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QUALITY ANALYSIS OF Al-Cu JOINT REALIZED BY FRICTION WELDING

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Original scientific paper

This paper outlines the bases of the friction welding process, especially when it comes to friction welding of different materials. This was illustrated on an example of friction welding of aluminum and copper, which is often applied in electrical engineering. The analysis of influential parameters was conducted based on the data obtained by an experiment, since the data on this topic are very seldom in the available literature.

Keywords: *friction welding, base metal, aluminum, copper, friction time, friction pressure, compression pressure*

Analiza kvalitete Al-Cu spoja ostvarenog zavarivanjem trenjem

Izvorni znanstveni članak

Ovaj članak daje osnove procesa zavarivanja trenjem, naročito kada je u pitanju zavarivanje trenjem različitih materijala. To je ilustrirano na primjeru zavarivanja trenjem aluminija i bakra, koji se često primjenjuje u elektrotehnici. Analiza utjecajnih parametara provedena je na temelju podataka dobivenih eksperimentom, jer su podaci o ovoj temi vrlo rijetko u dostupnoj literaturi.

Ključne riječi: *zavarivanje trenjem, osnovni metal, aluminij, bakar, vrijeme trenja, tlak trenja, tlak kompresije*

1 Introduction
Uvod

In modern industrial practice there is often the need for joining two completely different metals. Copper and aluminum are metals of high electrical and thermal conductivity, thus they have common application as cables, elements of cooling and heating engineering, civil engineering accessories. That is why it is necessary to join together Al and Cu very often. This is for example joining of copper and aluminum conductors or cable ends. There are several ways to join aluminum and copper: with addition of material (soft and hard solders) and without addition of material (electricity resistance-, cold-, friction-, explosion-, ultrasonic welding).

This paper outlines the friction welding procedure of copper and aluminum parts. Experimental part refers to the quality assessment of realized bimetal joint based on mechanical and micro structural tests.

2 Basic principles of the friction welding process
Temeljni principi procesa zavarivanja trenjem

Friction welding is the procedure of joining metals in solid state, because the welded joint is formed at the temperature that is lower than the melting temperature of the base metal that melts more easily. The essence of the process is transformation of mechanical energy into the heat, which gets released as the result of friction at the joint i.e., in the contact zone. The thin layer of the zone next to the contact line heats up and turns into a plastic state, with action of a pressure force, thus one actually gets the forge welding. The heat developed on the contact surface of the welded parts depends on the compressive force and the friction coefficient of the rotating parts.

The basic advantage of the friction welding is that it can be applied to mutual joining of metals with different mechanical and thermo-physical properties. In addition, it is very often the only possible way of joining some metals, which during welding by other methods form the inter-metallic brittle phases. The process itself and joint formation mechanism in solid state are very complex. There are several hypotheses that describe the process, starting from different assumptions, but none of them can give the full explanation for numerous phenomena that accompany this process. Essentially, all researchers agree that the process of joining in solid state is based on formation of metal bond (solid solutions) between components of the base metals. Such a bond occurs during closing of metal clear surfaces to the distance of the order of magnitude of crystal lattice parameters. Since metal surfaces of real metal pieces are not ideally smooth, the contact at the start of welding will be realized only on the peaks of wavy surfaces. The increase in the surface of the contact can be achieved by plastic deformation of coupled peaks. When the peaks are fully compressed, the boundary surfaces approach to the order of magnitude of crystal lattice parameters, so bonds that enable formation of mutual crystal lattices occur.

Technological time sequences during friction welding of Al and Cu are shown in Figure 1.

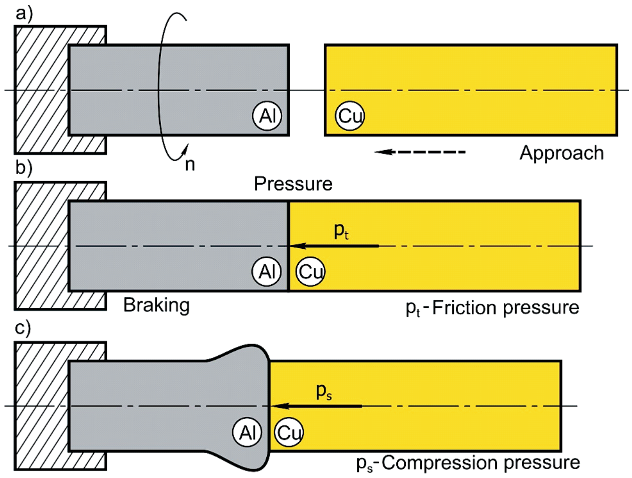

Figure 1 *Technological time sequences during friction welding of Al and Cu* [3]
Slika 1. *Tehnološki slijed tijekom zavarivanja trenjem Al i Cu* [3]

In the course of the friction welding process, the aluminum working object was rotating, and the copper object was steady in the beginning, and then it axially moved until it came face to face with the rotating Al-piece (Figure 1.a). That is when the friction starts affecting together with the heat release, the largest one being during the maximum friction pressure p_t, when conditions for realization of joint are acquired (Figure 1.b). In the next phase, the rotation of the rotating part (element made of Al) stops, and because of action of compression pressure p_s, maximum plastic deformation is achieved (Figure 1.c). Therefore, the drawing down of material that became plastic occurs, so a rim of the squeezed material forms along the perimeter of the joint that is the so-called "mushroom" (Figure 3). Solid joint is obtained after cooling. The pressure variation with welding time is shown in Figure 2.

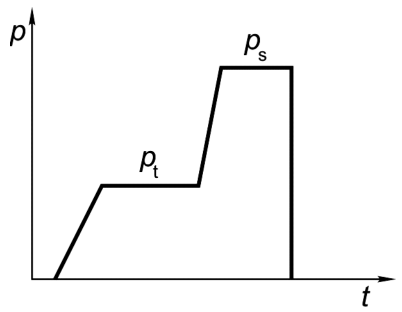

Figure 2 *Pressure variation during friction welding*
Slika 2. *Varijacija tlaka tijekom zavarivanja trenjem*

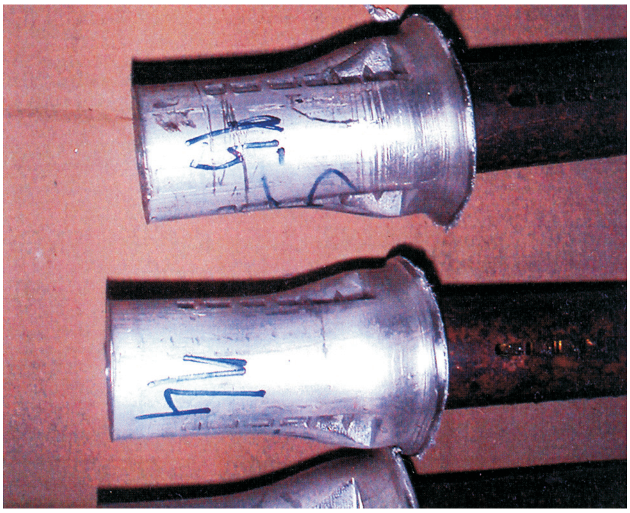

Figure 3 *Samples welded by friction* [7]
Slika 3. *Primjeri zavareni trenjem* [7]

3 Metallurgic processes in aluminum and copper joint zone
Metalurški procesi u području spoja alumunija i bakra

In analysis of the friction welding process of aluminum and copper, one must start from micro structural changes during heating, and then consider what takes place during cooling. The essence of this problem can be understood in a better way by means of equilibrium binary state diagram of Al-Cu (Figure 4). Aluminum-copper alloys on the aluminum side solidify as binary system with eutectic that contains 33 % of Cu, and consists of copper solid solution crystals α and brittle inter-metallic phase Al_2Cu (θ). One should keep in mind that copper, as alloying element, significantly increases aluminum resistance properties. For example, alloy that consists of 1 % of Cu, and the rest of Al, has hardness for some 5 % higher than technically pure aluminum.

Aluminum alloys can be divided into forging and casting ones. Practically, forged aluminum alloys contain up to 5,5 % of copper, and alloys for casting up to 16 % of Cu.

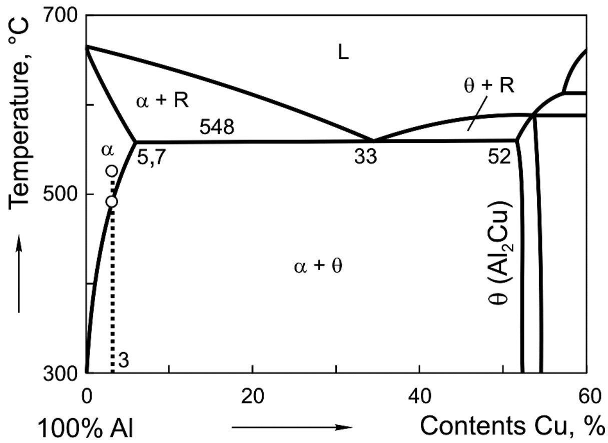

Figure 4 *Equilibrium constitution diagram of Al-Cu* [1]
Slika 4. *Dijagram uspostavljanja ravnoteže Al-Cu* [1]

Take for example alloy with 3 % Cu content (Figure 4) that has heterogeneous structure at the room temperature (α solid solution and inter-metallic phase θ (Al_2Cu)). The content of this phase extracted along the boundaries of α grain, grows with approaching to the maximum solubility of copper at α phase (5,7 %) [1].

Friction welding assumes joining of forging alloys of Al at the temperature below aluminum melting point (660 °C) but often above eutectic melting point (Al_2Cu, 550 °C), which is a very narrow temperature interval, so it can come to partial melting and occurrence of brittle phases.

Depending on the conditions (selected parameters) of friction welding, diffusion takes place during the process so at the distance of some 1 μm θ-phase occurs, and at the width of more than 5 μm of the phase Al_2Cu and Al_4Cu_9 [2].

Brittle phases are hazardous by its nature, so it is necessary to conduct the corresponding thermal treatment so that they do not occur or get dissolved. The aspect of thermal processing depends on to what extent one should reduce the hardness of brittle phases. On principle, one can recommend the heating at 300-400 °C for a relatively longer time interval, so as to create the conditions for equilibrium taking place of brittle phases transformation [5].

The copper content in α-solid solution at eutectic temperature of 548 °C is 5,7 % and only 0,1 % at the room temperature. The variable solubility with temperature drop creates the condition for forming of supersaturated solid solution of copper in aluminum during fast cooling from α-area. During a course of time, fine dispersed particles are extracted from that solution which results in reinforcement of the alloy (natural ageing) [4]. The reinforcement process can be significantly accelerated by subsequent heat treatment.

4
The experiment
Pokus

4.1
Base metal
Osnovni metal

Aluminum belongs to the group of light non-ferrous metals. Its density is 2,7 g/cm^3. The melting temperature is 660 °C. Metallurgic (technically) pure aluminum has purity of 99,5 % and it differs from chemically pure aluminum by its properties (99,99 %). Technically pure aluminum is applied in practice, and chemically clean aluminum is used for parts that operate in very corrosive environment.

Aluminum has extraordinary corrosion resistance owing to surface oxide Al_2O_3, (natural one or obtained by anodizing treatment), it is further distinguished by good workability by deformation, but has the small strength. The tension strength depends on the purity and it is 70-100 MPa, and hardness is 15-25 HB.

This metal has cubical crystal lattice centered on the surface, which stays all until the melting temperature, which means that it is not subject to allotropy. It is distinguished by high electrical and thermal conductivity, which makes it suitable for application in electrical engineering.

Copper is a reddish-colored metal and it is not magnetic. It belongs to the group of heavy metals, with specific mass of 8,96 g/cm^3. Copper melting temperature is 1083 °C.

Copper has the cubic crystal lattice centered on the surface, which has no property of allotropic modifications, i.e. cubic lattice centered on the surface does not change until the melting temperature.

Technically clean copper contains from 99 to 99,75 % of Cu and it is grouped in 4 groups, and electrotechnically clean copper contains from 99,9 to 99,99 % of Cu.

Mechanical properties of copper depend on the state of delivery, that is, on previous mechanical and thermal treatment. Tensile strength in the cast that is annealed state is 200-250 MPa, hardness 45-60 HB whereas in deformational reinforced state the strength grows to 400-500 MPa, hardness to 90-110 HB, and dilatability drops from 50 % to 2-6 %. Copper is very plastic material, so it is suitable for processing by deformation both in cold and hot state (at 680-780 °C).

Samples for friction welding (technically pure Al 99,5 and electrotechnically pure Cu 99,95) are made in cylindrical shape, with dimensions given in Figure 5.

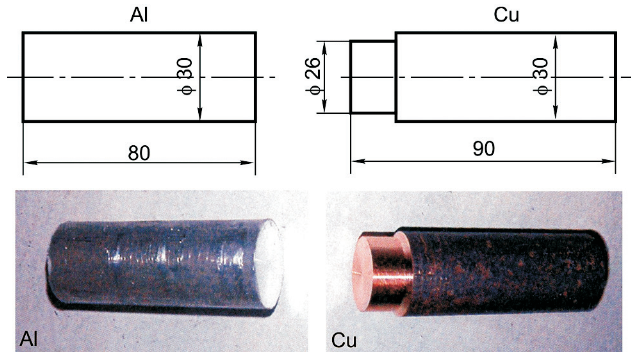

Figure 5 *Initial dimensions of samples made of Al and Cu for friction welding* [7]
Slika 5. *Početne dimenzije Al i Cu uzoraka za zavarivanje trenjem* [7]

Technological parameters of experimental friction welding were:

- No. of revolutions $n = 2500$ rpm,
- welding time $t = 4\text{-}15$ s,
- friction pressure $p_t = 50$ MPa,
- compression pressure $p_s = 150$ MPa.

4.2
Determining the size of permanent deformations
Određivanje veličine trajnih deformacija

Bearing in mind that different deformations of coupled parts occur during friction welding of aluminum and copper, both in radial and axial direction, it is necessary to know dimensional changes during friction time out of structural reasons.

Table 1 shows the results obtained by measuring of the initial and final dimensions of aluminum and copper samples welded by friction. The following dimensions were determined (in mm):

- L – initial length of Al and Cu parts,
- L_1 – the length of the same parts after welding,
- L_{1u} – total length of the welded sample,
- ΔL_1 – shortening of Al and Cu parts after friction welding
- ΔL_{1u} – total shortening of the welded sample.

The measuring results (Table 1) show that the shortening of aluminum part is much bigger than the shortening of copper part; depending on the welding parameters those differences even reach relations 10:1.

Table 1 *Change of length of Al and Cu samples during friction welding* [7]
Tablica 1. *Promjena duljine uzorka od Al i Cu tijekom zavarivanja trenjem* [7]

Friction time	Initial dimensions		Values measured after friction welding					
t, s	L, mm		L_{1u}, mm	L_1, mm		ΔL_1, mm		ΔL_u, mm
	Al	Cu		Al	Cu	Al	Cu	
4	80,4	90	161,2	72,3	88,9	8,1	1,1	9,2
5	79	90,2	157,6	68,7	88,9	10,3	1,3	11,6
6	79,2	90,4	156,2	67,5	88,7	11,7	1,7	13,4
7	79,2	90,3	155	65,9	89,1	13,3	1,2	14,5
8	79	90,2	154,3	65,8	88,5	13,2	1,7	14,9
9	80	90,1	154,4	65,9	88,5	14,1	1,6	15,7
10	90,2	90,1	154,2	66	88,2	14,2	1,9	16,1
11	80	90,2	152,9	65	87,9	15	2,3	17,3
12	79,1	90	150,6	64,2	86,4	14,9	3,6	18,5

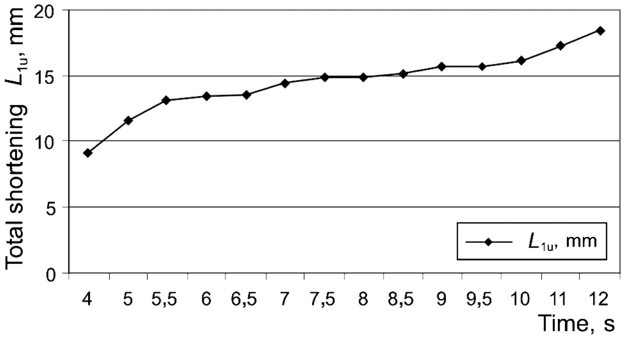

***Figure 6** Diagram of total shortening of the welded samples*
***Slika 6.** Dijagram ukupnog skraćenja zavarenih uzoraka*

Deformations in radial direction are difficult to follow because the "mushroom" is formed on the face side of aluminum element. In friction welding process, softened aluminum layers are extruded from friction plane towards periphery so big "mushroom" is formed, which is partially transformed to the face side of copper as well along the full perimeter. The diameter of the festoon rises in accordance with prolongation of welding time.

4.3
Tensile test of the Al-Cu welded joint
Ispitivanje vlačne čvrstoće zavarenog spoja

In favor of more complete assessment of properties of the welded joint obtained by friction, tensile test was performed. Disproportional, that is, "technical test tubes" made of the welded Al-Cu samples were used. Table 2 shows the test results of base metals and heterogeneous welded joints.

On samples welded by friction, the tearing mostly occurred on aluminum part or in joint area of Al-Cu.

4.4
Hardness test of the Al-Cu welded joints
Ispitivanje tvrdoće zavarenih šavova Al-Cu

Temperatures up to 500 °C develop in the contact area during friction welding of copper and aluminum. Homogeneity of the welded joint can be assessed by measuring hardness along the joint longitudinal axis. Samples for measuring of hardness in the direction that is transversal to the contact surface i.e. along the joint axis are shown in Figure 8. The measuring points are arranged in the manner that you start from copper then go into metal of the welded joint and go on to aluminum and all this in three directions (Figure 9): direction (I) matches the axis of the welded sample, direction (II) is 2 mm away from the axis and direction (III) is 6 mm away.

It can be noticed that longitudinal allocation of hardness is almost independent on the measuring position (I, II, III).

Thermal processes in the contact of Cu and Al during friction welding, and then cooling depend on the achieved temperatures in the contact area. If in some points of the contact, the temperature exceeds 660 °C, the local melting of aluminum will start, which leads to intense diffusion of Cu through local cast. This creates favorable conditions for occurrence of brittle intermetallic phases, hardness growth in HAZ, on the side of aluminum part of the welded joint (Figure 9) [6].

***Table 2** Tensile strength of base metals and samples welded by friction*
***Tablica 2.** Ispitivanje vlačne čvrstoće osnovnih metala i uzoraka zavarenih trenjem*

Time, s	Al/Cu	4	6	7	8	9	10	12
R_m, MPa	75/220	61	69	72	85	83	81	75
Tearing point	BM	joint	joint	Al	Al	Al	joint	Al

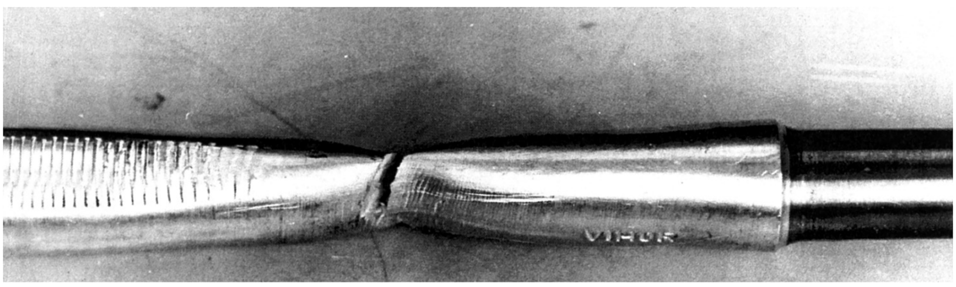

***Figure 7** Breach of Al-Cu test tube during tensile test*
***Slika 7.** Lom Al-Cu epruvete tijekom ispitivanja vlačne čvrstoće*

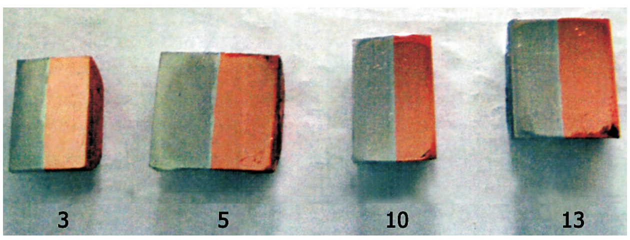

***Figure 8** Welded samples of Al-Cu intended for hardness test*
***Slika 8.** Zavareni uzorci od Al-Cu za ispitivanje tvrdoće*

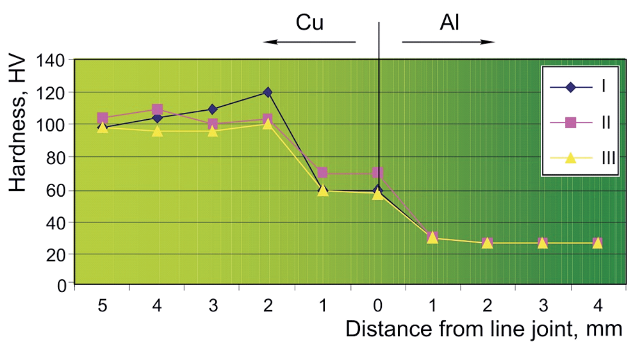

***Figure 9** Allocation of hardness along the axis of Al-Cu welded sample*
***Slika 9.** Distribucija tvrdoće duž osi zavarenog uzorka od Al-Cu*

4.5 Microstructure
Mikrostruktura

Metallographic tests, as an integral part of the analysis and control of heterogeneous Al-Cu joint welded by friction, are supposed to reveal possible inter-metallicphases and structure of the joint on the boundaries between pure Al and Cu and metal of the welded joint. It has been ascertained that diffusion area extends to 2-10 μm [3], and that the size of metal grain in that area is 0,1-0,2 μm. Figure 10 shows microstructure of diffusion area, i.e. metal of Al and Cu "welded joint".

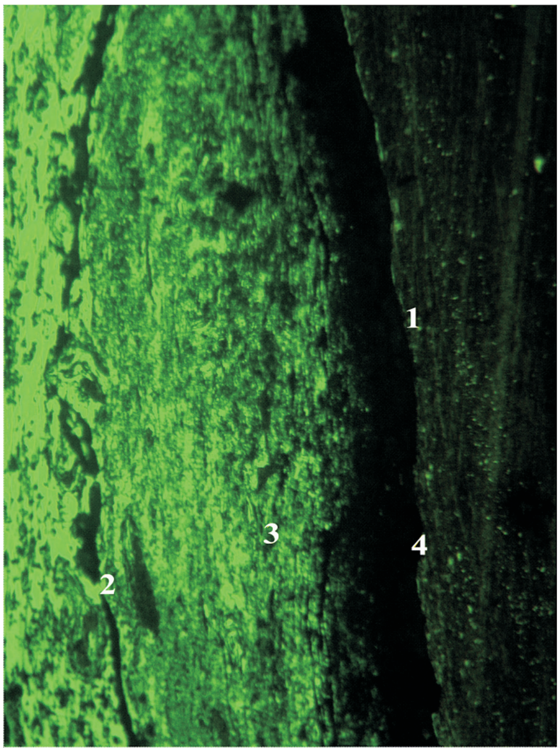

Figure 10. *Microstructure of area of Al and Cu joining (200×), 1- plane of joint, 2- plane of friction, 3- area of mixing, 4- binding layer.*
Slika 10. *Mikrostruktura područja spajanja Al i Cu (200×), 1- ravnina spajanja, 2- ravnina trenja, 3- površina miješanja, 4- vezni spoj.*

5 Conclusion
Zaključak

Friction welding can be successfully applied to joining of Al and Cu. With the aim of obtaining the welded joint, which fulfills the requested technical terms, it is necessary to pay special attention to the choice of process parameters. Aluminum has to be technically pure (Al 99,5) and copper – electrotechnically pure (Cu 99,95). During optimum welding conditions it is possible to achieve the hardness that is at aluminum level, meaning that during tensile testing of samples, tearing must occur outside of the place of joint. If that is achieved, bimetal joints of Al and Cu, welded by friction, can be produced in series.

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Oslo's beautiful location at the head of Oslo Fjord surrounded by forested ridges gives the city an atmosphere which is not expected in a capital city.

Oslo has a rich and varied cultural life. Would you like to visit some of the many attractions? Or maybe do some people watching from a sidewalk café? Oslo caters for every taste!

The history of Oslo goes back to around year 1000 AD. Since the Middle Ages Oslo has gone though great changes, even the name of the city has been changed a few times, before it became the city it is today.

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