

Characterization of Ultrasonic Metal Welding Process

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Abstract: The ultrasonic welding process for wires is being largely used on industry mainly on applications that involve the connection between similar or different metals. The biggest benefit of this technology is the possibility to perform the weld without addition materials, like terminals, metal rings or tapes. Manufacturing of wiring harnesses demands a significant amount of joining, such as welding, crimping or soldering, to fulfill the desired layout of the harnesses and capacity requirements, but conventional connection processes, face difficulties in joining multiple cross sections mainly due to the characteristics of the processes and equipment in use. Ultrasonic metal welding process overcomes these issues due to the solid-state characteristics inherent to the process itself that include the excellent electrical properties of the joint. Several researches on ultrasonic metal welding are being done to define the fundamental mechanisms behind this process and it is being seen that they are completely dependent on the cross section to be welded. With this research we are trying to develop methods for process characterization and define acceptable quality parameters in this process. The main topics addressed in this paper are the characterization the weld formation using copper-to-copper wires using optical microscopy and the analysis of insulation material when submitted to different thermal conditions.

Key words: Ultrasonic metal welding, wiring harnesses, insulated wires, splices, harness assemblies, PVC (Polyvinyl Chloride).

1. Introduction

Ultrasonic metal welding was discovered around 1950 and is now widely used on the industry in applications that involve softer and high conductivity alloys or metals like copper or aluminum [1, 2]. The metal joint is formed by the application of high frequency vibrations and moderate pressure. The application of vibrations is done parallel to the interface of the parts [3] and the applied frequency creates some motion between the parts to be welded that forms the solid-state weld by plastic deformation and progressive shearing of the metal that should disperse oxides or contaminates over the asperities, creating a clean area of metal contact [3]. The equipment used to perform the ultrasonic welding should be able to control welding variables and monitor energy and consequently solve oxidation problems,

high electrical and thermal conductivity [4]. The process overcomes easily the difficulties of multiple cross-sections connection due to its solid-state characteristics that creates a true metallurgical bond [5, 6]. Also, the temperature of the process does not exceed the melting point of the material which eliminates undesirable compounds and metallurgical defects that can be seen on other types of welding [7].

The ultrasonic welding process consists of the conversion of electrical into mechanical vibrations using a frequency of 20 to 40 kHz and the system should include a generator, a converter with piezoelectric ceramics, a booster and a sonotrode as shown in Fig. 1 [8].

Ultrasonic metal welding process is known for many years [3] but when considering the welding of copper insulated wires there seems to exist a lack of understanding of the welding mechanisms that should be known for a number of years, mainly when considering wires insulated with PVC (Polyvinyl Chloride).

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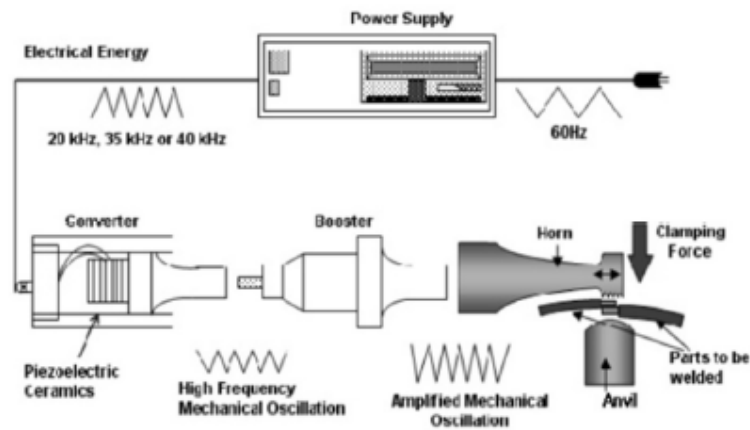


Fig. 1 Schematic of ultrasonic welding process [8].

Several researches are being done in order to determine the influence of the insulation materials on the welding process of wires. This study was focused mainly in two distinct areas: (1) the characterization of the weld formation of copper-to-copper wires using optical microscopy and (2) the analysis of insulation material when submitted to different thermal conditions. As mentioned, there were many studies already done on this topic but are mainly focused on material thickness, in the specific case of electrical wires the main issue is related to cross section to be welded and the sticking of material to the tooling [3], and the second issue is totally dependent on the type of insulation material used on copper wires.

2. Methods and Materials

Ultrasonic welding splices can be created in two different ways, one with all wires in the same side and second with wires distributed by both sides of the splice [8] as shown in Fig. 2.

For characterization of weld formation test samples were created with wires in one side using ultrasonic welding machine for splices [9] and the evaluation of characteristics of weld formation was done using electronic microscopic techniques.

Evaluation of the weld ability was checked by the results on the strength force measurement needed to break the connection between wires. A capability study (Eq. (1)) using the strength needed to remove one wire

from the splice was done.

$$Ppk = \frac{\mu - LSL}{6\sigma} \quad (1)$$

To evaluate the characteristics of the insulation material, samples were created by removing 50 mm of insulation from the electrical wire. To check if there is influence of insulation material on welds formation cables with two types of insulation were chosen, PVC as it is known that may cause negative effect on the welding process and ETFE (Ethylene Tetrafluoroethylene) that seems to have no impact on the weld formation.

According to automotive standard LV112 [10] samples should be analyzed by infrared spectroscopy technique to identify if degradation of materials exists and FTIR (Fourier-Transform Infrared Spectroscopy) was the method chosen as it is a faster technique to collect the infrared spectrum and technique main advantage is that all the radiation emitted by the source is continuously monitored [11]. In this specific case the material was analyzed on three different temperatures, RT (room temperature), 40 °C and 70 °C.

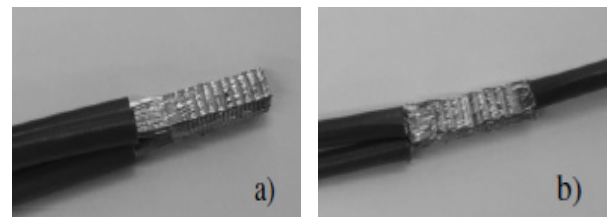


Fig. 2 Splice with all wires on one side (a) and both sides (b).

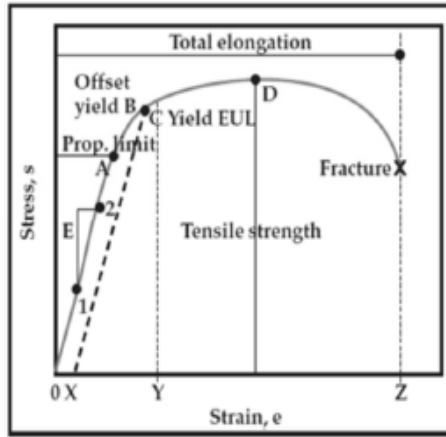


Fig. 3 Diagram stress vs. strain [13].

The tensile strength of a material (maximum force required to draw the material to break) refers to the ability of the material to withstand loads without failure due to excessive stresses or deformations. According to automotive standards, DIN EN 60811-1-1 [12] and LV112 [10], this test is also used to evaluate material degradation.

The tensile strength of a material is the ratio of the maximum load that the material can withstand without fracture when it is being stretched, relative to the original cross-sectional area of the material. When the tension is less than the tensile force the material or part of it returns to its original shape. As the tensile values approach the values of the tensile force, the material tends to rupture (Fig. 3) [13].

The chemical degradation of the insulation makes wires more fragile, a phenomenon that we intend to detect with this test.

In this study, the tensile strength (Eq. (2)) and the elongation until breaking (amount of uniaxial deformation at the break point) were calculated (Eq. (3)).

$$S = \frac{F}{A_0} \quad (2)$$

$$\varepsilon = \frac{(l_f - l_0)}{l_0} \quad (3)$$

3. Test Results

3.1 Characterization of Weld Formation

Capability study was done using 125 welded

samples using wires of cross section 0.50 mm² and insulated with PVC and ETFE. Samples were created using three wires of same cross section and same type of insulation (Fig. 4). It was removed the wires on the top of the splice using a pull force measurement device and the force needed to remove or break the wire was registered. With the results a Ppk was calculated according to Figs. 5 and 6.

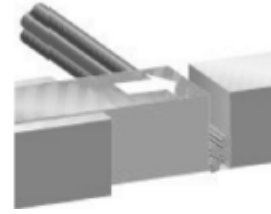


Fig. 4 Schematic of wire positioning on ultrasonic welding equipment.

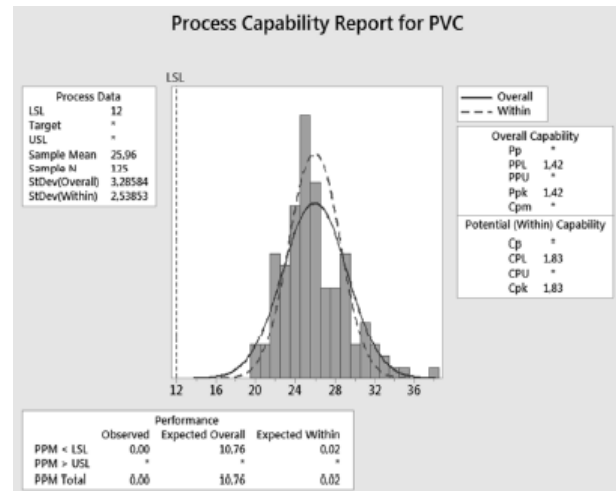


Fig. 5 Capability study for wires insulated with PVC.

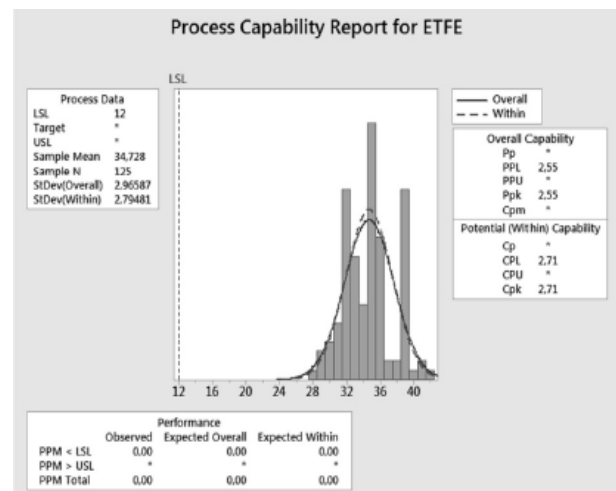


Fig. 6 Capability study for wires insulated with ETFE.

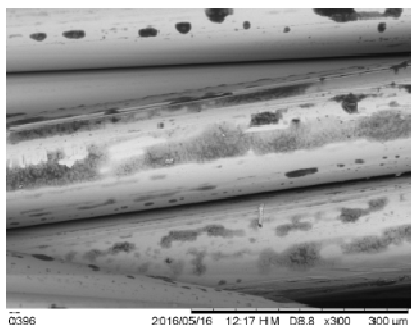


Fig. 7 PVC insulated wire analyzed by SEM.

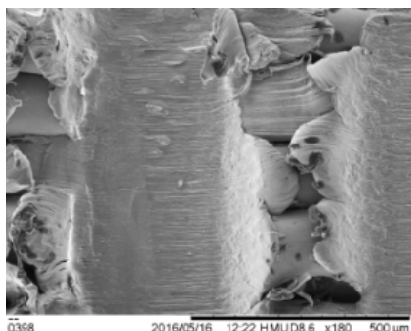


Fig. 8 Welded sample analyzed by SEM.

As results of Ppk for wires insulated with PVC were lower than expected, samples were analyzed on microscope to determine what may be causing the negative effect. Figs. 7 and 8 show the result of samples analyzed on SEM (Scanning Electron Microscope).

Samples showed some organic materials on the surface of copper strands that are causing the bad results as when samples were cleaning the results on Ppk were significantly increased.

Results of SEM analysis on ETFE insulated cables

are shown in Fig. 9 and did not had any material on copper surface and the Ppk results were much higher than on wires insulated with PVC.

3.2 Analysis of Insulation Material when Submitted to Different Thermal Conditions

FTIR analysis was done to PVC to define if components are migrating to copper surface. Wire samples were tested at RT and heated at 40 °C and 70 °C (Fig. 10). It should be mentioned that working temperature for PVC wires is 105 °C and for ETFE is 150 °C.

For ETFE FTIR was also done even knowing no major issues were found (Fig. 11).

To determine the tensile strength (Table 1) and percentage of elongation of insulation materials (Table 2), samples were tested using a Zwick-Roell tensile test machine and Force versus Strain graphs were created (Figs. 12 and 13). Samples of PVC and ETFE were tested at RT and after heating at 40 °C and 70 °C.

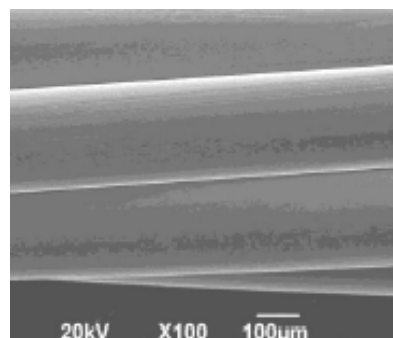


Fig. 9 SEM analysis of ETFE insulated wire.

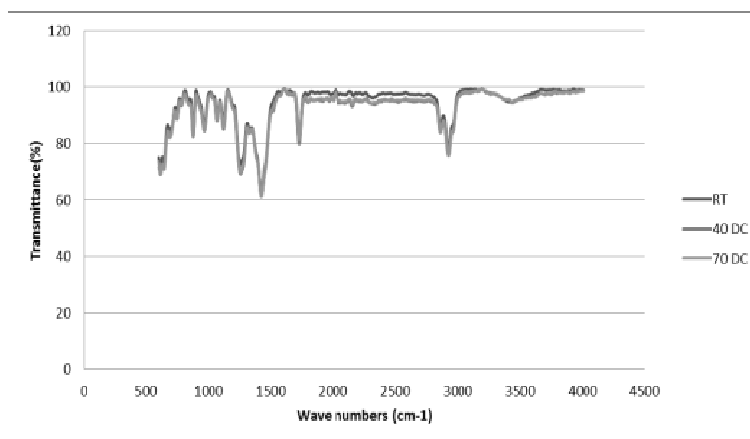


Fig. 10 FTIR for PVC insulation.

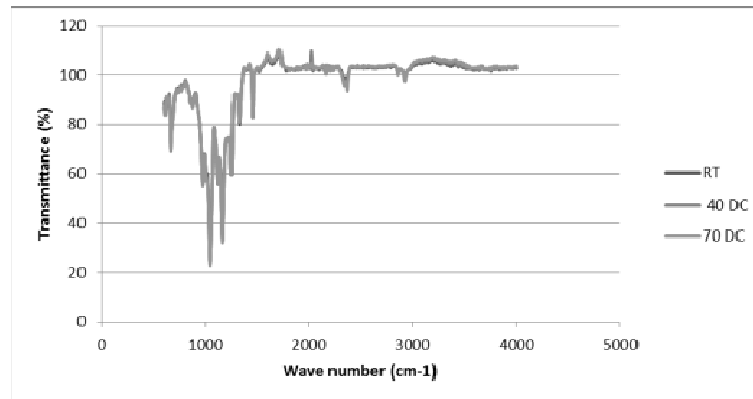


Fig. 11 FTIR for ETFE insulation.

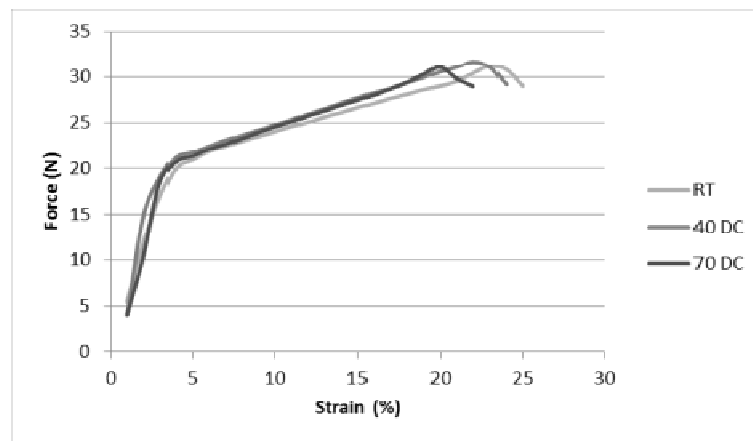


Fig. 12 Strength test for PVC.

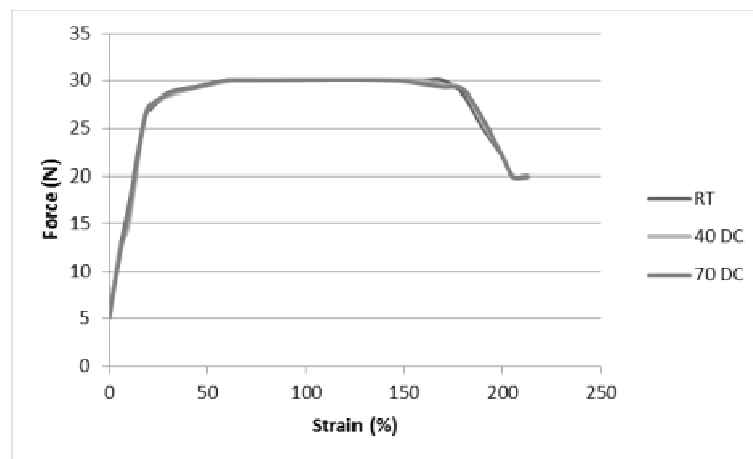


Fig. 13 Strength test for ETFE.

Table 1 Tensile strength for PVC and ETFE.

Insulation material	Tensile strength (N/mm ²)					
		PVC			ETFE	
Temperature (°C)	RT	40	70	RT	40	70
Force (N)	31.10	31.20	32.00	27.50	27.30	27.10
Area (mm ²)	2.01	2.01	2.01	1.96	1.96	1.96
Tensile strength (N/mm ²)	15.47	15.52	15.92	14.03	13.93	13.83

Table 2 Tensile strength for PVC and ETFE.

Insulation material		Elongation (%)				
		PVC			ETFE	
Temperature (°C)	RT	40	70	RT	40	70
Sample length (mm)	50.00	50.00	50.00	50.00	50.00	50.00
Length till break (mm)	107.50	112.00	110.00	129.74	132.40	132.30
Enlongation (%)	115.00	124.00	120.00	159.48	164.80	164.60

4. Conclusions

On PVC infrared spectrum the vibrational stretches of the C-Cl bond appears in the range of 700-600 cm^{-1} , have a complex origin and depend on the conformational structure of the polymer and the arrangement of the atoms near the C-Cl bond. The remaining bands in the spectrum correspond to different vibrations of C-C and C-H. In PVC, the C-H bond stretch of HCCl may be considered as major bands at 2,970 cm^{-1} , stretching the CH bond of the CH_2 at 2,912 cm^{-1} , deformation of the CH_2 at 1,435 and 1,427 cm^{-1} , deformation of the CH bond of the HCCl at 1,331 and 1,255 cm^{-1} , at 1,099 cm^{-1} and the rotation of the CH_2 bond at 966 cm^{-1} [14]. On this infrared spectrum it was possible to identify the characteristic of PVC bands as well as the bands referring to the different vibrations of the C-C and C-H bonds. The spectrum of material submitted to different temperatures did not show variation, which is the reason why it is concluded that the temperature does not affect the structure of the PVC.

The ETFE infrared spectrums are characterized by the existence of vibrational stretching of the CF bond between 1,365-1,120 cm^{-1} , by a small vibration band of the CH bond between 3,125 and 3,040 cm^{-1} and by a band of varying intensity for the C=C between 1,680 and 1,620 cm^{-1} . The characteristic strain bands can be found between 1,000 and 905 cm^{-1} , at about 890 cm^{-1} , between 730 and 665 cm^{-1} and between 1,820 and 1,785 cm^{-1} [14]. In the spectrum obtained, it was possible to identify the main characteristic bands for ETFE and it was possible to conclude that ETFE, under the test conditions, did not change its structure.

Considering the tests done on tensile strength it was

observed that insulation materials were not affected by the temperature variation. However, when analyzing the core of the wires it was seen on the surface of copper some pollutants, mainly carbon and oxygen that were initially supposed that they may be due to migration of insulation components to copper surface but after deep analysis, it was seen that compositions of polluted areas were different from compositions of insulation material. Based on that, it was concluded that the copper may be polluted before extrusion process. It was not possible to confirm the condition of copper before extrusion but it was proposed to be analyzed in a future work.

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