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Influence of Friction Welding Parameters on Properties of the Al-Cu Joint

In this paper is presented a theoretical-experimental analysis of the aluminum-copper joining by friction welding. Considering that such Al-Cu bimetal joints are widely applied in industrial practice, experimental analysis in this paper was performed on the concrete elements used in electronics. The fact that the joining is done of the two dissimilar materials points to complexity of the problem, since phenomena that appear in the joint zone extremely influence physical, mechanical and structural properties of the welded/base metals. Besides the theoretical analysis of the basic phases and mechanisms of the friction welding process, the research also included experimental analysis of the geometry changes due to the plastic deformation, the change of microstructure and hardness in the joint zone, as well as of the basic mechanical properties of the Al-Cu joint, such as tensile strength. This paper presents some significant results, which point to the possibility for realization of the reliable joints of the two dissimilar metals.

Keywords: *Friction welding, bimetal joint, aluminum, copper, mechanical properties, microstructure.*

1. INTRODUCTION

Certain physical properties of copper and aluminum, like the high electric and thermal conductivity, enable their common application in electronics, thermo-technique and other areas, in the form of bimetals. The necessity for their joining is indispensable in joining copper and aluminum electric conductors or the cable endings. Studying and improvement of advanced welding technologies of various metals and their alloys, mainly Al, Ti, Mg and different types of steels, are at present in focus of the modern research. The friction by welding plays a significant role in those researches, whether the matter is rotational continuous friction welding (when the cylindrical elements are welded) or the FSW (when the welded elements are plates or thin sheets). Friction welding of various materials was the subject of these authors previous research [1-3], as well as of certain other authors [4-11]. In those articles, it was shown that successful joining by friction welding could be done for different classes of steel [1-5], steels and other metals [6] or the light metals [7-10]. In addition, joints realized by classical friction welding, considered in this paper, can be compared to joints obtained by the friction stir welding procedure [11-14]. Joints obtained by either of the two mentioned friction welding processes exhibit advantages, compared to joints executed by some other welding procedure and it was proven that they could withstand successfully both static and dynamic loads in exploitation [13, 14].

The procedure of continuous friction welding of parts made of aluminum and copper is presented in this paper. The purpose was to determine the influence of the basic welding parameters (friction time, friction pressure and compacting pressure) on the mechanical and microstructural characteristics of the weld, since the bimetal joint characteristics depend on them.

2. BASIC CHARACTERISTICS, PHASES AND PARAMETERS OF THE FRICTION WELDING PROCESS

The friction welding process is very complex. When observing on the micro level, the mechanism of the joint realization is based on forming the metal bond (solid solution) between the base metals, all due to the diffusion process. That bond is created when the metal clean surfaces are coming close at distances that are of the order of magnitude of the crystal lattice parameters. At the beginning of welding, the contact of the welded parts is being realized only at the roughness tips, while the increase of the contact area is achieved by the plastic deformation of the surfaces in contact. Compacting is done until the boundary surfaces are brought close to each other to a distance that is of the crystal parameters size, what enables forming of the common crystal lattices. The technological process of the friction welding is done in three phases, as presented in Figures 1 and 2.

Friction welding was first applied for joining parts of various types of steel, while welding of light metals started later. The friction welding is a procedure of the compression welding, when the joint is realized by plastic deformation of by friction of the heated contact surfaces. The physical essence of the process is in

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transformation of the mechanical energy into heat, which is released because of friction at the joining spot, i.e. in the contact zone of elements that are being joined. The released heat is supposed to soften and to plasticize the near-the-contact layers of materials, but the melting temperature of the easier melting material must not be exceeded. In the considered case that is aluminum, which means that the joint weld should be formed at temperature little below of 600 °C. The quantity of the released heat depends on the nature of the base metals, thermo-mechanical properties and the friction coefficient.

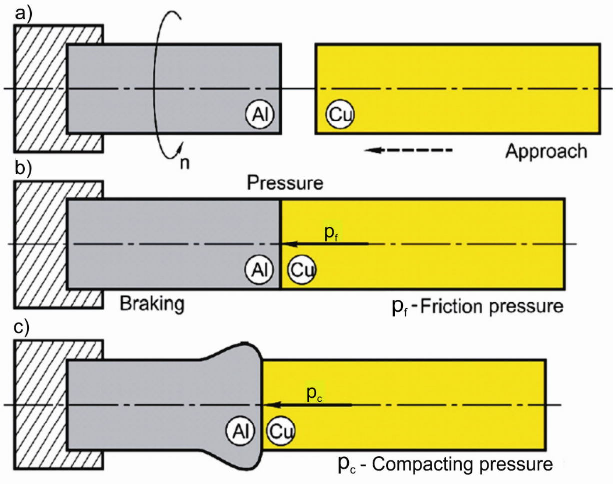


Figure 1. Phases of the technological process of the friction welding - schematics

In the first phase, one part is rotating (aluminum) while the other part (copper) is not moving (Figures 1a, 2a). In the next phase, when the aluminum part reaches sufficient angular velocity, the copper part is being brought into contact by the axial force. The friction pressure (p_f) increases up to the maximum (Figures 1b, 2b). Then the heat is released and with maximum friction pressure, the conditions are achieved for realization of the joint. After the process is finished, rotation of the rotating part stops, what represents the third phase (Figures 1c, 2c) in which the maximum compacting pressure is being introduced (p_c). At that point, the extrusion of the plasticized material occurs, so at the rim of the joint a "wreath" of the extruded material is formed, the so-called "mushroom". After the cooling, the solid joint is obtained.

Quality of the joint is determined by the three basic variables, which influence mechanical and micro-structural properties of the welded joint. Those are the relative speed (number of rpms), pressure and time.

The friction speed influences, to the great extent, the character, shape and magnitude of the realized plastic deformation, as well as the heat generating process. It has been proven that within the range of the small angular velocities the plastic deformation process is being realized at larger depth. Unlike that, at large values of speed, either the complete welding cannot be realized, or the joints are of the poor quality.

The pressure during the friction phase has a strong influence on the thermo-deformation phenomena. There are two different pressures – the friction pressure (p_f) and the compacting pressure (p_c). The friction pressure action during the heating causes intensive deformation of material, heat release and temperature increase. The friction welding cycle could be realized by different variations of pressure vs. time, while as the optimal is considered the step-wise variation cycle [7].

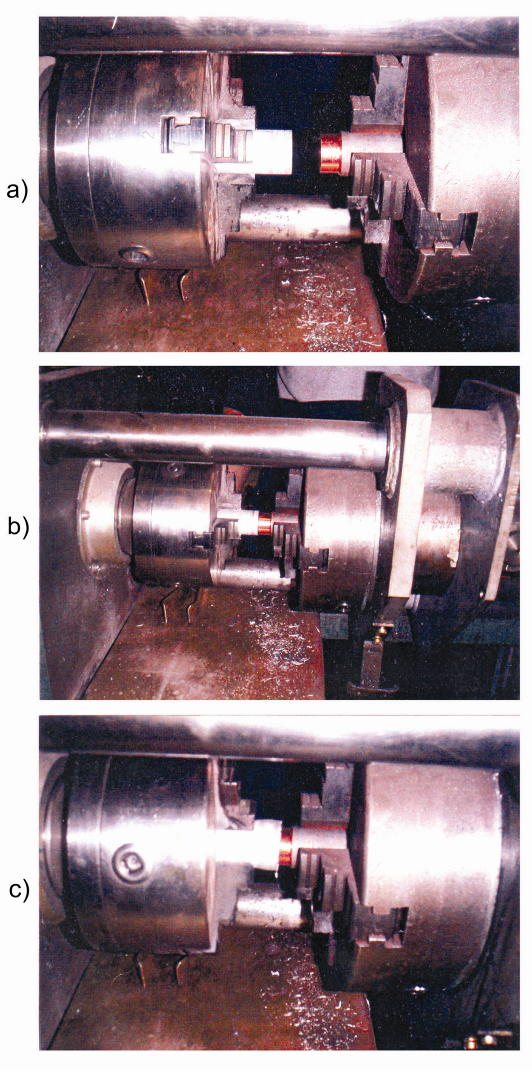


Figure 2. Phases of the technological process of the friction welding – actual appearance

The time depends on other factors that are influential in the welding process, like base metal properties, friction speed and pressure, shape and sizes of the welded parts. The friction time is the time needed for the contact surfaces to heat up to the maximum temperature.

The complete influence and dependence of the friction welding parameters, during the process, are presented in diagram in Figure 3.

Technological parameters of the friction welding were adopted based on experience, literature recommendations and large number of trials. The proper selection of parameters affects the output characteristics of the joint, so accordingly, it is necessary to select the optimal parameters. The adopted parameters were:

- number of rpms n = 2500 rpm,
- welding time t = 4 – 15 s,
- friction pressure $p_f = 50$ MPa,
- compacting pressure $p_c = 150$ MPa.

Estimate of the selected parameters optimality is done experimentally by the tensile test, hardness measurement and analysis of the joint's microstructure.

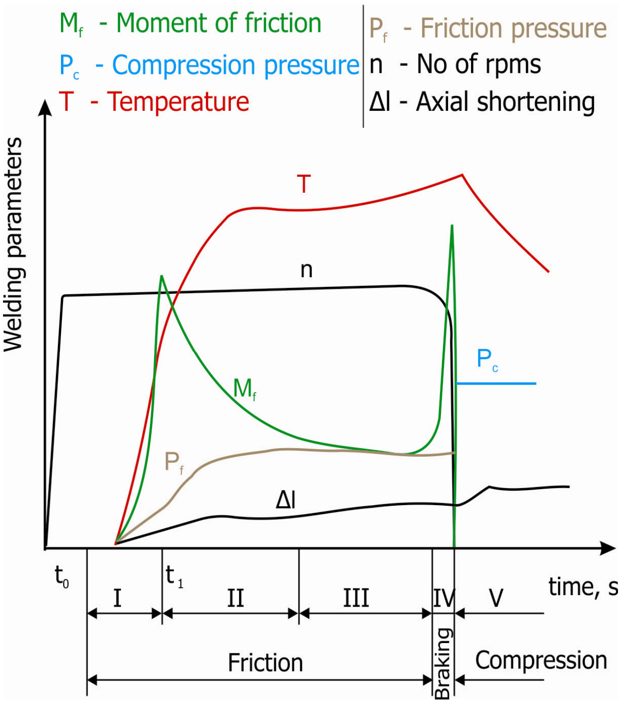


Figure 3. Dependence of friction welding parameters of welding process phase

3. BASE METALS, STRUCTURES AND METALLURGICAL CHANGES IN THE MIXING ZONE OF THE AL-CU JOINT

Base metals. The two used base metals, copper and aluminum belong into a group of the colored metals and are characterized by the excellent thermal and electrical conductivity, corrosion resistance, high plasticity, etc. Their mechanical and physical properties are given in Table 1.

In this experiment, samples for friction welding were prepared from technically pure Al99.5 and electrotechnically pure Cu99.95. Samples were made in form of cylinders with sizes presented in Figure 4.

Structural and metallurgical changes in the mixing zone of the AC-Cu joint. The essence of microstructural and phase processes of the two-component system aluminum-copper for the friction welding could be explained with help of the equilibrium binary phase diagram Al-Cu, Figure 5 [7, 15].

Table 1. Physical and mechanical properties of aluminum and copper

Property	Al	Cu
Melting point, °C	660.4	1083
Thermal conductivity, *W/mK*	222	395
Density, *g/cm³*	2.699	8.96
Coefficient of linear expansion, *1/°C*	23.9	16.5
Tensile strength, *MPa*	50 ÷ 80	150
Hardness, HB	15 ÷ 20	25
Elasticity modulus, *MPa*	71000	127000
Elongation, %	30 ÷ 45	52
Plasticity	good	good

Al-Cu alloys on the aluminum side solidify as the binary system with eutectics that contains 33 % of Cu and consists of Cu (α) solid solution crystals and the brittle intermetallic phase Al_2Cu (θ). One should keep in mind that copper, as an alloying element, significantly increases the resistance properties of aluminum. For instance, the alloy consisting of Al + 1 % Cu has the strength for 5 % higher that the pure aluminum [7].

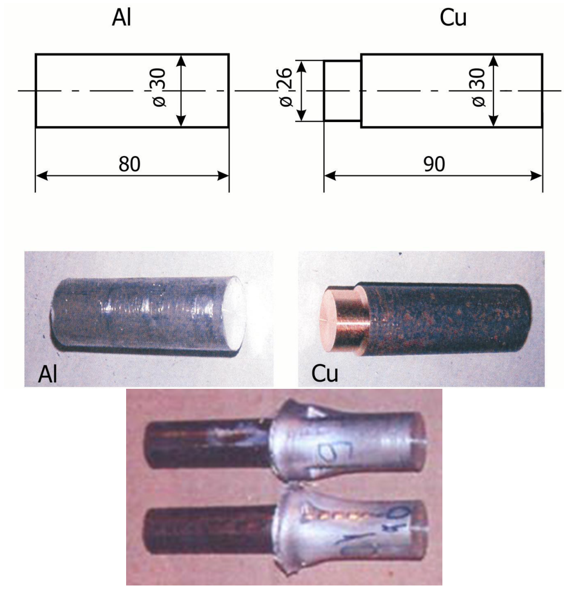


Figure 4. Technical drawing and physical appearance of initial and welded Al-Cu samples

When the copper content is larger than 5.7 %, both brittle phases can exist, Al_2Cu and Al_4Cu_9.

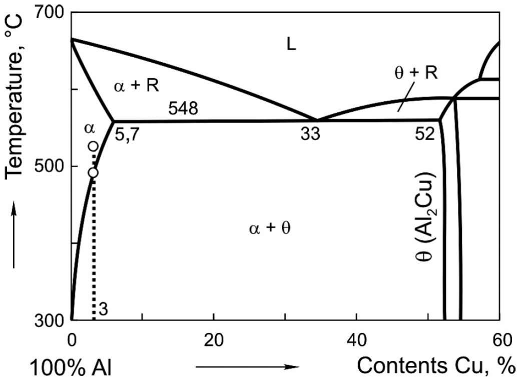


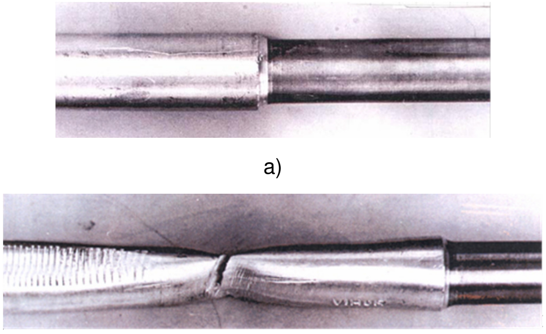
Figure 5. Equilibrium phase diagram Al-Cu

4. EXPERIMENTAL INVESTIGATIONS

Quality and properties of the realized joints were determined experimentally by the tensile test, hardness measurement and analysis of the microstructure of the joint's characteristic zones.

Tensile test. For this test, the cylindrical samples were prepared made of the welded Al-Cu joints (Figure 6(a)). Samples were obtained in different conditions – the duration of the welding process was varied what directly influences the tensile properties of the joint.

On samples welded by friction, the breaking occurred mainly on the aluminum part, Figure 6(b) or in the zone of the Al-Cu joining, what is a very important indicator that the friction welding parameters were adequately selected.



a)

b)

Figure 6. Sample for tensile test (a) and high-quality welded joint after test – fracture in base metal (b)

Results of tensile tests of the base metals and heterogeneous welded joints are shown in Table 2 in terms of the friction time.

Table 2. Tensile strength of the base metal and friction welded joints' samples

Time, s	R_m, MPa	Breaking spot
4	61	WJ
6	69	WJ
7	72	Al
8	85	Al
9	83	Al
10	81	WJ
12	75	Al

Based on results presented in Table 2 one can conclude that the shorter welding time results in obtaining the joint with properties that are worse than those of the base metals. This is why the recommendation is that the welding should last longer (> 7 s), for the welded joint to obtain better mechanical properties (higher strength).

Measurement of hardness and microstructure analysis. Hardness measurement was performed to determine the homogeneity of the welded joint, namely the presence of the undesired brittle phases (θ–$CuAl_2$ and δ–Cu_9Al_4). Hardness was measured along the three directions and at 5 points along the sample axis, according to Figure 7(a). The measurement points are distributed like this: direction I coincides with the welded sample's axis, direction II is at a distance of 3 mm from the axis and direction III is 8 mm away from the axis.

Measurement points are at the distance of 1 mm. Obtained results for four tested samples are shown in Table 3, while the distribution hardness for sample # 1 is shown in Figure 8, with microstructures of the joint's characteristic zones. In majority of samples, hardness was pretty uniform and evenly distributed. As expected, the highest increase of hardness was recorded in the zone of melting/diffusion, where, besides the achieved high temperature, the Al melting occurred what created conditions for intensive diffusion of Cu and appearance of the intermetallic phases of high hardness. That was confirmed also in [7]. The θ ($CuAl_2$) phase has the body centered cubic (BCC) lattice. By increasing the Cu content in the alloy, it crosses into the θ-phase area, where the θ-phase transforms into the body centered tetragonal (BCT) lattice. Microhardness of such a θ-phase is 450 to 650 HB.

What concerns the microstructure, it could be said that it depends largely on the welding parameters, since during the friction welding of copper and aluminum occurs creating and breaking of micro joints, as well as surfacing of copper layer on the aluminum front surface in the initial phase. That causes the friction plane to move away from the joining plane, while the microstructural processes occur within the mixing zone (Figure 8, position 3). From microstructure analysis of joints, it was established that the diffusion zone width was within range 2 to 10 μm, while the grain size was 0.1 to 0.2 μm.

4.1 The welding time influence on the plastic deformation and the samples' lengths

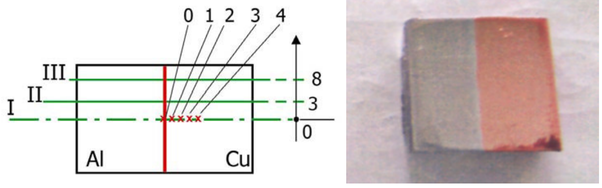
Investigation of the welding time influence was done at the end, since due to friction, the samples are shortened and the part of material is lost into the so-called "mushroom". During the welding of Al and Cu, a very intense plastic deformation of the coupled parts occurs both in the radial and axial direction, of both materials, especially aluminum, as the weaker and softer one. By monitoring the dimensions' changes with time, the relationship was established between the process duration and the samples' deformation (Fig. 9).

Measurements results show that length reduction of the aluminum part is much bigger than that of the copper one. The difference, depending on the welding parameters, could reach even 10:1 ratio.

Table 3. Results of hardness measurement for four samples: #1 for 6 s, #2 for 7 s, #3 for 8 s; #4 for 9 s.

Sample No.	Sample 1*			Sample 2			Sample 3			Sample 4		
Direction	I	II	III	I	II	III	I	II	III	I	II	III
BM Cu	78	91	97	97	106	92	97	103	97	111	110	106
	96	68	72	96	96	95	103	110	97	110	100	110
	96	68	86	95	105	93	110	99	95	99	103	111
	82	79	84	95	93	92	119	102	99	103	99	106
	-	75	-	-	-	-	-	-	-	-	-	-
HAZ	99	102	72	44	77	72	59	70	57	40	39	102
	136	100	72	45	78	74	60	70	57	38	39	101
BM Al	27	27	29	32	30	33	34	32	33	34	40	31
	29	30	32	30	30	33	31	31	32	35	32	32
	29	30	35	30	33	32	30	30	32	32	32	32
	29	30	34	30	32	32	30	30	32	35	32	32

*Hardness distribution and microstructure of Sample 1 are shown in Figure 6.



(a) (b)

Figure 7. Sample for hardness measurement: (a) schematics of the measurements points and (b) physical appearance.

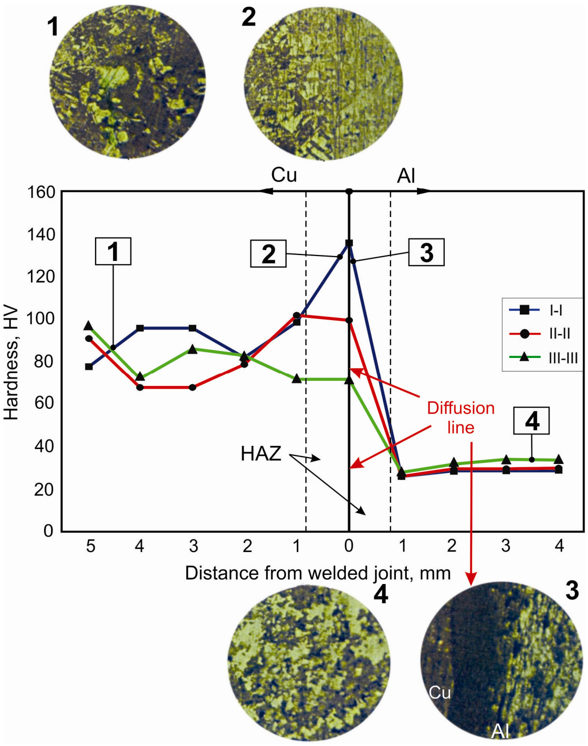
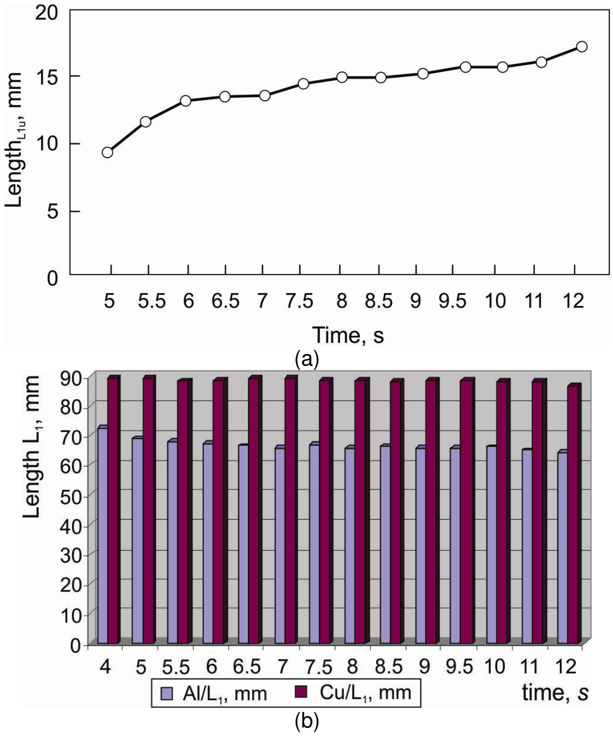


Figure 8. Hardness distribution along the axis for sample 1 with microstructures of the joint's zones.



(a)

(b)

Figure 9. Total welded samples' shortening as a function of time: (a) diagram and (b) histogram.

Deformation in the radial direction is much harder to measure since the "mushroom" is formed on the front side of the aluminum element. During the welding process the softened aluminum layers are being extruded from the friction plane towards the periphery so the big "mushroom" is formed, which is partially transferred to the frontal part of copper, over the whole perimeter [7]. The wreath diameter is increasing with extension of the welding time.

4.2 The welding time influence on the plastic defor–mation and the samples' diameter

Deformation in the radial direction is harder to monitor due to formation of a "mushroom" which is created at the frontal side of the aluminum element. During the welding process, the aluminum layers are moving out of the friction plane towards the periphery; they are extruded into the wreath and the big "mushroom' is formed, which covers the frontal side of copper over the whole perimeter (Fig. 4).

The wreath diameter is changing with variation of the friction time. Increase of time causes enlargement of the wreath's diameter (Fig. 9). Depending on the friction time, as well as on the friction and compacting pressures, the wreath diameter can be increased within range 2 to 40 % with respect to the initial diameter of the aluminum part.

5. CONCLUSION

Joining of Al and Cu can be successfully performed by the friction welding; however, to obtain the welded joint, which fulfills all the required technical conditions, it is necessary to pay special attention to selection of the process parameters.

Analyses of the experimental results have shown that the basic process parameters significantly influence joint's structural and mechanical characteristics. If the optimal welding conditions were applied, it is possible to achieve the joint's strength, which is at the level of the aluminum strength, which means that during the tensile test the break must occur outside the joint zone. If that was achieved, then the bimetal Al-Cu friction welded joint is considered as the high quality joint.

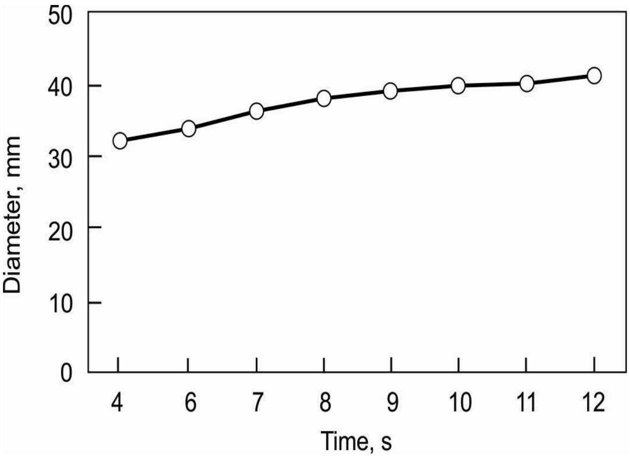


Figure 9. Dependence of the wreath diameter on the friction time

However, the welding time influence should also be kept in mind. With increase of the welding time the tensile strength increases, while the shortening of the sample, especially the Al part, is much bigger. In addition, increase of hardness in the joint zone is expected, where it could reach 130 HV, as well as the grain size increase to 0.1 to 0.2 μm, with the diffusion zone width of 2 to 10 μm.

The presented results can be especially useful in designing the parts, joined by the friction welding procedure, when it it is necessary to obtain the precise desired length and strength of the joined elements.

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NOTE:

The shorter version of this research was presented at the "TEAM 2015" Conference, reference [9].

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УТИЦАЈ ПАРАМЕТАРА ЗАВАРИВАЊА ТРЕЊЕМ НА СВОЈСТВА AL-CU СПОЈА

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У овом раду је дата теоријско-експериментална анализа споја алуминијума и бакра оствареног заваривањем трењем. С обзиром на то да се овакви биметални спојеви Al-Cu у великој мери примењују у индустријској пракси, експериментална анализа у овом раду је изведена на конкретним елементима који се користе у електроници. Чињеница да је реч о спајању два различита материјала указује на сложеност проблема, пошто феномени који се јављају у зони спајања изузетно утичу на физичке, механичке и структурне карактеристике заварених/ основних материјала. Поред теоријске анализе основних фаза и механизама процеса заваривања трењем, истраживање је обухватило и експерименталну анализу промене геометрије услед пластичне деформације, анализу промене структуре и тврдоће у зони споја, као и основних механичких карактеристика Al-Cu споја. Овај рад даје значајне резултате који указују на могућност остваривања поузданих заварених спојева два различита метала.