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Strength of copper wire connections welded by ultrasonic

T. Kuprys*, J. Janutėnienė, R. Didžiokas****
**JSC "Phillip Morris Lietuva", Vilniaus plentas 16, 94104 Klaipeda, Lithuania, E-mail: kuprys@gmail.com*
***Klaipėda University, Bijūnų str., 92294 Klaipėda, Lithuania, E-mail: mechjtfku@mail.lt*

1. Introduction

Ultrasonic welding is a technological process to get permanent connections. Mostly it is used to weld non-ferrous metals like a copper. The technology of ultrasonic welding is used in various areas but mostly in electronics, electrics industry and automotive industry. Safety requirements for cars constantly grows, accordingly grows the requirements for copper wires used in cars. The set of wires is stronger, cheaper and lighter compared to a single wire. The problems of ultrasonic welding are investigated in the works [1-6]. In the work [1] the welding characteristics of thin coated copper wires are studied using 40, 60, 100 kHz ultrasonic vibration welding equipment. Polyurethane coated copper wires and copper plates are used as welding specimens. A part of copper wire is completely welded on the copper substrate and insulating coating material is removed from the welded area of the wire specimens by high frequency vibration.

The characteristics of aluminum and stainless steel plates welded by ultrasonic method are studied in the work [2]. The specimens without special surface treatment are joined by ends with the welding seam strength of 100 MPa. It is defined that the hardness of stainless steel increases by approximately 20% near the welded surface.

In the work [3] the characteristics of aluminum and copper plate specimens welded by ultrasonic method are studied. It is shown that plates of various thicknesses can be welded with large welding areas and high welding seams strengths independently of the welding positions and directions. Aluminum-copper and copper-copper plate specimens were welded with the strength of welding seams almost equal to the specimen strength.

Microstructure and mechanical characteristics of ultrasonically welded AA6111-T4 specimens are investigated in work [4]. The impact of welding time on the mechanical characteristics of welded connections is defined. A longer welding time results in a more even welded connection, higher yield limit and higher fracture strengths. Accordingly the metal fatigues characteristics of the welded specimens with longer welding time are improved.

In the work [5] the modification of ultrasonic welding equipment for the thin plates welding is presented. The research results were used for aluminum and copper plates welding. Using ultrasonic energy it is possible to weld several elements at one time [6]. Ultrasound effects on tensile strength and solid state reaction mechanism studied in the work [7]. The possibility to use copper wires with very small diameter (less than 38 μm) is investigated. It is found that cooper wires with very small diameters theoretically can change gold and silver wires.

Sound waves and high frequency vibrations are present in ultrasonic welding. Therefore ultrasonic welding can be used for the welding of the metals with different melting-points. The technology of ultrasonic welding is superior by quality of welding and price. Ultrasonic welding is used in the production of the vehicle wire also. The requirement for quality and reliability of the vehicle is still growing. One of the main characteristic of the reliability of the vehicle is light and mechanical strength wire array. The results of tensile testing of the ultrasonically welded connections are presented in this work. The strength of ultrasonically welded copper connection depends on wires preparation before welding and their number in the connection.

2. Testing procedures of ultrasonically welded connection

Mechanical vibrations in metals during ultrasonic welding propagate in horizontal direction. The ultrasonically welded connection of copper wires is presented in Fig. 1. The ultrasonic welding process runs due to static force, shear forces due to vibration and temperature in the welding zone. These factors depend on the thickness of welding layers, surface condition and mechanical properties of welding materials. Mainly the frequency of vibration (work frequency) is about 20 kHz.

The insulation must be removed from wires before welding. Looking through microscopes some filaments of the insulation after its remove were noticed on the surface of wires.

During welding process the filaments melt and adhere in to the connections. Therefore the strength of ultrasonically welded connections of copper wires declines

Fig. 1 The ultrasonically welded copper wires

Table

Data of the tested ultrasonically welded connections

Connection sign	Total area of connection, mm^2	Composition		Number of wires
		Wires in left part	Wires in right part	
1.4	1.4	0.35	0.35+0.35+0.35	4
1.9	1.9	0.5	0.35+0.35+0.35+0.35	5
2.0 I	2.0	0.5	0.5+0.5+0.5	4
2.0 II	2.0	0.5	0.5+1.0	3
2.4	2.4	0.5+1.4	0.5	3
3.0 I	3.0	0.75+0.75+0.75	0.75	4
3.0 II	3.0	0.35+0.35+0.35+0.35+0.75	0.5+0.35	7
3.4	3.4	0.5+1.4	0.5+0.5+0.5	5
6.45	6.45	0.35+0.35+0.35+0.35+0.35+0.5+0.5	1.0+0.35+0.35+2.0	11
7.0	7.0	2.5	0.75+0.75+3.0	4
8.0	8.0	3.0	2.0+3.0	3
10.1	10.1	0.5+1.4+2.0	0.35+0.35+0.5+5.0	7
10.7	10.7	0.35+4.0	5.0+0.5+0.5+0.35	6
15.4	15.4	7.0	1.4+2.0+5.0	4
25.0	25.0	5.0+5.0+10.0	5.0	4

and that is a negative factor. Therefore additionally the wires were cleaned by compressed air (5-6 bars).
The tensile test has been done for two cases:

1) the wires were cleaned only mechanically,
2) the wires additionally were cleaned by compressed air (5-6 bars).

Fifteen different compositions of ultrasonically welded connections of cooper wires were tested. The connections were different by the composition of wires, by cross-section areas and by total perimeter of wires in the connections. The experiments were performed by tensile machine "Mecmesin AFG 1000N", and the speed of machine was 50 mm/min (tolerance max + 5 mm/min). Thirty specimens of each connection were tested and the tensile forces were measured when the connections broke.

Based on the testing results the following characteristics were calculated:
mean

$$X_m = \frac{1}{n}\sum_{i=1}^{n} X_i$$

Dispersion

$$S^2X = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - X_m)^2$$

standard

$$SX = \sqrt{S^2X}$$

coefficient of variation

$$\delta X = \frac{SX}{X_m}\cdot 100\%$$

here n is the number of tensile experiment, X_i is the result of experiment.

The data of tested connections is presented in Table.

3. Results of experiments

The results of the tensile test are presented in the Figs. 2, 3 when the wires were cleaned only mechanically. Next group of the wires was cleaned additionally by compressed air. Tensile test results of experiments are presented in Figs. 4, 5.

For comparison the results of tensile test of connections with the same size of cross section but different numbers of wires in the connection are presented and Figs. 2 and 3.

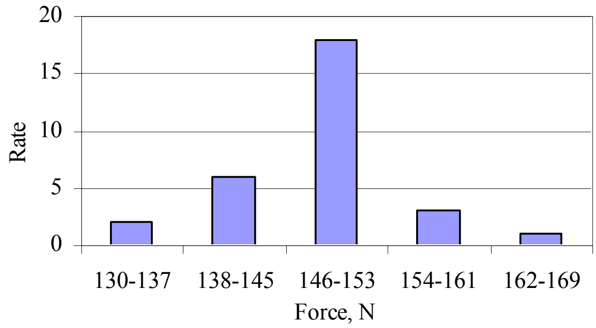

Fig. 2 Results of tensile test of connection 3.0 I

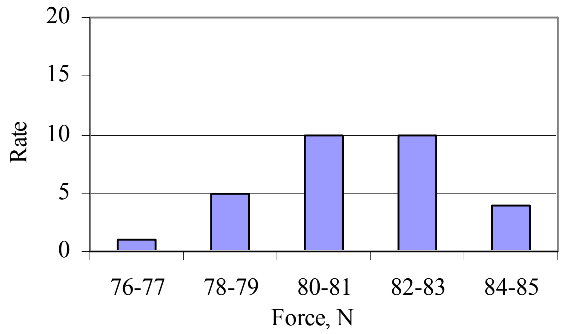

Fig. 3 Results of tensile test of connection 3.0 II

The results of tensile test for ultrasonically welded connection cleaned only mechanically may be rated as sure, because the coefficient of variation (fracture) of the tensile force is less than 5-6 percent.

Mechanical strength of ultrasonically welded connection depends not only on the cross-section of connection but also on the number of wires and their composition in connection.

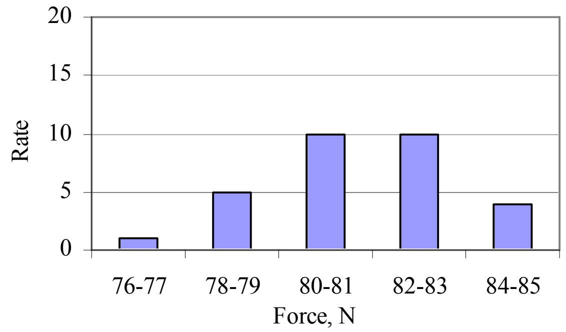

Fig. 4 Results of tensile test of connection 3.0 I

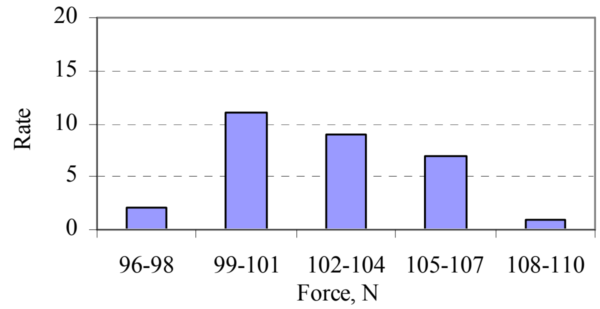

Fig. 5 Results of tensile test of connection 3.0 II

Obviously, the strength of ultrasonically welded connection is higher when the wires additionally were cleaned by the compressed air. The tensile force is higher aproximaltelly by 13 - 35 percent, when the connection consists of greater number of the wires. Linear dependence of tensile force on cross-section of the connection is deduced (Fig. 6)

$$y = 7.19x + 95.76 \quad (1)$$

$$y = 7.48x + 79.78 \quad (2)$$

where y is tensile force, x is cross-section of the connections, R^2 is squared value.

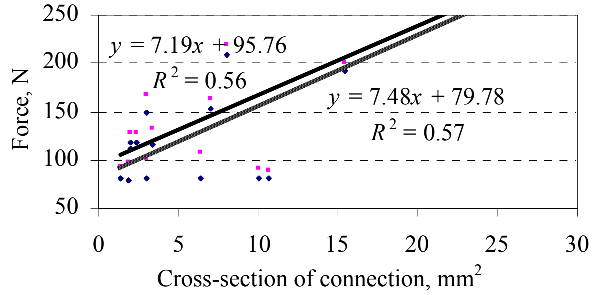

Fig. 6 Linear dependence of tensile force on cross-section of the connection

The ratio of perimeter and cross-section of the wires in connection is calculated. The following ratios specify the influence of the number of wires for strength. The linear regression is obtained between the ratio (perimeter and cross-section of the wires in connection) and mean of tensile force in connection (Fig. 7).

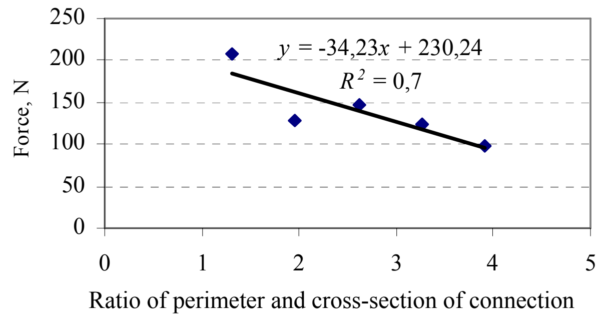

Fig. 7 Relationship between the ratio perimeter / wires cross-section and the average of tensile force

The tensile force of connection has grown up when the wires were additionally cleaned by compressed air. The linear dependence (Fig. 8) from the change of tensile force and the ratio perimeter / cross-section is derived:

$$y = -34.23x + 230.\ 24 \quad (3)$$

The sum of perimeters of all the wires in connection is calculated. The results are separated in to 5 intervals.

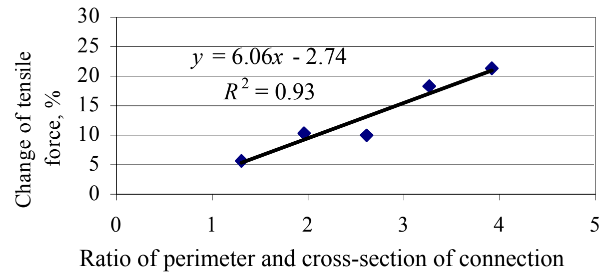

Fig. 8 Relationship of tensile force change and the ratio perimeter / wires cross-section in connection

The results of tensile test are more stable in case when the wires are additionally cleaned by the compressed air.

The distribution of tensile test results in case of additionally cleaned wires is approximately 16% less than in the case of only mechanically cleaned wires. Therefore the conclusion may be done – additional cleaning of the wires by compressed air allows to achieve more stable results of the tensile test for ultrasonically welded connections.

4. Conclusions

1. The obtained rezults of tensile test of ultrasonic coper wires welding are stable. The variation coefficient does not vary more than 5 percent.

2. The ultrasonically welded connection of copper wires sustain the greater tensile force when the wires are aditionally cleaned by compressed air. The strength of

ultrasonic connection in that case grew up by 13-35 percent.

3. Composition of the wires and their number in the connection has an influence on the strength of ultrasonic connection of copper wires. It is possible to calculate the strength of ultrasonic connection using formula $y = -34.23x + 230.24$.

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T. Kuprys, J. Janutėnienė, R. Didžiokas

ULTRAGARSU SUVIRINTŲ VARINIŲ JUNGČIŲ STIPRUMO TYRIMAS

R e z i u m ė

Straipsnyje nagrinėjama, kaip ultragarsu suvirintų varinių jungčių stiprumas priklauso nuo laidų išorinio paviršiaus paruošimo suvirinimui. Eksperimentai atlikti naudojnt ultragarsu suvirintas varines jungtis, besiskiriančias laidų skaičiumi ir jų kombinacija. Nustatyta, kad prieš ultragarsinį suvirinimą nuvalius nuo laidų izoliacines medžiagas, lieka nedidelių izoliuojančių medžiagų plaušelių, kurie mažina suvirintos jungties stiprumą. Eksperimentai atlikti vienu atveju nuvalius laidus tik mechaniškai, kitu – papildomai nupūtus suspausto oro srove. Papildomai nuvalius jungtis prieš suvirinant, jungčių stiprumas padidėja iki 35 procentų. Tai ypač akivaizdu, kai jungtis sudaryta iš daug laidų. Atlikus eksperimentinių tyrimo rezultatų analizę, nustatyta jungčių trūkio jėgos priklausomybė nuo jungtyje esančių laidų perimetro bei ploto santykio. Gauti tyrimų rezultatai gali būti sėkmingai taikomi ultragarsu suvirintų varinių jungčių kokybei gerinti.

T. Kuprys, J. Janutėnienė, R. Didžiokas

STRENGTH OF COPPER WIRE CONNECTIONS WELDED BY ULTRASONIC

S u m m a r y

The results of tensile test of ultrasonically welded connections of copper wires are presented in this article. The connections differ by the number o wires in the connection and also by the combination of wires number at the different sides of connection. The dependence of tensile test results on surface preparation of the wires is settled. When the wires are cleaned from the insulation only mechanically small fibers of insulation remain on the surface of the wires. Those fibers reduce connection strength. Additional cleaning of the wires by compressed air before welding increases the strength of connection up to 35 %. The influence of additional cleaning is especially obvious for connections with large number of wires. The analysis of experimental results is done and the dependence of fracture force on the ratio of perimeter / welded connection area is derived. With reference to the results of tensile tests the suggestion for quality development of ultrasonic welding of copper wires is proposed.

Т. Куприс, Й. Янутене, Р. Диджиокас

ИССЛЕДОВАНИЕ ПРОЧНОСТИ МЕДНЫХ СОЕДИНЕНИЙ, СВАРЕННЫХ УЛЬТРАЗВУКОМ

Р е з ю м е

В статье представлены исследования прочности сваренных ультразвуком медных соединений, в зависимости от приготовления поверхности проводов перед сваркой. Эксперименты проведены с соединениями из медных проводов, сваренных ультразвуком, которые отличаются разным количеством проводов в соединении и комбинацией. Установлено, что после механического очищения проводов от изоляции на поверхности остаются их мелкие частицы, которые понижают прочность соединения. Эксперименты проведены очистив провода от изоляции только механически в одном случае, а в другом случае - дополнительно сжатым воздухом. Дополнительное очищение сжатым воздухом повышает прочность соединения до 35 процентов. Это очень характерно в том случае, когда соединение состоит из большого числа проводов. После анализа результатов эксперимента установлена зависимость силы прочности соединения от отношения периметра и сечения проводов. Полученные результаты могут быть применены для улучшения качества сварных медных соединений.

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