

Electrical Crimp Consolidation

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ABSTRACT

Aluminum wire is receiving increased attention for automotive applications due to the potential for cost and weight savings. Termination of aluminum wire is problematic due to the tenacious surface oxide on the strands. The oxide is an electrical insulator and is difficult to displace during termination. Consequently, many of the strands within a crimped wire bundle can be electrically isolated from the terminal, which can result in higher than expected crimp resistance, less stable crimp resistance, and the potential for excess heating of the termination. Prior solutions employed additives such as brass powder to puncture the oxide film and form a diffusion bond between strands, or features such as screens or serrations that increase wire deformation and displace the oxide mechanically to promote strand-strand bonding. Both solutions have drawbacks. Additives increase cost and process complexity and can serve as contaminants to adjacent processes. The required features can be difficult to produce and may require high crimping effort. This present work uses an electrical potential applied at the moment of crimp formation to puncture the surface oxide and allow the formation of conductive a-spots. Increased current flow then welds the wires together at the a-spots to increase electrical conductivity and stabilize the crimp mechanically. A simple nodal resistor model was developed to explain operating principles and to help predict the correct working parameters. The process was implemented on a bench press with 6mm² wire. Test data showed a significant reduction in crimp resistance over unprocessed terminals, and the resulting process is clean and requires no consumables.

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MOTIVATION

Aluminum wire is receiving increasing attention as a means of reducing vehicle weight and cost. Although aluminum's electrical resistance is higher than copper, its resistivity-density product is only half as great, which makes aluminum much lighter than copper for the same current-carrying capability. By switching from copper to aluminum wire, the 15 kg mass of a typical mid-size automotive wiring harness could be reduced by 20% or more [1]. The larger 50-70mm² cables used for starter motors and in electric vehicles would provide even greater weight reduction due to their lower insulation and connector content. Switching to aluminum wiring can also reduce material cost and exposure to copper's cost volatility. Based on IMF commodity pricing from 1989 through mid-2016, the cost of copper reached as much as 4x the cost of aluminum, and the cost variability of copper was almost 5x that of aluminum [2].

A significant barrier to the use of low-cost open-barrel crimp terminations with aluminum wire is the aluminum oxide film present on the surface of the wire strands. This oxide film is an electrical insulator and is difficult to displace during crimping. Consequently, many of the strands can be electrically isolated from the crimp barrel, which can result in higher than expected crimp resistance, less stable crimp resistance, and the potential for excess heating of the termination.

Several possible solutions have been investigated. Iron can be alloyed with the aluminum to make the wire harder, which promotes mud cracking of the oxide film as the wire is deformed [3]. High pressure contact points such as serrations or indentations increase wire deformation and enhance the displacement of the oxide film that contacts the crimp barrel [4]. Additives such as brass powder puncture the oxide and form intermetallic bridges between strands [5]. Each solution has some problems. Iron can raise the wire's electrical resistance and negate some of the weight advantage. High contact pressure features can be difficult to produce and can require increased crimping force. Brass powder is an additional consumable item and, as a fine dust, has the potential to contaminate adjacent processes.

The goal of this work is, therefore, to find a way to overcome the aluminum oxide film while using a conventional crimping press and inexpensive terminals and without the need for additional materials or special wire preparation.

THEORY

Contact physics theory describes the development of low-resistance electrical interface between a contact pair in terms of A-fritting, B-fritting, and a-spots [5]. The mating surfaces of a contact pair first touch at their aspherities to form a-spots across a contact area. The interface is initially non-conducting due to the oxide film that covers the surfaces of the a-spots. At a field strength of about 10⁶ volts per meter, A-fritting starts as electrons begin to tunnel across the oxide

Electron tunneling and increasing mechanical pressure break down the oxide film, which leads to metal-metal electrical conduction at the a-spots. B-fritting occurs when the current density increases and metal melts at the a-spots to further decrease the contact resistance. These effects combine to produce a rapid decrease in electrical interface resistance as the contacts are brought together and result in a much lower interface resistance than mechanical force alone would provide.

A similar sequence of events can be made to occur during crimp formation. As the crimp tooling closes and the area index falls, the wire strands begin to make contact at their asperities. A properly-timed electrical current can then facilitate breakdown of the oxide film (A-fritting) and promote consolidation of the wire bundle (B-fritting). The result can be a crimped terminal with lower interface resistance than one made with mechanical consolidation alone. The improvement would be expected to be much greater in a material such as aluminum whose surface oxide is more difficult to displace mechanically than the oxides that form on copper or silver.

IMPLEMENTATION

Shown schematically in Figure 1, key components of the electrical crimp consolidation implementation include Model G II Terminating Machine (press) [7] and applicator, a condenser bank, and a trigger circuit. The condenser bank comprises of an array of eight capacitors ranging from 100 μ F through 1800 μ F that are charged through a current-limited voltage source for independent adjustment of discharge energy (3.25-13J) and charging potential (60-180V). A series air-core inductor (25-125 μ H) allows selection of pulse width and peak current. The trigger circuit consists of a Triac and driver circuit. The trigger signal is derived from a sensor on the press flywheel whose position can be adjusted to achieve a prescribed pulse start time. Instrumentation consists of a current transformer coupled to an oscilloscope to measure and record the discharge current over time. A camera was used to help position the wire properly in the terminal prior to crimping. Crimp height was measured periodically and maintained within the prescribed range for the wires and terminals used.

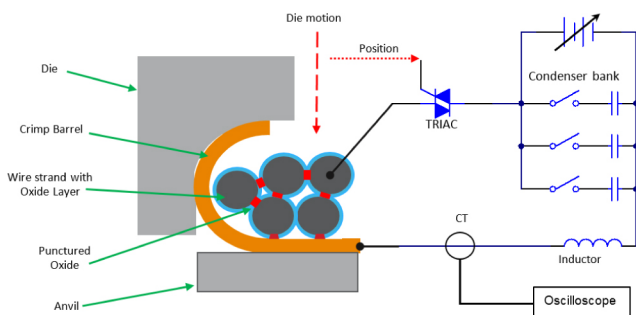


Figure 1. Schematic of terminal and test setup

The component values and operating conditions were selected based on wire size and press speed. The range of charging potential V_D and discharge energy E_D were chosen empirically to be sufficient for the range of wires investigated (2.5mm² - 6.0mm²). The inductor was

chosen to match the pulse width to the press timing. The discharge should start when the wire bundle has started to compress but prior to strand deformation. For 6mm² stranded aluminum wire and TE 1842004 LITEALUM terminals, compression starts at AI (Area Index) of about 60-80%, or a CH (Crimp Height) of about 2.3-2.5mm. The crimp would be completed about 4ms later, so the pulse width should be on the order of 1 ms to provide an adequate process window.

The condenser bank and trigger circuit were shown to be reliable and could produce pulses of as much as 1000A and as short as 300 μ s depending on the charging potential, total capacitance, and inductor value. Fitting the predicted current pulse height and width to the measured pulse parameters showed that there was about 50m Ω of external resistance in the circuit, and that the external resistance varied dynamically through the crimping cycle.

EXPERIMENTAL WORK

A series of tests were conducted to demonstrate the effect and determine a useful range of charging potential V_D , discharge energy E_D , pulse width, and pulse timing. The test matrix is shown below in Table 1. The inductance was set at 125 μ H, which resulted in a nominal pulse width of 1 ms and I_{PK} ranging from 120-250A depending on the capacitor bank settings. Five parts were made at each set of test conditions. The test articles for this first group of tests were 12cm lengths of 6.0mm² stranded aluminum wire with TE 2-1842404-1 LITEALUM terminals on each end. The first terminal was crimped with no current pulse applied. The second terminal was crimped with a current pulse. Current was introduced into the wire through a check tab inserted into the first crimped terminal. Current was returned through a crocodile clip connection to the carrier strip. The response variable was end-to-end resistance R_{ETE} , which included the unprocessed crimp, the pulsed crimp, and the wire. R_{ETE} was measured with a Keithley 580 4-wire micro-ohmmeter with mating terminals made of double-sided copper clad printed circuit board to isolate the source and sense signals and remove the effect of the terminal interface resistance.

Table 1. Test Matrix used to demonstrate effect and find useful range of parameters

Factor	Unit	Level			
Potential	Volts	0	60	120	180
Energy	Joules	0	3.25	6.5	13

Timing of the pulse was established by adjusting the trigger position as a function of R_{ETE} . NO change in R_{ETE} was seen until the pulse started with the press ram no greater than 0.25mm away from bottom, which corresponded to an AI (Area Index) of 73%. The process window based on crimp height is shown in Figure 2. That window represents a time span of about 2ms in the press. A representative current pulse is shown in Figure 3.