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Milica Ivić Nikolić[1], Snežana Jovanović[1], Aleksandar Nikolić[1], Branislav Đorđević[2], Aleksandar Sedmak[3], Ana Petrović[3]*

SOME REMARKS ON THE BASIC PRINCIPLES OF ULTRASONIC WELDING OF CONDUCTORS IN THE AUTOMOTIVE INDUSTRY

NEKA ZAPAŽANJA U VEZI OSNOVNIH PRINCIPA ULTRAZVUČNOG ZAVARIVANJA PROVODNIKA U AUTOMOBILSKOJ INDUSTRIJI

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Adresa autora / Author's address:
[1] Technical Test Centre, Military Scientific Research Institute, Serbian Armed Forces, Belgrade, Serbia
M. Ivić Nikolić https://orcid.org/0009-0007-6217-4929 ,
*email: milicaivicnikolic@gmail.com ,
S. Jovanović https://orcid.org/0009-0004-6468-7726
[2] University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Belgrade, Serbia
B. Đorđević https://orcid.org/0000-0001-8595-6930
[3] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia A. Sedmak https://orcid.org/0000-0002-5438-1895 ;
A. Petrović https://orcid.org/0000-0002-5996-1485

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- conductors
- splice
- wiring harness
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Ključne reči
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- provodnici
- spoj
- kablovski snopovi
- automobilska industrija

Abstract

The application of ultrasonic welding has increased over the last decade due to the rapid technological development and its availability at lower cost. In this paper ultrasonic welding of conductors is presented as one of the most important manufacturing processes in the automotive industry. Using this method of welding, conductor joints are created that represent a crucial part of any electrical installation such as wiring harnesses for vehicles. Additionally, connections between conductors and components, such as metal terminals, can also be achieved using the same welding process. These conductor joints or connections between conductors and terminals must provide high electrical conductivity and satisfying mechanical properties in order to create a safe and reliable product. The conclusions of this study provide some advantages of ultrasonic welding application, particularly in the automotive industry, and further trends in this field.

Izvod

Primena ultrazvučnog zavarivanja je porasla poslednjih decenija zbog brzog tehnološkog razvoja, kao i njegove dostupnosti i niže cene. U ovom radu prikazano je ultrazvučno zavarivanje provodnika kao jedan od važnijih proizvodnih procesa u automobilskoj industriji. Koristeći ovu metodu zavarivanja stvara se spoj između provodnika, koji predstavlja važan deo svake električne instalacije kao što su kablovski snopovi provodnika za vozila. Pored toga, veza između provodnika i komponenata, kao što su metalni priključci, se takođe može postići primenom istog procesa zavarivanja. Ovi spojevi provodnika i veza provodnika i priključaka treba da pruže visoku električnu provodljivost, ali i zadovoljavajuće mehaničke osobine da bi se dobio siguran i pouzdan proizvod. U zaključku ovog rada sumirane su prednosti primene ultrazvučnog zavarivanja, konkretno u automobilskoj industriji, kao i budući trendovi u ovom polju.

INTRODUCTION

As it is well known from the acoustic domain, ultrasonic represent vibrations of frequencies higher than the upper limit of audible range for humans, above 20 kHz. Ultrasound waves of very high amplitudes define the term sonic which is applied to ultrasound, /1/. In engineering practice, ultrasound waves are typically used for non-destructive test methods, especially on welds, with the purpose of detecting volumetric defects in welded joints, /2-3/. However, the application of the welding process since the 1960s was initially meant for welding plastics and was later on applied for the joining of metallic materials. Ultrasonic welding (USW) is a well known technique in recent years that has established itself as a standard method in the automotive industry. In the production of wiring harness for different types of vehicles, the USW process becomes unavoidable. A wiring harness or cable assembly is a combination of electrical cables, or assembly of conductors, that connect all electrical and electronic components in the automotive vehicle, like sensors, electronic control units, batteries and it is important to mention that a well designed harness is a specially designed system that keeps the large number of conductors and cables organised. The purpose of the wiring assembly is to transmit a signal or electrical power. Automotive wiring harness is the electrical distribution system in the vehicle.

The USW process provides connections between conductors or connections between conductor and metal terminal.

This process uses vibrations for the acoustic softening of materials during welding. High frequencies between 15-70 kHz generate vibrations. These vibrations generate enough heat which melts the material and weld together creating a strong bond. The wiring harness represents an end product in manufacture, as such it must provide high electrical conductivity, along with satisfying mechanical properties, providing product safety for further installations in the vehicle. In the USW process with copper (Cu) and aluminium (Al) conductors are made. Cu is used in terminals, foils, and wiring harnesses of new vehicles due to its good electrical conductivity /4-8/, while the application of Al conductors is toughly described by Mostafavi et al. /9/ along with their welding requirements. Copper has a density approximately three times that of aluminium and slightly higher electrical conductivity than Al /9, 10/.

In order to improve the USW of conductors, authors in /11-14/ show the optimisation of ultrasonic welding parameters, such as amplitude, pressure, time of welding and energy. The impact of ultrasonic welding parameters on the weldability and sustainability of Cu wires is shown in /15/. An important advantage of ultrasonic welding is the possibility of welding a wide range of different types of wire cross-sections and braids using the same tool and real time quality control of the welding process. USW enables the welding of a broad spectrum of wire cross-sections as a single tool. This process of welding ensures excellent thermal and electrical conductivity and produces splices without melting the base material, /16/.

Quality requirements of welded joints in this particular case (where the welded joint actually represents the splice), involves a few different types of inspections that need to be carried out. Presented in this paper is one general view of the USW of conductors, as well as the principle of the ultrasonic welding machine. Key requirements are given referring to the new standard in the solderless connection part of IEC 60352-9:2024 which covers ultrasonically welded connections and includes requirements, test and practical guidance information. Also, the authors give a general description about visual inspection, bend testing, pull-out testing, peel testing and finally the microsection of different types of splices (i.e., aforementioned welded joints).

UWS MACHINE AND WELDING TECHNOLOGIES

The USW machine represents a welding system consisting of an ultrasonic generator, an ultrasonic converter, sonotrode and the necessary electrical and mechanical accessories to operate it. Schematic representation of this welding system is given in Fig. 1.

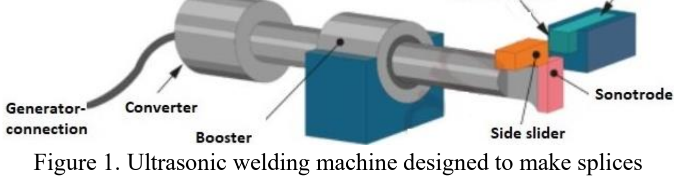


Figure 1. Ultrasonic welding machine designed to make splices between at least two wires.

The ultrasonic generator represents the source that generates high frequency electrical energy to the transducers. The ultrasonic converter uses electrical energy at the ultrasonic frequency and converts it into mechanical oscillations. The sonotrode is the component that transmits ultrasonic vibrations directly to the parts to be welded. The shape of the sonotrode determines the final amplitude that will be used to weld two metallic materials. The anvil is component of a USW machine and is located at the opposite side of the sonotrode, forming one wall of the welding room. An ultrasonic side slider is a device used to control the width of welding and can be positioned either over the sonotrode or above the anvil depending on the type of USW machine. The USW room can be described as a specific area designed for manipulating the materials and components that need to be welded. USW uses high frequency ultrasonic acoustic vibrations, applied locally to work pieces that are held together under pressure. When enough heat is generated from vibrations, the materials start to melt, and two parts of conductors are connected creating an aforementioned splice. In this type of welding process, it is important to emphasize that properties of metallic materials remain unchanged. There is no need for any adhesive, lubricant or similar material. Before starting the USW process, the machine must go through a learning process. In the case of new splice meant for production, it is important to check the following steps before the start of the USW process:

1. computer unit must be turned down,
2. turn on the switch,
3. press the switch (signal lamp lights up),
4. turn on the computer unit.

Figure 2 shows the position of the switch where the signal lamp is on during the learning process of the machine. Most machines have a learning process, and after welding is over, the welding process is saved to the software library for the next time when the same splice is needed for the wiring harness. Following that, the operator can select from the software any USW splice with already defined parameters for the welding process.

Figure 2. USW machine during learning process.

In the USW machine it is necessary to place conductors horizontally, from the largest to the smallest cross section, but only in the case where cross sections of conductors have different numerical values. In another case, if all conductors have the same cross section, it is only important to place them adequately which means that they must be in a horizontal position. After mounting the conductors in the USW machine, the conductors are pneumatically fixed. For a better understanding, an explanation on the basic concept and the geometry of a welded joint (i.e., splices) is necessary. Figure 3 shows the geometry of two welded wires, where A represents splice length, and B represents the part where some of the strands are outside the splice, and according to the experience from manufacture, the dimension of B is in the range 0-2 mm or it can be in the range 0-5 mm, C is distance from insulation and it can be within 1-5 mm. Parts of the strands should not be above recommended values, otherwise the isolation can fail. Dimension B as part on inline splice is in the range 0-2 mm, but as part of end splice it can be 5 mm maximum. Isolation is not allowed to be in the zone of welding, and any melting of the isolation is forbidden. Besides that, it is important to pay attention on the colour change of conductors, where blue colour makes them unacceptable for visual control.

Figure 3. Sizes of two welded wires: a) inline splice; b) end splice.

All strands of a conductor shall lie complete lengthwise in the welding zone. In order to avoid failure during ultrasonic welding, no missing strands, no loose strands or similar, from the conductor cutting and stripping process is not allowed. The final welding position distance is set according to individual requirements. For Cu conductors, the smallest allowed cross section is 0.8 mm^2 and maximal total cross section in a bundle should not exceed 200 mm^2. Also, conductors made of Al or its alloys should be at least 2.5 mm^2. It is very important that conductor insulation has a defined distance from the splice, otherwise during welding the heat can affect and change the physical properties of the insulation. During USW, the temperature of conductor insulation should not reach the flash point of the material. If signs of insulation melting occur, extra attention must be paid during welding, and the last resort welding process must be repeated. At the start of machine operation, it is necessary to make 3 splices of large cross section in order to achieve the appropriate operating temperature. In the wiring technology, two types of splices are recognised. In Fig. 4 these two types are shown: (1) end splice, and (2) inline splice.

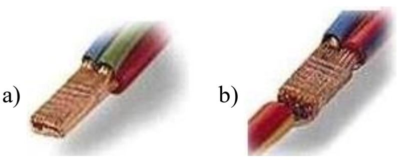


Figure 4. a) End splice, b) inline splice.

Due to technical issues, it is recommended that end splices should be created with no more than 6 individual cables, while for inline splices it is not allowed to weld together more than 5 + 5 individual cables. These recommendations are important to wiring harness designers during the design process. Another requirement refers to the cross section of splices where the:
- ratio between the thickest and thinnest wire must be 3:1 or smaller;
- ratio between the width and height of splice must be 1:1 in case of small splices from 0.70 mm^2 or smaller;
- ratio between the width and height of splice must be 2:1 in case of larger cross sections or smaller.

Inline splices can be symmetrical or asymmetrical. Figure 5 shows an example of symmetrical and asymmetrical connection. Symmetrical splices are made up of more than 3 cables with the same numerical value of total cross section. For example 3 conductors with cross section of 0.75 mm^2, 1.0 mm^2 and 1.5 mm^2 located on the left side, and on the right side of the splice, as shown in Fig. 5. Asymmetrical connection means that splice connection does not have the conductors with the same cross section on both sides.

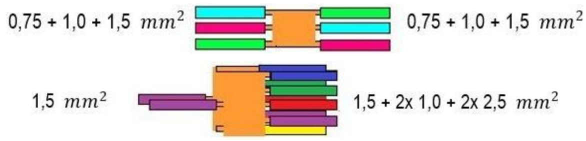


Figure 5. Symmetrical and asymmetrical connections for the inline splice.

Using adequate software, the operator selects the welding programme (example illustrated in Fig. 6). For this specific example the splice must be created from conductors of 3×0.75 mm^2 at the left side and 2×0.75 mm^2 from the right side. The screen shows the welding parameters. This specific splice is 5×0.75 mm^2, with a total cross section of 3.75 mm^2. Parameters already defined included pressure of 2.23 bar and the welding time of 301 ms.

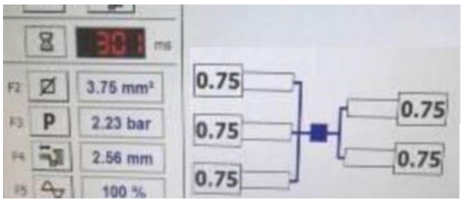


Figure 6. A selected USW splice from the software library.

REQUIREMENTS ABOUT CONDUCTORS

During USW, only approved conductors (cables, wires) can be used. Mostly conductors of FLRY type A and type B are approved for ultrasonic welding. Galvanised cables, or Cu cables with a layer of Sn on their surface cannot be used for USW. The storage time of coiled conductors should not exceed 8 months. The storage time of already catted materials should not exceed 8 weeks, and finally the storage time at already welded positions is maximum 8 hours. Cable insulation must be removed directly before use. Therefore, the principle of absolute purity must be respected. In case of dirty wires and cables it is necessary to clean and dry them. It should be emphasised that all strands of conductors have to be in the zone of welding which prevents the so-called ‘broom’ effect leading to a bad and inadequate splice. The cable with thickest individual wires should be on sonotrode and the weaker ones should lie down on the anvil side. All strands of the conductor shall lie completely lengthwise in the welding zone.

INSPECTIONS

General conditions for all tests are prescribed in the IEC 60512-1 standard, where ideal environmental conditions involve the range 15-35 °C, with relative humidity range 25-75 % and atmospheric pressure range 86-106 kPa. In practice it is very hard to provide all three parameters in the specified ideal limits. It is important that in all tests measurement reports are represent according to real conditions.

1-Visual optical inspection

Visual inspection is a very important inspection process in order to ensure the quality of components. All specimens have to be visually inspected, representing the first step in quality control. Visual inspection includes measurements of splice dimensions and the calculation of compaction ration (VUS) of the ultrasonic splice. First of all, it is necessary to calculate the ultrasonically welded cross section area:

$$A_{us} = 1_{us} \times 2_{us}, \tag{1}$$

where: A_{us} is splice area; 1_{us} is splice height; and 2_{us} is splice width.

The second parameter to be calculated is conductor area

$$A = \frac{n\pi d^2}{4}, \tag{2}$$

where: A is conductor area; n is the number of strands; and d is the diameter of each strand.

Compaction ratio (V_{us}) is calculated as follows:

$$V_{us} = \frac{A_{us}}{A} \times 100, \tag{3}$$

where: A_{us} is weld cross section area; A is the conductor area.

The degree of compaction ratio should be in the range 95-120 % for Cu wires, while for Al wires this range is 60-115 % according to IEC 60352-9:2024. In some manufacturing processes the compaction ratio (for Cu wires) is in the range 85-95 % as an ideal scenario. Visual examination of ultrasonic, end or inline splices, must be performed according to illustration given in Tables 1 and 2.

Table 1. Good welds for end- and inline splices.

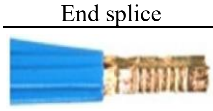
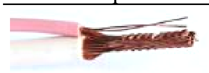
End splice	Inline splice	Comment
		Correct and good weld
		

Table 2. Errors of end- and inline splices.

End splice	Inline splice	Description
		Strands are out of splice
		Isolation is in splice area
		Cables are too close to splice
		Cables are too far away from splice
		Splice is burned out
		Insufficiently welded conductors

2- Bending test

According to IEC 60352-9:2024 the splice is in the fixed position and cannot be moved. The top red wire must bend twice at a 90° angle and then is returned to its original position with an actuation point 30 mm away from the splice. The bending test must be done in the case of terminal and wire, where the metal terminal is in a fixed position and the top wire again must be bent twice at a 90° angle and then returned to its original position with actuation point 30 mm away from metal terminal. Two main requests must be met:

- no strands of conductors shall break at the transition to the welding zone;
- no strands shall become loose at the welding package.

Figure 7 shows examples of bending setup with fixed splice and ultrasonically welded wire to metal terminal.

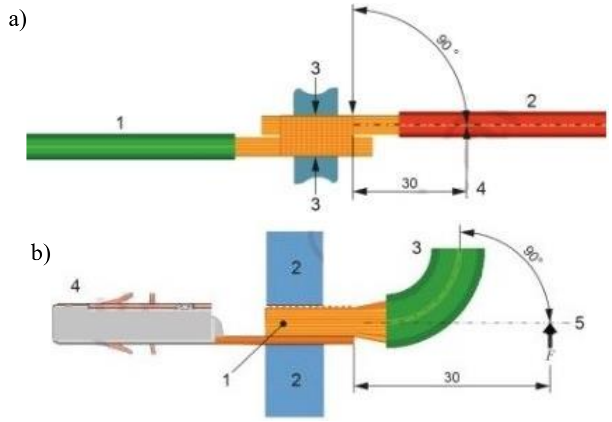


Figure 7. Schematic bending test setup: a) fixed splice between two wires (1 - first wire, 2 - second wire, 3 - fixation, 4 - actuation point); b) fixed welded package between wire and metal terminal (1 - weld package, 2 - fixation, 3 - wire, 4 - metal terminal, 5 - actuation point).

3- Pull test

In order to check the archived connection strength of ultrasonically welded inline splice, the pull-out force method is an officially adopted method according to IEC 60352-9:2024, but also in the manufacturing process (illustrated in Fig. 8) the pull-out force method should be performed with a speed of 50 ± 5 mm/min. It is important during the clamping of the wires; the wires must be aligned so that no bending moment can affect the measurement results.

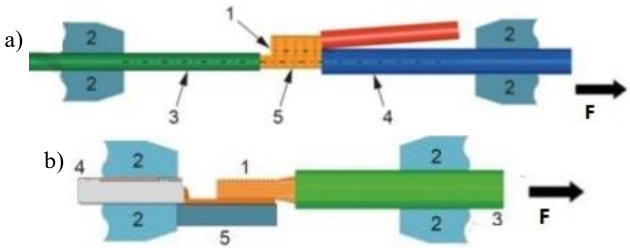


Figure 8. Schematic test setup for pull-out force test (1 - splice, 2 - fixations, 3 - wire type 2, 4 - wire type 2, 5 - tensile axis): a) pull-out force test for splice; b) pull-out force test for connection between wire and metal terminal (1 - weld package, 2 - fixations, 3 - wire, 4 - metal terminal, 5 - terminal support).

This test should be performed be according to IEC 60512-16-4 standard.

The diagram of recommended minimum pull-out force compared to cross-section values is shown in Fig. 9. The first curve shows dependency for Cu wires, and the second curve represents the dependency for Al wires.

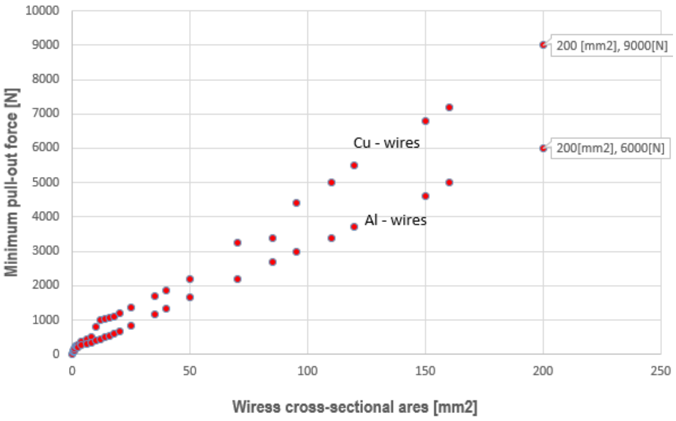


Figure 9. Dependency diagram of pull-out force and conductor cross sections for Cu- and Al wires.

4 - Peel test

The peel test is also a very important method for testing splice connections or the welded package. This test must be done according to ISO 10447 standard and according to the setup shown in Fig. 10.

In the case for splice between conductors peel testing, it is recommended that the smallest conductor cross section area shall be checked, where selected wires at the splice with strands must be lying on the anvil side package surface. It is important to emphasize that the cross section area of the second conductor has to be larger than the conductor to be tested, and if it is necessary, a combination of several conductors can be combined and fixed. In case of peel testing for a connection between conductor and metal terminal, it is recommended to use material with cross section areas up to 35 mm^2 and the test must be performed with pulling speed of 50 ± 5 mm/min the same as the pull testing of the splice. Recommended values for peel force are shown in Fig. 11, depending on conductor cross section, both for Cu and Al conductors.

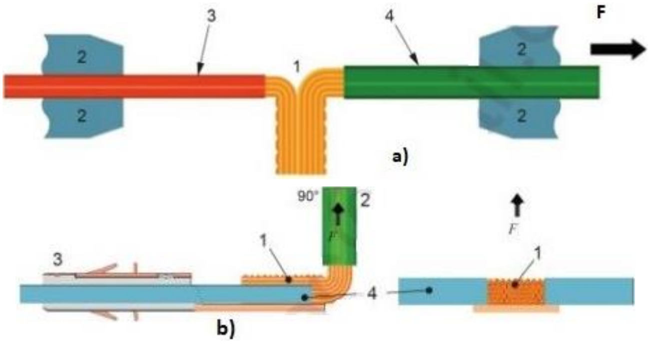


Figure 10. Schematic test setup for peel test: a) peel test for splice (1-splice, 2-fixation, 3-conductor 1, 4-conductor 2); b) peel test for connection between wire and metal terminal (1-ultrasonically welded package, 2-wire, 3-metal terminal, and 4-fixations).

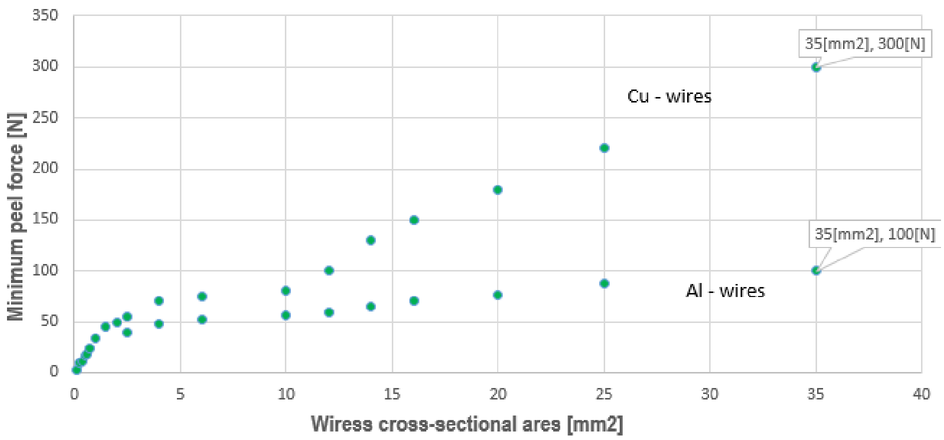
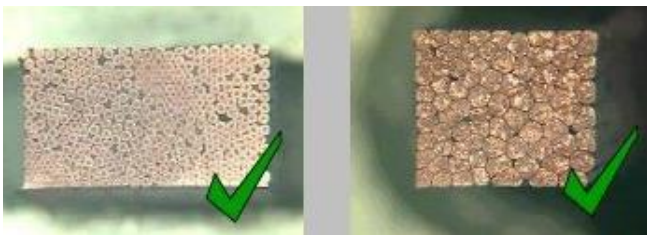


Figure 11. Dependency diagram of peel force and conductors cross section for Cu wires and Al wires

5 - Microsection image inspection

This type of inspection provides the analysis of welding splice image. Microsection analysis is also known as cross section analysis. Using this method the quality of welds can be seen, detected, and evaluated. This is a destructive method of analysis that measures splices. Microsection should be performed at the position of the highest compression, mainly in the middle part of the splice. During microsection image analyses no contiguous spaces shall be visible. This means that all strands must be mechanically connected to other surrounding wires. During the UWS process, the cutting edge can be part of the weld, and it is expected that the cutting edge exists in minimal tolerance. For the largest cross section of individual wire, maximal height is 0.5 mm and the width is 0.2 mm. Every deviation above this tolerance for the cutting edge can indicate wrong settings or installation of tools or problems with the ultrasonic welding machine. Figure 12 represents how the cross section looks like with and without the cutting edge. Individual wires outside of the welded joint are not allowed. All individual wires must completely be part of welds. Suitable software for microsection inspection can show dimensions of splices. An example is given in Fig. 13. Blue lines show indications of the tolerance field, where a measured height value 0.715 mm is in the tolerance field, but also it can be visually concluded that second measured height value of 0.991 mm is out of tolerance range.



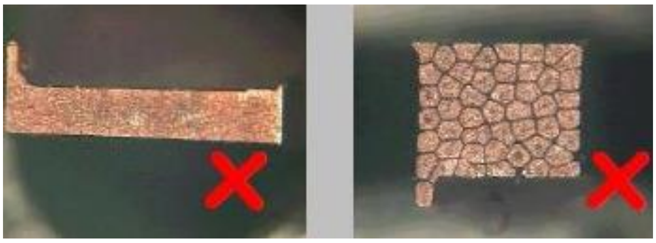


Figure 12. Microsection representation of welds with and without cutting edge.

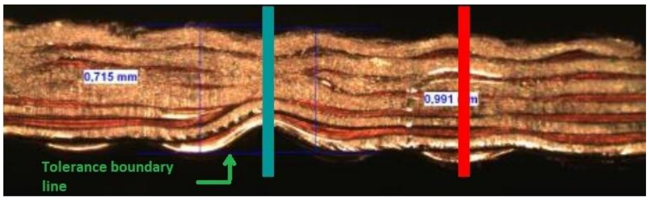


Figure 13. Example of weld (side view) with dimensions using microsection inspection.

Also, in some specific cases before the start of USW, the shrink tube must be put on cables (wires, conductors) but also the shrink tube can be put on slice after the welding process during the final assembly of wiring harness.

CONCLUSION

Expected increasing number of electrical vehicles in the future suggests that the wiring harness manufacturing technology will be more popular, therefore, the USW process is going to be used more than nowadays.

According to the latest standard for the solderless connection IEC 60352-9 and practical experience in the manufacture of wiring harness, a general concept of USW machine is represented, as well as parts of the several procedures, methods of testing etc. USW process discussed in this paper is applicable to Cu wires or its alloys, as well as Al or its alloy.

There are lots of advantages of USW. Firstly, it is a fast process, during welding deformations are kept to minimum, welded joints (splices) made by this method are very clean and precise. USW equipment is safe to operate with and potential injuries that can occur are not that serious, etc. This welding process is very cost-effective because scrapping is kept to a minimum, highly precise, etc.

Further steps of this research will involve the investigation on USW parameters for specific conductors with a special focus on mechanical properties.

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