CHARACTERIZATION AND DEVELOPMENT OF WELDABILITY IN THIN SECTION MULTISTRANDED CABLES OF COPPER ALLOY

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ABSTRACT

Ultrasonic Metal Welding (USMW) is applied in many industrial areas; from metal plate welding, electrical wiring, tube sealing, micro welding for electronic applications, etc. USMW presents better results and better quality when compared with other competing welding processes. USMW is a solid state welding process that allows bonding in solid state of metals through application of vibratory energy and pressure. This technique is based in tribological effects when a joint between two surfaces is created. Energy, pressure, amplitude, width, superficial and tooling condition are the main variables that affect overall weld quality.

This work is focused in the application of a statistical quality control factor, developed for this specific purpose and the study of the best parameter combinations to maximize weld quality of alloyed copper cable splices. It implies a metallurgical analysis of interface bonding through SEM analysis.

Keywords: Ultrasonic metal welding, Statistical Quality Control, Copper alloys, Metallographic analysis, Adhesion; Diffusion.

1. INTRODUCTION

In the recent past, a continuous development of new applications and technology, in automotive industry, led to an increase of wiring length and weight of cables in a car. A 21st century car has about 20Kg of cables [1]. Copper is the current metal used as a conductor in a car. One option to be considered is the permutation with aluminum wiring, another is using a stronger, thinner, copper alloy cable in signal applications. In order to obtain the necessary electrical and mechanical properties that the connections require inside a car, a CuMg alloy was considered with PVC insulation.

USMW is a solid state welding process where the union between two parts of metal is promoted by application of ultrasonic vibration under moderate pressure, the vibration being transmitted parallel to the contact interface between both parts [2, 3, 4, 5, 6]. The relative motion between them promotes distortion and progressive plastic deformation of superficial asperities existing in the interface between parts [2, 3, 4, 5, 6]. Plastic deformation disperses oxides and superficial contaminants creating pure, chemically active, metal contact surfaces that bond by application of pressure [2, 3, 4, 5, 6].

In a practical point of view exists a hampering to further progression of USMW application associated with variability of the obtained weld quality in a single batch of welds made with the same welding parameters [2, 6]. The application of new materials implies the development of new welding parameters, with low amount of samples and high performance, according to destructive techniques criteria. For this a statistical quality control factor was developed and different welding parameters were applied considering the attained mechanical performance and latter analysed via SEM. Two welding equipments were considered, in order to study the effect, in overall quality and process stability, of different tooling shapes, splice width and vibration amplitude.

2. USMW BONDING MECHANISMS

The bonding mechanisms present in USMW are metallic adhesion and diffusion in solid state, existing with thin interface layer, independently of material. The bonding occurs due to the intense plastic deformations at the interface between welded parts [2, 3, 4, 5, 6]
With the application of vibration a discrete number of micro welding points begin to form at the contact surface [2, 3, 4].

The obtainable welding resistance does not depend upon the external deformation applied to the welded parts; it depends on the dimension and number of welding points existing in the interface. Plastic deformation is the main source of localized heat generation at the interface. [2, 6]

During the process, the welded parts are compressed between the sonotrode (vibrating part) and the anvil (rigid part). This promotes relative motion between parts which will promote the welding points to develop. The welding points will coalesce while the applied vibratory power is high enough to plastically deform the welding interface [2].

Metallographic exams show that with the introduction of vibratory energy, interfacial phenomena occur (interpenetration and disruption of superficial oxide layers); mechanical effects (plastic flux, grain distortion and material extrusion); thermal phenomena (recrystallization and diffusion) [5]

The deformed layer thickness in USMW is extremely thin, a few micron [7]. This layer is characterized by extremely small grain structure with signs of dynamical recrystallization and diffusion due to high plastic deformations and temperature suffered in the interface only. Diffusion is severely limited due to the short welding time periods [6].

3. THE WELDING EQUIPMENTS

For this work two welding equipments were used, Telsonic Telsosplice and Schunk Minic IV. Both are lateral drive systems. In these systems, the sonotrode is parallel to the welding plane with longitudinal vibration [2, 6]

The welding material is pressured between the anvil and the sonotrode while the sonotrode inducts vibration to the system to promote the weld.

The energy flux through the welding system comes first from electrical power, converted by piezoelectric converter to mechanical vibration and amplified through the transducer up to the welding tip, by the sonotrode/horn [6].

The system also comprises an anvil, rigidly fixed, in order to promote longitudinal relative motion between wires, which are trapped between the welding tip of the sonotrode and the anvil [6]. The main difference between the equipments lies in the knurl pattern of both anvil and sonotrode. The Telsosplice has a standard 9 wave knurl pattern, 12.5mm long, while the Minic IV has an 11 radial knurl pattern, 9mm long (Fig.1a,1b).

4. MECHANICAL TESTING OF MATERIALS

The test materials were samples of stranded copper alloyed cable (CuMg), for low powered electrical applications, insulated with orange PVC. Each sample had 300mm of length with a cross-section of 0.13mm².

| Table 1. Copper comparison, ETP vs CuMg |
|-------------------------------|----------------|---------|
| Cable            | Stress [MPa] | Strain [%] |
| Orange - PVC     | 850           | 3.68    |
| ETP copper [8]   | 240           | 35      |

By looking at fig.2 and table 1, it can be stated that
the copper alloy (CuMg) has a very high ultimate strength, but at very low strain. The CuMg alloy is brittle when compared to ETP copper. This makes the CuMg alloy splices more susceptible to bending and breaking problems.\[9\]

5. SPLICE MECHANICAL ANALYSIS AND QUALITY FACTOR DEVELOPMENT

The USMW process when used for production is controlled via statistical sampling and application of Capability Analysis with statistical data from the destructive pull test and peel test [1, 6, 10].

In order to incorporate other information considered important for the stability of the USMW process, a new type of statistical quality control indicator was developed, the Quality Factors. These consider the parameters used for Ppk calculations but also use the sample standard deviation and minimum value of sample.

The $QF_{\text{Integrated}}$ is the weighted sum of the three other $QF$: Welding Time, Peel, Pull. $QF_{\text{Pull}}$ and $QF_{\text{Peel}}$ differ only in the considered LSL. The $QF_{\text{WT}}$ is only a penalizing factor for welding time samples with big range, it will not increase $QF_{\text{Integrated}}$, and has a maximum value of 1.

The $QFs$ were developed to be at value of 1 when $Ppk$ is 1.67, the correspondent of a Sigma Level of 5 [11]. The $QFs$ were applied to make the 3D graphs, referring to the different destructive tests made for each parameter combination considered and the respective welding time.

Since each $QF$ uses more parameters than the standard $Ppk$, it is possible to have $Ppk$ of 1.67 and have a $QF$ level below 1 because $QF$ is more conservative.

The developed $QFs$ aren’t directly proportionate with $Ppk$. This nonlinearity and the differentiated weights given to $QF_{\text{Pull}}$ and $QF_{\text{Peel}}$ for the calculation of $QF_{\text{Integrated}}$, reduce the influence of very high $Ppks$ that are sometimes attainable in pull. Also in practical terms, the force values necessary to break a splice are much lower for Peel, so Peel has greater importance for quality than pull, it was our intention to let this influence the $QF_{\text{Integrated}}$.

6. USMW WELDABILITY STUDY AND DEVELOPMENT

The objective of this weldability study is to study the process and the effects of variations in parameters have on global mechanical quality of the produced splices.

Experimental procedure

The weldability will be developed in a 0.65mm$^2$ splice. The welding equipments have reference parameters for such cross sections but not for this CuMg alloy. These have to be tested, analyzed and improved. The mechanical results will be produced by destructive peel and pull test, which will be used to determine the values of the quality factors for each energy-pressure combination.

Equipment: Telsonic telssplice

In table 3, it can be seen the reference parameters, the maximum and minimum values applied in this study and the variation for each parameter. In this study a scan was performed with different combinations of pressure and energy.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>0.65mm$^2$</th>
<th>Ref</th>
<th>Min</th>
<th>Max</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [Ws]</td>
<td>64</td>
<td>44</td>
<td>84</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Amplitude [%]</td>
<td></td>
<td>51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure [bar]</td>
<td>2.1</td>
<td>1.7</td>
<td>2.5</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Width [mm]</td>
<td></td>
<td>0.88</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
By the evaluation of QF\textsubscript{Integrated}, fig. 3a, it can be stated that there is a very specific set of parameters that optimize welding of splices with this CuMg alloy, these are very similar to those of QF\textsubscript{Peel}, fig. 3d, because of the weight this specific QF has and because QF\textsubscript{Pull} is high overall, fig. 3b. Due to the increased mechanical properties of this alloy, the energy levels applicable to obtain QF\textsubscript{Peel} over 1 need to be higher than the machine reference and the pressure reduced. This comes due to the specific nature of the peel test. High pressure promotes higher plastic deformation of the top cable (the one being tested out), and for its improved performance we need developed welding islands at the welding interface without destroying the upper surface of the splice.

QF\textsubscript{WT} is a penalizing factor due to welding time variations in each sample, with a value approaching 1. It was stable, which demonstrates that the overall process had the same behavior, although with different welding times.

**Amplitude change**

Once the adequate parameters were optimized, it was defined that a variation in vibration amplitude was needed to check the influence that this parameter had in overall quality of the mechanical welds. Thus the energy-pressure parameter combinations of QF\textsubscript{Integrated} and QF\textsubscript{Peel} were chosen as a basis for an amplitude variation; from the equipment’s recommended value of 51% (26\(\mu\)m) to its maximum of 100% (approximately 50\(\mu\)m).

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**Figure 3. Weldability scan, for Telsosplice equipment**

**Figure 4. Amplitude effect for original parameters of: a) best QF\textsubscript{Integrated}; b) best QF\textsubscript{Peel}**
Amplitude is considered a fundamental parameter to produce totally developed welding islands inside the welding interface \[2, 12\]. It is required to promote plastically deformed areas to develop the referred islands. Higher amplitudes promoted an increase in the QF, due to increased sample averages and lower standard deviations, promoting stability in the welding process.

Higher amplitudes promote higher plastic deformations and heat generation at the interface, increasing diffusive process and welding point coalescence \[2, 12, 13\]. From fig. 4a and 4.b, the QF\textsubscript{Integrated} increased at 90% and 100% amplitude, thus demonstrating that higher amplitude is required and recommended.

**Equipment: Schunk Minic IV**

In table 4, it can be seen the reference parameters for this equipment, the maximum and minimum values applied in this study and the variation for each parameter. In this study a scan was performed with different combinations of pressure and energy.

Schunk Minic IV was developed to be equipment dedicated to small cross-sections. For this effect, it has a smaller anvil and sonotrode, with smaller, specially designed knurls, dedicated for copper alloyed cables, vide figures in §3.

When comparing results between both equipments, fig. 3 and 5, it is clear, either by the peak QF levels reached as is by the area that each level occupies in the maps presented that the Minic IV equipment is better for small cross-sections of alloyed cables. All quality factors are higher than the ones from Telsosplice equipment. QF\textsubscript{Peel} remains too low, only reaching one corner at values above QF of 1. It can be concluded that either amplitude or width needed also variation testing.

**Width change**

Considering this equipment has different width reference, it was decided to apply the Telsosplice equipment’s width in order to evaluate the influence of this parameter. So in the results presented in

![Figure 5. Weldability scan, for Minic IV equipment, width 1.02mm²](image)
fig. 6 the width is of 0.88mm$^2$. It can be stated that the width reduction of the splices reduced its quality. The QF$_{Pull}$ demonstrated now an instability area while QF$_{Peel}$ never presented an area above 1. While these results demonstrate the importance of the width parameter in mechanical performance of the splices it is clear that single ended splices are very difficult to weld at acceptable QF levels.

![Figure 6. Weldability scan, for Minic IV equipment, width 0.88mm$^2$](image)

### 7. SEM ANALYSIS OF WELDED SPLICES

Metallurgical analysis of the splices was made to characterize the welds, evaluate its shape and the phenomena that are occurring in the welds. Since there are far too many combinations made, it was defined that only the parameter combinations where best QF were found were put to SEM testing.

**Experimental procedure**

All welded clips were assembled in epoxidic resin, cut with diamond bladed disc at the central part of the knurled area of the splices. Later they were polished with sequential roughness sandpaper and water and finished with diamond polishing paste, for final surface finishing. The etching sequence was made with a etchant composed of chloridric acid, sulphuric acid and water. At the lower surface of the samples, in order to get the best possible visualization of the welds, the cables were exposed and covered with a gold layer. The evaluated splices are identified with an auxiliary table, in fig. 4 to 7, which identifies the equipment, the parameters used for the splicing and what QF is being studied at that configuration. The sonotrode contacted the lower part of the SEM tested cross sections and the anvil the upper part of the cross sections.
Experimental Results

<table>
<thead>
<tr>
<th>USMW equipment:</th>
<th>Amp 51%</th>
<th>Pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Amp 44</td>
<td></td>
<td>QF Pull</td>
</tr>
<tr>
<td>Energy [J]</td>
<td>74</td>
<td>64</td>
</tr>
<tr>
<td>QF Pull</td>
<td></td>
<td>QF Peel</td>
</tr>
<tr>
<td>QF RTG</td>
<td></td>
<td>QF RTG</td>
</tr>
</tbody>
</table>

- Evaluated combination

Figure 7. Metallurgical analysis of best QF_Pull

Figure 8. Metallurgical analysis of best QF_Peel
In the metallurgical analysis of the SEM results, it can be stated that the figures 7 to 9, which represent the best QF there is a low compaction level at the cross section, particularly in the top area (close to the anvil). The section has big interstitial spaces, distributed through the entire cross section. The welding points formed in the interfaces of the wires of the tested cable (top cable) are small, with areas of kissing bonds or adhesive bonds with a maximum length of approximately 30 \( \mu m \). The splices with highest energy values (QF\text{Peel} and QF\text{Integrated}) present an area severely deformed near the contact area of the sonotrode (bottom surface), where a fish scale effect can be detected in the bottom wires. This happens due to the applied stress state between wires which also makes this the area with less interstitial spaces of the cross sections. The highest energy values (74J and 84J) also promote staking effect in the wires, thus creating more and bigger welding points at a local level.

When an increase in amplitude is applied to the splices, which are welded with the parameters that had the best QF prior but at 90% and 100% amplitude, it can be seen that the compaction level of the splices was greatly increased, with smaller interstitial spaces and higher plastic deformation at the wire surfaces. The distribution of these spaces is not uniform along the cross section because there is zone with severe plastic deformation close to the sonotrode, with no interstitial spaces. The increase in amplitude increases the power output of the equipment and the plastic deformation and heat generation rate of the splice, with heat further reducing the alloy’s yield strength. This promotes diffusive bonding and coalescence of the welding islands, all along the cross section. The staking effect was also very present in these welds as was fish scale effect in the proximity of the sonotrode surface. However, when comparing between both situations, it can be stated that the top wires (anvil surface) now have bigger welding islands, but mainly of adhesive nature, with maximum length of 60\( \mu m \).
Schunk Minic IV

The splices performed by the Schunk Minic IV equipment, were welded with the equipment’s recommended width of 1.02mm and with parameters for optimized pull shows a homogeneous but low compaction level. Interstitial spaces are uniformly distributed along the cross section. The welding islands on the top wires (anvil surface) are mainly of diffusive nature, interface line is no longer visible and the structure of the material and the porosities close to the wire surface, have changed significantly. The maximum detectable length of the welding islands being of approximately 45µm, with only two outer wires in kissing bond or loose, close to the outer surfaces of the tooling. The plastic deformation level is low along the entire cross section, with no fish scale effect detectable. The wires demonstrate stacking, with welding islands between them in the entire cross section.
For the splices welded with parameters for best QF_{Peel} and QF_{Integrated}, an homogeneous compaction, with reduced interstitial spaces, uniformly distributed, along the entire cross section. The welding islands formed between wires are, again, of mainly diffusive nature, with maximum length of 55µm. There is a very low level of plastic deformation of the wires that are in almost hexagonal distribution, minimizing interstitial spaces.
The compaction level and the plastic deformation of the wires remain low with bigger interstitial spaces close to the top surface, due to the bad distribution of the applied energy to the splice, which will make diffusive bonding much more difficult to occur.
For the welds with less energy and 0.88mm of width, in comparison to the same situations with 1.02mm of width, it was gotten less plastic deformation of the wires with smaller welding islands between the top wires of the splice.
It is important to refer that there was no evidence of cross section variation of single wires, which demonstrates that the absorbed energy in splices made by this equipment is used in the development of welding islands between wires. This is due to the shape of knurls of the sonotrode and anvil surface, designed to be an equipment dedicated to small section welding.

8. Conclusions

For this work, a new type of statistical quality control index was developed in order to use mechanical as well as statistical data to define quality levels of the product.
The experimental characterization of the multi stranded alloy cable tested indicated that this cable has very limited ductility, which makes processing by plastically deformation processes such as USMW much more difficult and unstable.
With the weldability characterization it was possible to define ideal welding parameters and test the cables processability by USMW. It was clear that pull results are much more stable than peel tested samples.
The amplitude increase created more compact welded splices, but with much higher plastic deformation and heat generation, at the sonotrode surface due to the increased power output of the machine and the effect of such output in the material’s yields strength. The amplitude increase also created much better samples in average mechanical resistance and a more stable process, with lower deviation. Thus it is essential to have high amplitude to have diffusive bonding, the harder the metal the higher the amplitude.
The sonotrode and anvil’s knurled design is specific to a certain range of cross sections, out of which the splices weld with lower quality. Thus, very small cross sections require tooling with a specific design. The equipment with correct tooling utilized the energy applied to develop the welding islands between strands, while a standard tooling promoted deformation of the strand’s shape and individual cross section.
High energy-pressure combinations promote a severely deformed zone, close to the sonotrode, when welding with equipment with standard tooling, fish scale and stacking effects become visible in areas
close to the sonotrode, while the remaining cross section areas maintain interstitial spaces, bigger or smaller, according to amplitude.
The width is also important for the positioning of the wires inside the cross section, to minimize interstitial spaces and promote hexagonal disposition. If the width is small the wires will not have correct positioning and compaction will not be maximized.

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