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ADVANCES IN ULTRASONIC WELDING OF THIN SECTION CuMg CABLE SPLICES

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ABSTRACT

One permanent trend in automotive industry is the reduction of weight of the vehicles. Considering the importance of the electric systems and electronic control within the automotive industry, reducing the mass of the increasing cable wiring by reducing the cross sectional area of the cables without affecting the reliability of the systems is one major challenge. New dedicated Cu alloy cables are already available in the market, and joining them by ultrasonic metal welding (USMW) is the typical solution complying with the high productivity demands of automotive industry. But the application of USMW with conventional equipment and parameters is not feasible. Thus new technological conditions for the USMW have to be developed. This work focus the development of the best parameter combination to maximize weld quality of thin section CuMg cable splices with a cross section of 0.13 mm^2, with PVC strip insulation layer. The Cu alloy and polymeric strip insulation layer materials were selected based on the mechanical properties of different commercially available cables. The quality of the joints was established via the application of a new statistical quality factor index that uses more input information than the standard Ppk index.

USMW is a solid state welding process that allows superficial joining between multiple metallic surfaces through the combined application of high frequency vibratory energy and forging pressure. This thermo-mechanical technique is based in hysteresis deformation phenomena and localized tribological effects during the weld cycle. Vibrational energy, forging pressure, vibrational amplitude, width of the closed die, tooling geometry and condition are the main parameters that affect overall weld quality.

The results of the present work include the evaluation of different equipment and different tooling. The weldability is tested based on mechanical resistance and metallographic analysis of interfacial joining mechanisms. The technological conditions for best weldability are established by application of the innovative quality factors to evaluate the statistical results achieved.

Keywords: Ultrasonic metal welding; Statistical quality control; Copper alloy cable; Metallographic analysis; 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, which have from 15 kg to 30 kg of cables [1]. To save weight and cost, one option is the permutation with aluminium wiring, another is using a stronger, thinner, copper alloy cable in signal applications. The challenge is to replace pure Cu wires, e.g. with typical wiring with section of 0.35mm^2 by new stronger Cu alloy wires with section of 0.13 mm^2. In order to obtain the necessary electrical and mechanical properties that the connections require inside a car, a cable of CuMg alloy with PVC insulation was considered in this work. This cable was selected based on its mechanical resistance after a comparative analysis with other commercially available cables with different Cu alloy and insulation materials and is representative of the new trends for automotive wiring.

The high productivity and good quality levels delivered from Ultrasonic Metal Welding (USMW) makes this welding technique the most common solution to join all the permanent joints in the wiring applied in automotive industry [2]. Nevertheless the USMW of the new thinner copper alloy cables present new challenges. Some of these challenges are addressed in this work.

The deformed layer thickness in USMW is extremely thin, a few micron [3]. This layer is characterized by extremely small grain structure with signs of dynamic 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 [4] but ultrasonic vibration promotes ultrasonic softening of the parts and also the diffusive nature of the joint [5].

As most of the other manufacturing processes, USMW has inherent statistical variability of the weld quality. Thus quality must be inspected even in a single batch of welds made with the same welding parameters [4, 6]. The process is evaluated usually by application of a process performance index, Ppk [7] to estimate the process' capability for its setup. For this work a new statistical quality index, named Quality Factor, QF index, was developed and different welding parameters were applied considering the attained mechanical performance in order to obtain a faster optimized set of parameters. Two welding equipment were tested to study the effect, in overall quality and process stability for different tooling shapes, splice width and vibration amplitude.

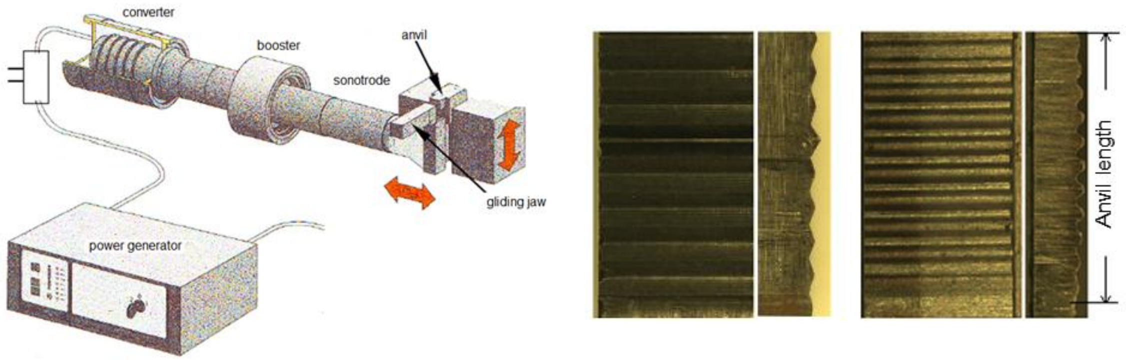
2. Technological fundaments of USMW

USMW is a solid state welding process where there is a superficial union between the multiple metallic components promoted by application of ultrasonic vibration under moderate compression pressure. The pressure is applied between the sonotrode (vibrating tool) and the anvil (rigid tool). The vibration is then transmitted parallel to the contact interface between both parts [6, 8]. The relative motion between them promotes distortion and progressive plastic deformation of superficial asperities existing in the interface between parts [6, 8]. The plastic deformation at the interface between components is intense due to hysteresis cycle of stress-strain that these welding points undergo. The combination of the vibration and pressure trigger the development of a discrete number of micro welding points between the components interfaces [6, 8]. The welding points will then coalesce. Plastic deformation generates the heat that locally reduces the yield strength of the materials in the welding points. The plastic deformation also disperses oxides and superficial contaminants creating pure, chemically active, metal contact surfaces where the solid state joining mechanisms are activated under the application of pressure [6, 8]. The joining mechanisms present in USMW are metallic adhesion and diffusion in solid state, existing within a thin interface layer. The strain rate is influent in the diffusion process by increasing effective vacancies concentration by creation of strain induced vacancies [9]. The complete weld cycle period is typically small and thus the productivity is high [4]. The obtainable welding resistance does not depend upon the external deformation applied to the welded components; it depends on the dimension and number of welding points existing in the interfaces and the nature of the joining mechanism [5, 9]

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, 10].

3. EXPERIMENTAL CONDITIONS AND PROCEDURES

For this work two commercially available USWM equipments were used. Both equipments are lateral drive systems, stimulated at 20 kHz. In these systems, the sonotrode is parallel to the welding plane with longitudinal vibration [4, 6]. The main difference between these equipments lies in the knurl pattern of sonotrode, as depicted in Figure 1,where: i) Equipment A have standard tooling for copper welding; and ii) equipment B have dedicated tooling for weld wires with small sections of Cu alloy. The tooling for USMW of standard cross sections of pure Cu wires have 9 wave, parallel knurl patterns, 12 mm and 12.5 mm long respectively. The dedicated tooling (equipment B) is an 11 knurl, radial pattern, 9 mm long. These different tooling are represented in Figure 1. As was referred by R. Jahn et al. [11] sonotrode and anvil (size and shape) will influence the mechanical resistance of the welds. The differences between equipment will help evaluate the influences of tooling in the attainable mechanical resistance of the welds.



a) b) c)

Figure 1 - Knurl patterns of sonotrode and anvil applied in the different USMW equipment conditions tested: a) Generic representation of a USMW equipment to produce cables splices; b) Knurl patterns of anvil of equipment A; c) Knurl patterns of anvil of equipment B

For both equipments several batches of five welded splices were made for each parameter combination. After each weld the samples were identified to later match the mechanical test results with the respective welding time and parameters. In Figure 2 it is represented the strategy implemented for implementing the weldability analysis. The parameters tested are the ones that typically most influence has on the weld quality, namely: i) pressure; and ii) energy. The values are incremental variations from the reference parameters of the equipment for the selected cable. All the remaining parameters are constant and correspond to the equipment reference parameters. From each batch of welded splices, the statistical values are determined for welding time, *peel-out* and *pull-out* tests, enabling the determination of the QF index.

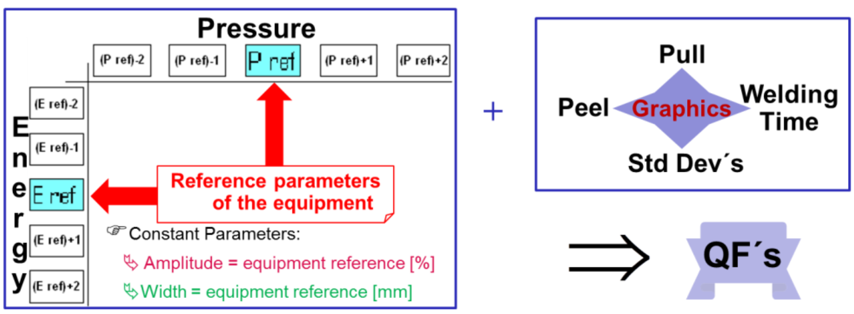


Figure 2 – Schematic representation of strategy implemented for the weldability analysis.

The mechanical *peel-out* and *pull-out* tests were made with the use of a tensile tester MAV DIP M 100, at a speed of 50 mm/min, according to SAE AS39029 standard [12]. For the application of the QF index the average and standard deviations of the measurements were made.

Selected representative welded clips were assembled in epoxy resin, cut with diamond bladed disc at the central part of the knurled area of the splices. Later they were polished and finished with diamond polishing paste. The etching sequence was made with hydrochloric acid, sulphuric acid and water.

At the lower surface of the samples, in order to get the best possible visualization of the welds in SEM, the cables were exposed and covered with a gold layer. Only parameter combinations that maximized QF index were analysed by SEM.

The materials tested were samples of stranded copper alloyed cable (Cu alloy), for low powered electrical applications, insulated with polymeric strip. Each sample had 400 mm of length and 7 strands with a total cross-section of 0.13 mm^2. The cables features are established in Table 1. The composition of the metallic conductor of the cables is established in Table 2 The conditions are i) different Cu alloy, namely CuMg; and CuSn; and ii) different materials for the strip insulation layer, namely PVC and PPE.

Color	Number of Wires	Wire Section $[mm^2]$	Coating	Supplier	Material	SAE
Purple	7	0,01942	PVC	Coficab	CuSn Alloy	CC
Orange	7	0,01956	PVC	Erbakir	CuMg Alloy	CC
Green	7	0,01926	PPE	Erbakir	CuMg Alloy	CC

Table 1 – Identification of the main features of the cables tested.

Conductor	PURPLE (PVC)		GREEN (PPE)		ORANGE (PVC)	
Element	Weight [%]	σ_{Weight} [%]	Weight [%]	σ_{Weight} [%]	Weight [%]	σ_{Weight} [%]
Cu	99,83	0,22	99,86	0,23	99,68	0,26
Mg	-	-	0,14	0,23	0,32	0,26
Sn	0,17	0,22	-	-	-	-

Table 2 – Identification by EDS of the chemical composition of the cables tested.

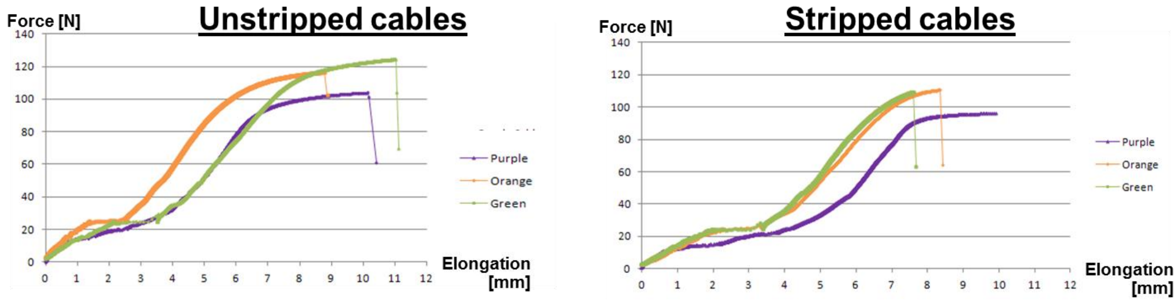
The mechanical tensile properties of the cables were measured both for cables with insulation and without strip insulation layer, via a INSTRON 5566, equipped with a load cell of 10 kN. The length of the samples was 400 mm and a special device was produced for perfect clamping and alignment of the cable wires as presented in Figure 3.

Figure 3 – Experimental apparatus developed for full clamping and alignment of multistranded cables with and without strip insulation layer.

4. MECHANICAL TESTING OF MATERIALS

Static tensile mechanical testes were made to the three different cables for conditions of as supplied with strip insulation layer and also in unstripped condition to evaluate the properties of the metallic conductor and to be able to decouple the combined effect of metal+insulation strip. This is relevant because the properties of the welding resistance will focus the resistance of the joint mechanisms activated during welding but also the metallic material properties of the cables in the unstripped region, i.e., with no influence of the insulation strip.

From the analysis of Figure 4 it is possible to conclude that the CuMg metallic conductor presents always better mechanical resistance than the CuSn. Thus CuMg will be selected. Concerning the material of the strip insulation the PPE contributes significantly for the increase of the cable resistance resulting in a bigger dissimilarity between the properties of stripped and unstripped conditions. Thus in order to investigate the weld properties in the unstripped zone, the PVC condition is the ideal solution to apply the *pull-out* and *peel-out* tests without the risk of influence of the resistance of the insulation layer on the mechanical properties on the USMW zone of the splices. The PVC also corresponds to the most common and economical solution for cables available in the market, thus is the most representative condition.



	Max. Strength [N]	Cross Section [mm^2]	Strain Percentage [%]	$\sigma = \frac{strength}{cross\ section}$ [MPa]
Purple	107	0,13	4,43	823,08
Oranje	117	0,13	3,87	900,00
Green	125	0,13	4,86	961,54

	Max. Strength [N]	Cross Section [mm^2]	Strain Percentage [%]	$\sigma = \frac{strength}{cross\ section}$ [MPa]
Purple	96	0,13	4,37	738,46
Oranje	111	0,13	3,68	853,85
Green	109	0,13	3,35	838,46

Figure 4 – Stress-strain diagram of CuMg alloy

For the cable CuMg with PVC strip insulation layer, the maximum stress resistance is of about 854 MPa and the elongation of about 3.7 %. Considering the properties of ETP copper [13] with stress resistance is of about 240MPa and the elongation of about 35 %, it is possible to conclude that the CuMg alloy splices are more susceptible to bending and impact loads.

5. STATISTICAL INDEX 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-out* and *peel-out* test [4]. These tests are depicted in Figure 5. This is done typically based on the process performance index, Ppk (1) to estimate the process' capability for its setup [7].

$$P_{PK_{PULL}} = \frac{\overline{P}_i - LSL}{3\sigma_i}; LSL = 50 \quad ; \quad P_{PK_{PEEL}} = \frac{\overline{P}_i - LSL}{3\sigma_i}; LSL = 10 \tag{1}$$

Where: LSL is the lower specification limit [N], and $\overline{P}_i$ and σ_i are respectively average and standard deviation values of sample *i*.

Figure 5 – Representation of destructive test *for quality evaluation of USMW clips: pull-out* test (left) and *peel-out* test (right).

$$QF = \frac{1}{9}T_{WT} + \frac{2}{9}T_{Pull} + \frac{6}{9}T_{Peel} \tag{2}$$

$$T_{Peel} = e^{-\left[\left(\frac{3\sigma_i}{\overline{P_i}-LSL}\cdot\frac{5}{3}\right)-1\right]} \cdot \left(\frac{min(P_i)-LSL}{\overline{P_i}-LSL}\right)^{\frac{1}{3}} \tag{3}$$

$$T_{Pull} = e^{-\left[\left(\frac{3\sigma_i}{\overline{P_i}-LSL}\cdot\frac{5}{3}\right)-1\right]} \cdot \left(\frac{min(P_i)-LSL}{\overline{P_i}-LSL}\right)^{\frac{1}{3}} \tag{4}$$

$$T_{WT} = e^{-\frac{\sigma_i}{\overline{t_i}}} \cdot \frac{\min(t_i)}{\overline{t_i}} \tag{5}$$

A new Quality Factor, QF index (2) was developed and implemented integrating the mechanical properties and productivity of each USMW setup. QF index result from the linear combination of three independent terms; referring to the i) *peel-out* test (3); ii) *pull-out* test (4); and iii) welding period (5). The term referring to the *peel-out* has a substantial weight regarding the other two terms due to its instability and narrower parameter window for optimum results, e.g. when compared with the *pull-out* test. The term regarding welding time serves as a penalizing term because the increase in the welding time's range is a decrease in productivity and typically an identification of process instability. These terms consider the same data used for the Ppk calculations and use the sample's minimums criteria to penalize the existence of outlier elements in the sample (see Figure 6). The QF index is simultaneously more conservative and a unified approach to evaluate different quality outputs in a single statistical index. The terms T_{peel} and T_{pull} in QF index were developed to be at value of 1 when Ppk is 5/3 = 1.67, the correspondent of a quality Sigma Level of 5 [7], although they aren't directly proportionate with Ppk. This nonlinearity reduces the influence of very high Ppk.

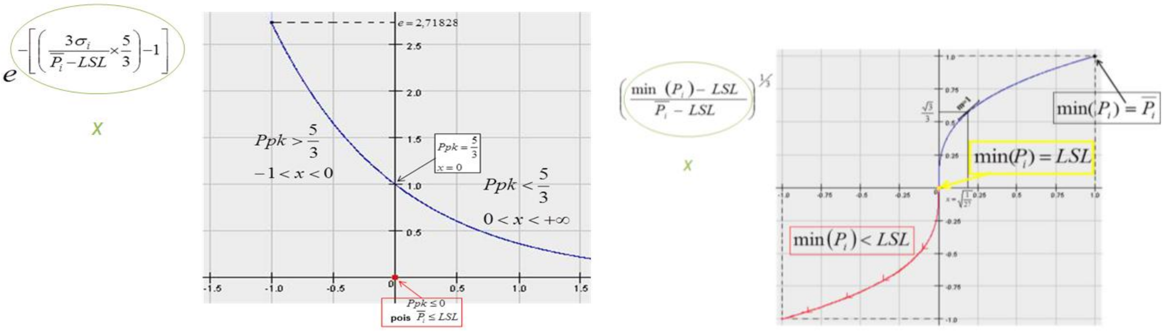


Figure 6 – Graphical representation of the development of the sub-terms within the expressions considered for the T_{peel} and T_{pull}.

6. ANALYSIS OF RESULTS FOR QUALITY FACTOR, QF INDEX

Equipment A, standard tooling

The parameters implemented in weldability tests of equipment Aare present in Table 3.

Total Cross Section: 0.65 mm^2 Clip = 3 (0,13 cable) X 2 (0,13 cable) 	Reference value.	Min.	Max.	Increment
Energy [J]	64	44	84	10
Amplitude [µm]	12.5			
Pressure [bar]	2.1	1.7	2.5	0.2
Width [mm]	0.88			

Table 3 – Set of welding parameters implemented for testing equipment A.

The results obtained for QF index for equipment A are present in Figure 7. This figure shows that the reference values for the parameters of the equipment A do not corresponded to the maximum QF index. The maximum quality for the USMW of splices with this CuMg alloy obtained was QF=1.158 corresponding to higher energy levels of about 74 J and lower pressure levels of about 1.9 bar.

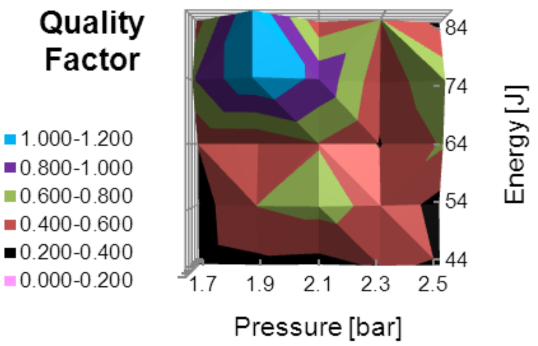


Figure 7 – Quality Factor, QF index distribution for equipment A with variation of the parameters: energy and the pressure.

This variation in optimum parameters can be better understood considering that the reference values of this equipment A have been developed for ETP copper. Due to the higher mechanical resistance of this CuMg alloy, the correct energy levels applicable need to be higher than the machine reference and the pressure reduced to avoid severe indentation in the splice by the bigger and lees number of knurls of the sonotrode.

These results are mainly driven by the nature of the *peel-out* 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.

Amplitude influence for equipment A

Once energy and pressure were optimized to maximize the QF index, the amplitude was tested to evaluate its influence in overall quality of the mechanical welds; from the equipment's recommended value of 15 µm up to 25 µm, as depicted in Figure 8.

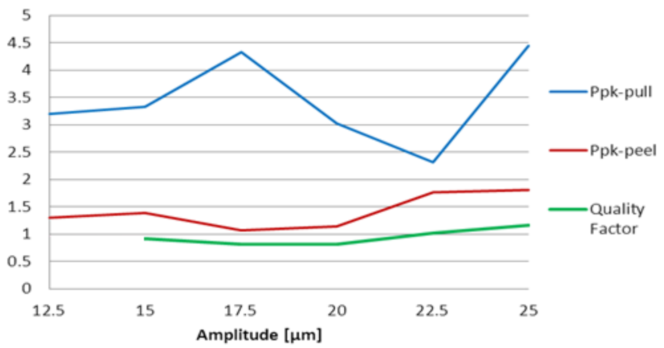


Figure 8 – Evolution of the quality indexes for USMW: Ppk for *pull-out* test and *peel-out* test, and QF, according to equation (1) and (2), respectively.

Amplitude is also considered a relevant parameter in USMW to produce totally developed "weld points" at the several welding interfaces [6, 14]. Higher amplitudes promote higher plastic deformations and heat generation at the interface, increasing diffusive process and welding point coalescence [14, 15]. Figure 8 shows that higher amplitudes promote an increasing QF index, up to a maximum of QF=1.185, due to increased sample averages and lower standard deviations, resulting from higher stability in the welding process. The figure 8 also evidences one significant advantage of QF index, that is the stable evolution, where QF=1 corresponds to maximum quality. Emphasis should be put in the big dispersion of values and opposite variations of Ppk for *peel-out* and *pull-out* tests, values not allowing an efficient assess of the quality of the USMW splices.

Equipment B, dedicated tooling

This USMW equipment has installed a tooling with dedicated design to small cross-section cables. It has a smaller anvil and sonotrode; specially designed knurls, radial shape, different surface finishing. The parameters implemented in the tests are present in Table 4.

Total Cross Section: 0.65 mm^2 Clip = 3 (0,13 cable) X 2 (0,13 cable) 	Reference value.	Min.	Max.	Increment
Energy [J]	67	47	87	10
Amplitude [µm]	15 (60%)			
Pressure [bar]	1.8	1.5	2.1	0.3
Width [mm]	1.02			

Table 4 – Set of welding parameters implemented for testing equipment B.

The Figure 9 shows that the QF index is higher at the lowest pressure tested of 1.5 bar and highest energy of 87 J. This equipment reached the highest quality factor level: QF=1.259.

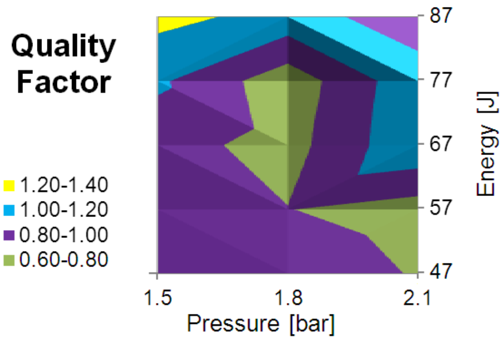


Figure 9 – Quality Factor, QF index distribution for equipment B with variation of the parameters: energy and the pressure.

When comparing results between equipments A and B (Figure 7 versus Figure 9), it is possible to conclude that i) the peak value of QF index reached an higher value for equipment B; and ii) the area for QF over 1 occupied in the maps is larger for the equipment B. Thus the equipment B conditions is better for small cross-sections of alloyed cables. Since the major variation between equipments is the tooling, it can be concluded that the tooling design is a significant factor in obtainable quality for USMW.

Width change for equipment B

Considering the equipment B has a different width reference (1.02 mm) from equipment A, it was decided to apply the equipment A reference width (0.88 mm) in order to evaluate the influence of this parameter. Figure 10 present the results for this new width.

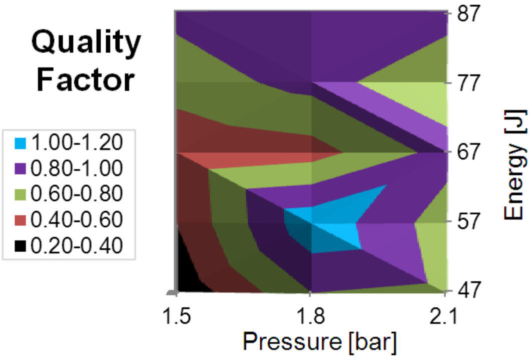


Figure 10 - Quality Factor, QF index distribution for equipment B, with the same conditions of Table 4, except the width=0.88mm.

Considering the equipment B has a different width reference (1.02 mm) from equipment A, it was decided to apply the equipment A reference width (0.88 mm) in order to evaluate the influence of this parameter. From figure 10, it can be stated that the width reduction of the splices reduced its quality. The QF index was reduced overall and the peak value was now QF=1.149. These results demonstrate that the modification of the width parameter from the reference values had a detrimental effect.

7. SEM ANALYSIS OF WELDED SPLICES

Metallurgical analysis of the splices was made to characterize the welds by evaluating its shape and the distribution of contact points and level of joining mechanisms that are occurring in the welds.
In all the Figures 11-14, the sonotrode contacted the lower part of the SEM tested cross sections and the anvil the upper part of the cross sections.
For both equipments A and B only the parameter combinations, presented before, that maximized QF index were analysed by SEM.

Equipment A, standard tooling

In the Figure 11, representing the SEM image of a cross section of the welded splice with the best QF index for equipment A, it is present the typical loss of energy transmitted from the sonotrode in direction to the anvil through the weld splice. The number of welding points formed in the interfaces of the wires of the tested cable (top cable) is small, with areas of kissing bonds / weak joints with a maximum length of approximately 30 µm.
The splices 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 applied at the bottom also promoted *staking* effect in the wires, thus creating a bigger number of welding points and more extensive.
The corner adjacent to the sonotrode present a clear material flow through the inconvenient gap existing between the sonotrode and the lateral constraining plate, showing the visco-plastic character of the deformation, mainly near the sonotrode.

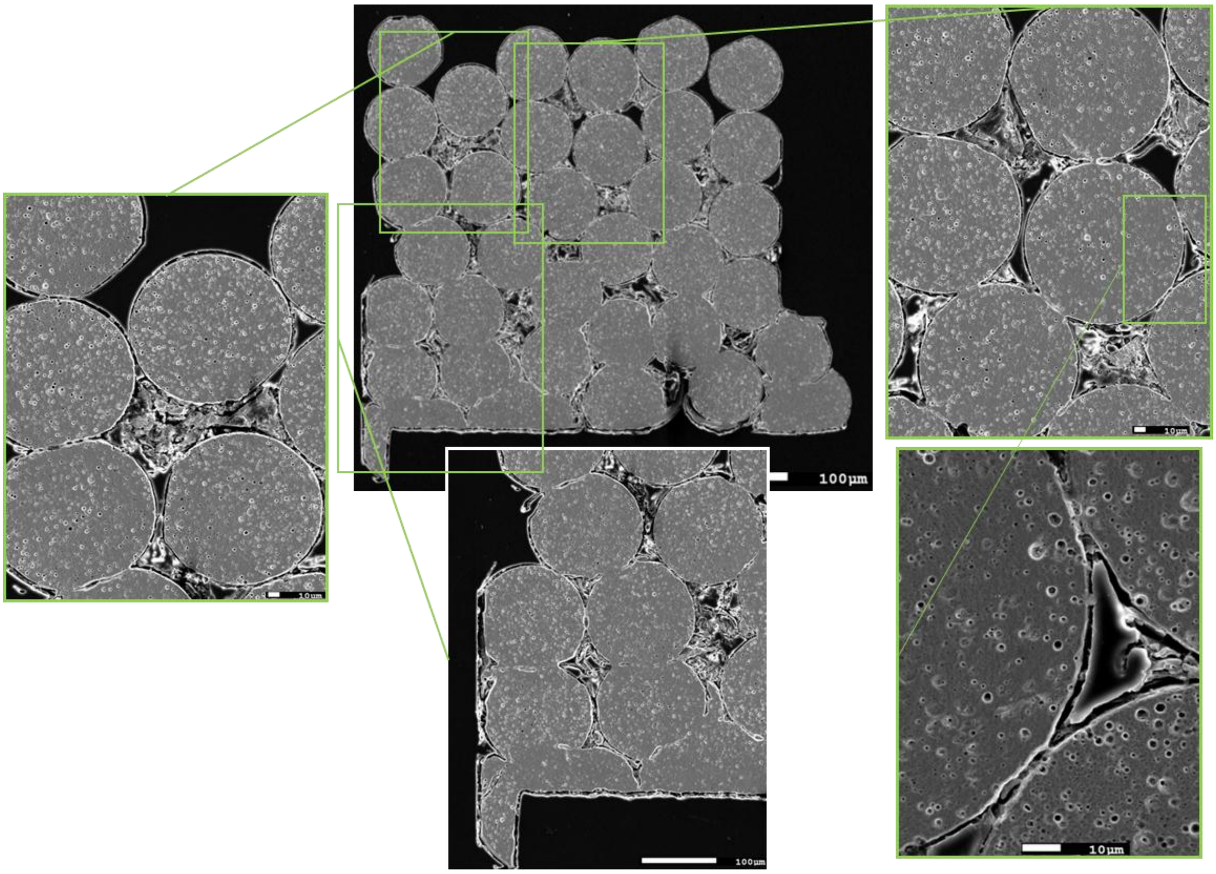


Figure 11 – SEM image of cross section of the welded splice produced with equipment A with parameters maximizing the QF index.

Amplitude change for equipment A

When an increase in amplitude is applied to the splices, as can be seen in Figures 12, which is welded with the parameters that had the best QF index but at 25 µm of amplitude, it can be seen that the compaction level of the splices at the top zone is slightly increased, with smaller interstitial spaces and higher plastic deformation at the wire interfaces. When comparing Figure 11 and Figure 12 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 µm in some situations. The distribution of these spaces is still not uniform along the cross section because there is zone with severe plastic deformation close to the sonotrode, with almost no interstitial spaces in this area. The *staking* effect was also present in these welds as was *fish scale* effect in the proximity of the sonotrode surface.

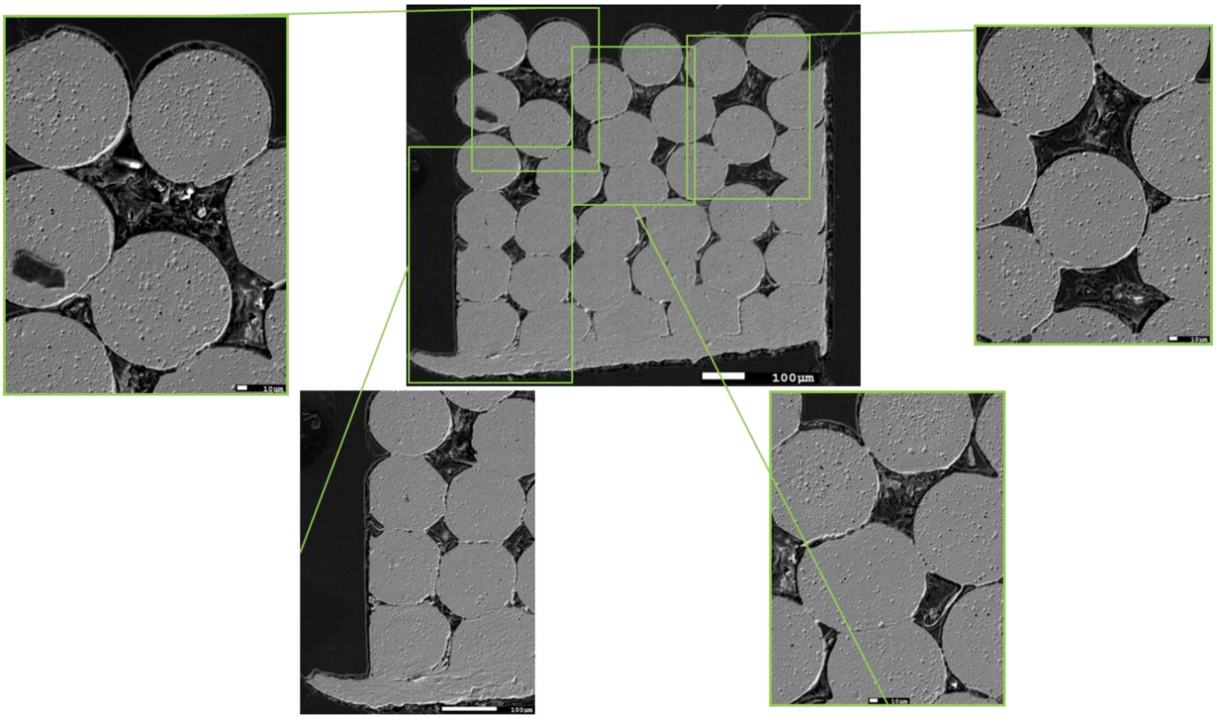


Figure 12 – SEM image of cross section of the welded splice produced with equipment A with parameters maximizing the QF index and amplitude=25 µm.

Equipment B, dedicated tooling

From Figure 13 it is possible to conclude a more homogeneous compaction level with almost uniform distribution of the deformation and joining mechanism along all the splice, not showing any relevant concentration of the deformation near the sonotrode at the bottom part of the splice, as present in Figure 11 and Figure 12 from equipment A. This result is evidence of a more efficient transmition of the ultrasonic vibration energy from the sonotrode into de anvil along the splice. Figure 13 shows 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 between strands is no longer visible and the structure of the material and the porosities close to the wire surface has changed significantly. The maximum detectable length of the welding islands being of approximately 45 µm, 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. The strands are in almost hexagonal distribution, reducing interstitial spaces and optimizing stress distribution along the cross-section.’

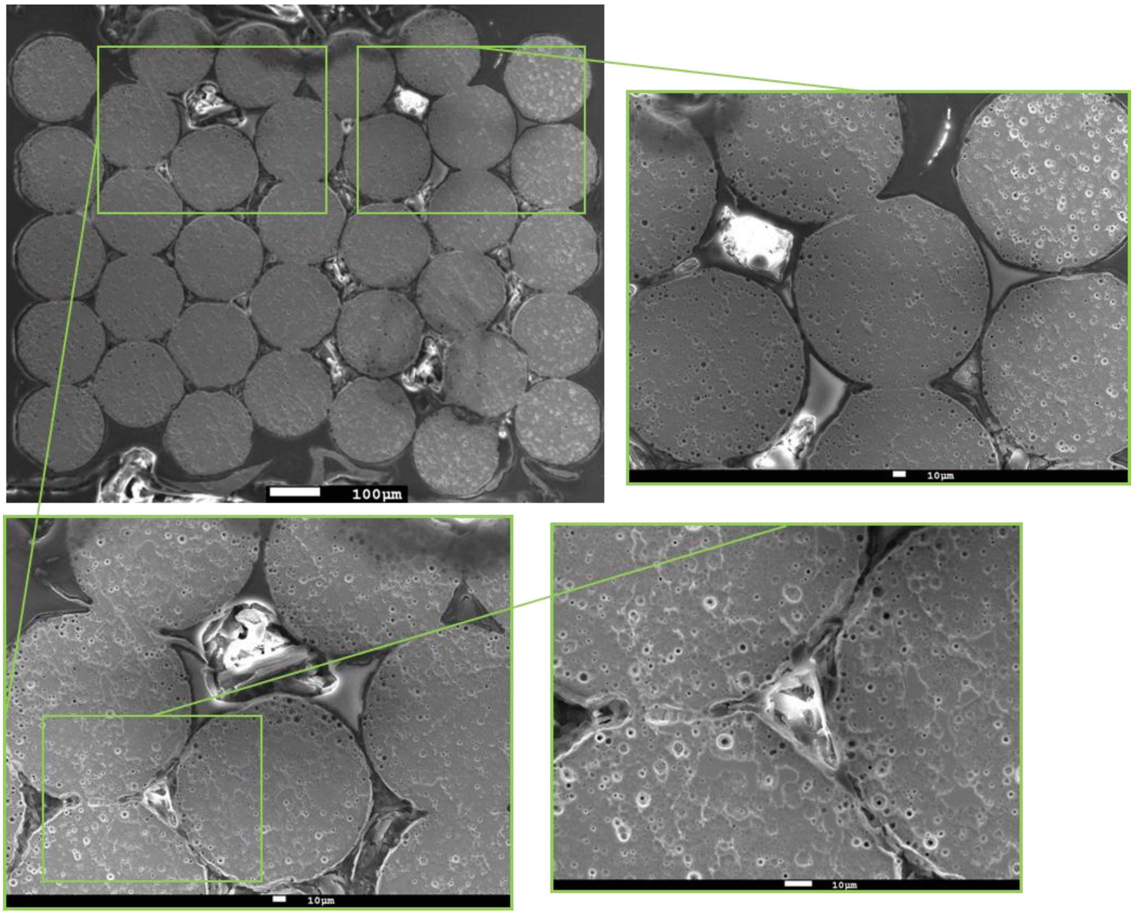


Figure 13 – SEM image of cross section of the welded splice produced with equipment B with parameters maximizing the QF index.

Width change for equipment B

In Figure 14, it can be seen that the reduction of the splice's width reduced its compaction level, the plastic deformation of the wires remains low with bigger interstitial spaces close to the top surface, due to the bad distribution of the applied energy to the splice. This will drastically reduce diffusive phenomena between strands, with smaller welding islands between the top strands of the splice.

It is important to refer that there was no evidence of cross-section variation of single individual strands, which demonstrates that the absorbed energy in splices made by this equipment B is used mostly in the development of joining mechanisms between wires. This is due to the shape of knurls of the sonotrode and anvil surface that improve the transmissibility of the mechanical wave across the strands of the splice.

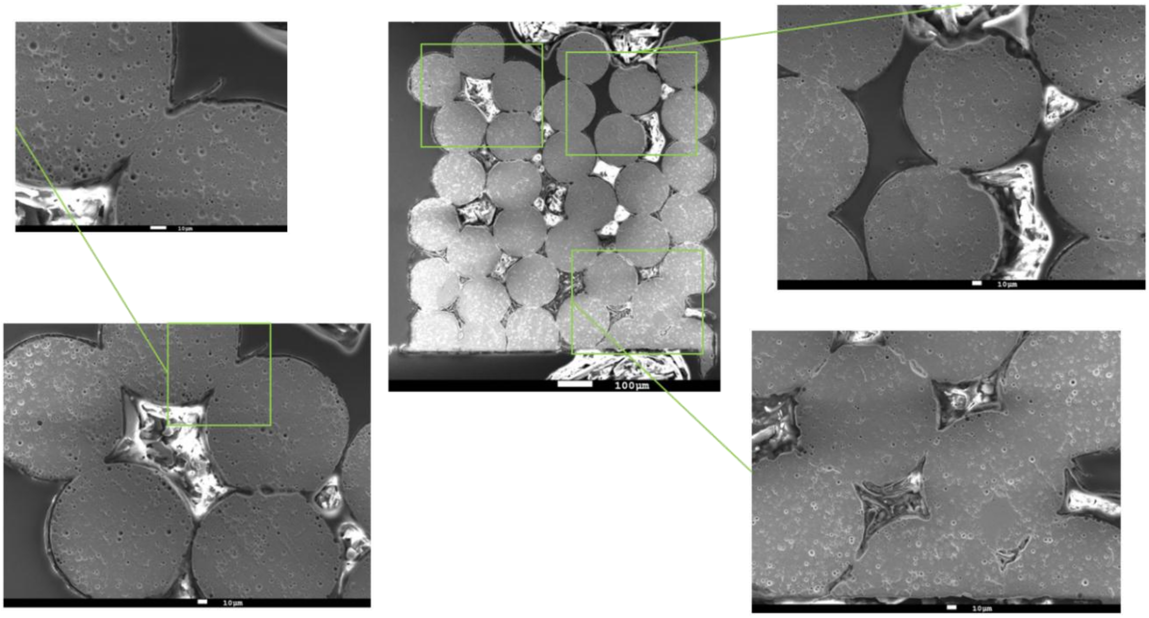


Figure 14 – SEM image of cross section of the welded splice produced with equipment B with parameters maximizing the QF index and width=0.88 mm.

8. CONCLUSIONS

The most significant conclusions from the present work are the following:

- The thin section cables of copper alloy welded by USMW may result in an automotive industrial evolution but demand new equipment features and parameters development;
- A new of statistical quality factor, QF index was developed based on the typical industrial mechanical test: peel-out and pull-out tests; and on the productivity of the USMW. This index shown to be stable and enable a fast and efficient assessment of the overall properties of the weld splice;
- The characterization of the multi stranded copper alloy cables tested indicated that these cables have more mechanical resistance and significant less elongation than the conventional EPT copper cables;
- The tooling size and shape are determinant factors to the weld quality. The tooling dedicated for USMW thin sections of copper alloy cables, equipment B, shown higher QF index, than the standard tooling;
- The dedicated tooling in equipment B is able to transmit the ultrasonic vibration from the sonotrode into the anvil, through the splice, with higher efficiency than the conventional tooling that promoted very intense, but localizes deformation of the strands near the sonotrode and less capacity of transmit the energy, resulting in very weak joining mechanisms for the strands more distant from the sonotrode;
- The equipment A with standard tooling, produced more *fish scale* and *stacking* effects mainly visible in areas close to the sonotrode, while the remaining cross section areas shown increasing interstitial spaces. The dedicated tooling of equipment B, promoted a more reduction of interstitial spaces resulting from a more hexagonal distribution of the strands;

- The weldability analysis implemented enabled to define ideal welding parameters in the vicinity of those given as machine references. Typically higher energy and lower pressure resulted in better quality;
- The increase in amplitude increased compaction in welded splices, but with much higher plastic deformation and heat generation at the sonotrode surface. The amplitude increase resulted in a more stable process, with lower deviation showing that should be considered for USMW of harder Cu alloys;
- The width parameter shown some relevance for the positioning of the wires inside of the cross section. If the width is small the wires will not undergo correct compaction and mechanical resistance is reduced.

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