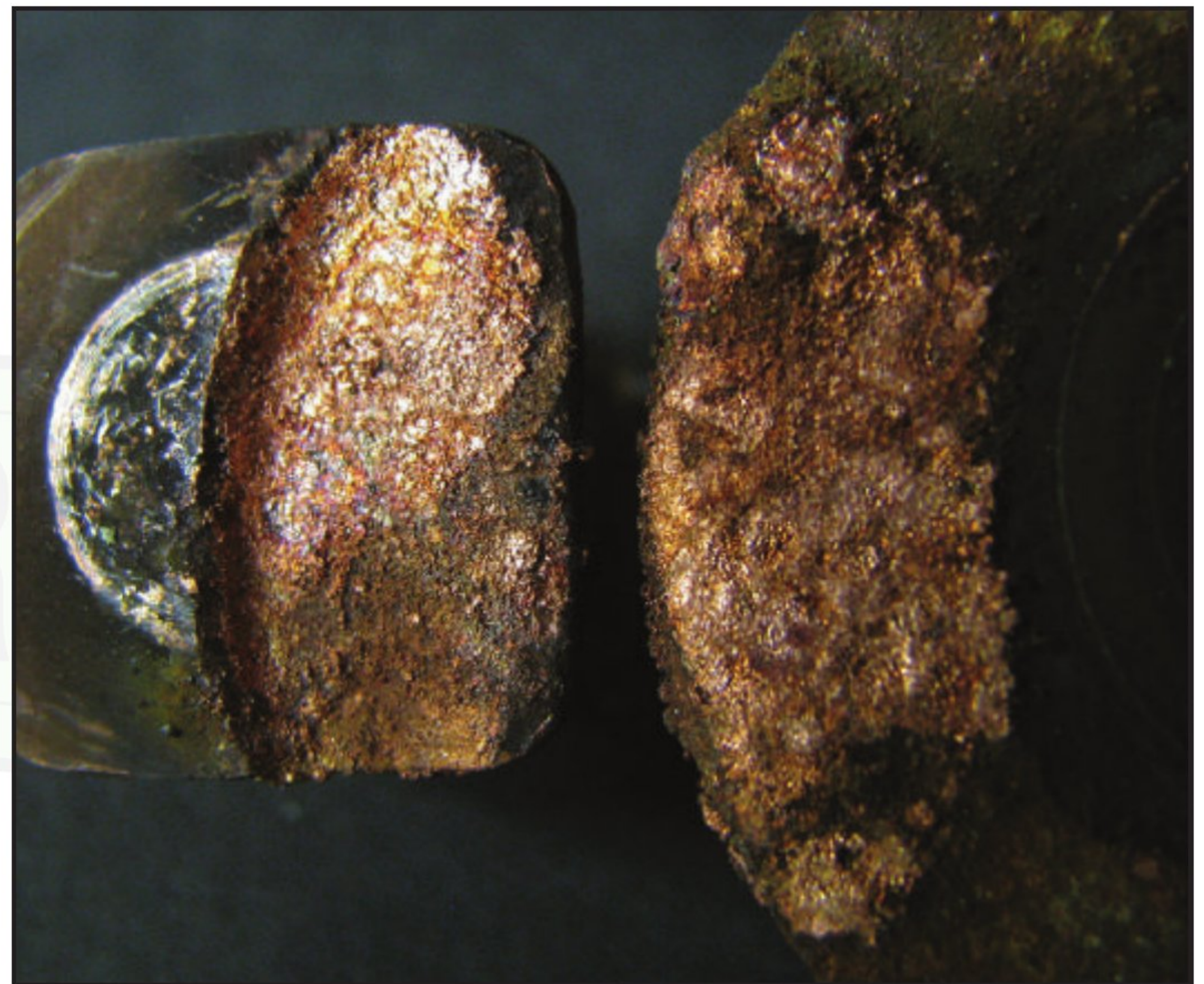


Figure 14 – Note the roughness of the contacting surfaces in this close up view.

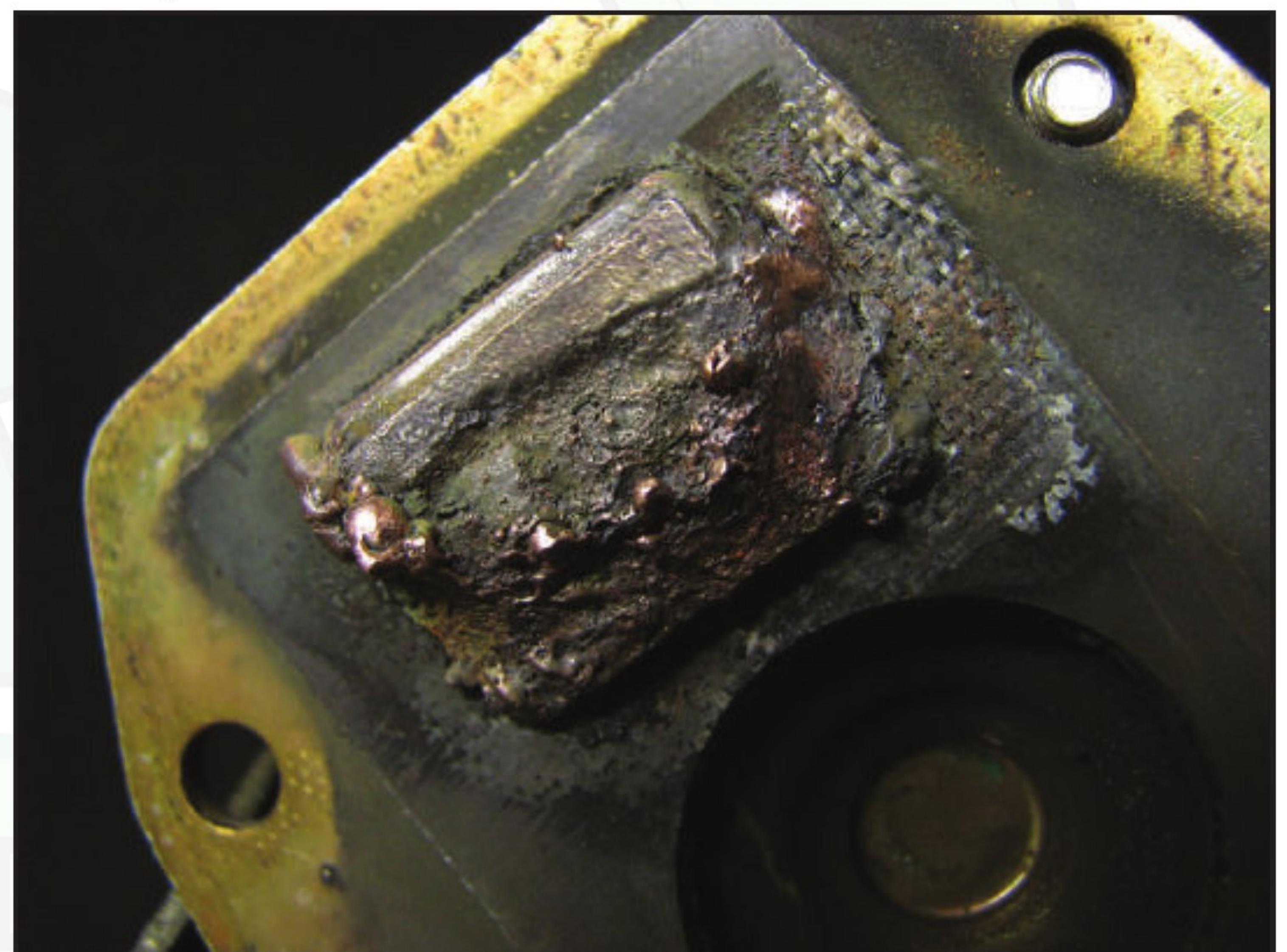


Figure 15 – A close up view of the 32 volt solenoid's battery contact, shown earlier.



Figure 16 – This copper residue was once part of the moving contact where it last touched the battery contact.

SWITCHES, RELAYS AND SOLENOIDS – PART TWO

TYPE OF DEVICE OR CONTACT	REQUIRED PROPERTIES	MATERIAL *	SHAPE OF CONTACT
Rotary switch on printed circuit	Resistance to frictional wear, low contact resistance	Fixed: Au on Ni; Sliding: AgPd, AgCu	Fixed: plated; Sliding: plated, welded or riveted
Sealed relay in metal can	Very reliable and long life, fast bounce-free switching	PdCu, Mo with Au-plating	Fixed: plated parts or welded foils; Blades: FeNi plated with Mo and Au
Large Low Voltage contactors with arcing contacts	Withstanding high short circuits On make and break, low resistance on rated current, anti-weld	Arcing contacts Cu. WAg. Main contacts AgCu, AgNi, AgCdO, AgZnO, AgSnO	Solid contacts in Cu. others brazed or welded
Rotary switch, Manually operated	Reliable switching of rated and overcurrent with compact shape	AgCu, AgNiCu, phosphor bronze	Rivets, solid or faced, automatically welded, profiled
Generator, commutator alternator	Hard, creep resistant low contact resistance	Cu + 0.1% Ag	Solid
Sliprings	Low mechanical wear under brushes easy manufacturing	Cu, gummetal, Cupronickel, “Monel”, for corrosive atmospheres	Cast and machined
High current d.c. breakers	Low transfer, low erosion at high current, low contact resistance	Cu	Laminated strip
Small circuit breakers	Anti-weld on short-circuit, low temperature rise at rated current, moderate erosion	Dependent on rating and construction Cu, AgCdO, AgW, AgWC, AgC mixed: AgC against Cu	Profiled, pressed, brazed, welded
*Ag – silver, Au - gold, Pd - palladium, Rh - rhodium, Ni - nickel, W - tungsten, Zn - zinc, Cd - cadmium, Mo - molybdenum, O - oxide, e.g. CdO = Cadmium oxide, C - carbon, Sn - tin			

References Cited (in this document): Copper Development Association (CDA), 1980, Copper in Electrical Contacts, Technical Note 23, CDA, 5 Grovelands Business Centre, Boundary Way, Hemel Hempsted, HP2 7TE, UK