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Thermically Evaluation and Modelling of Friction Welding

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Original scientific paper

Welding technique is a method used in order to join various materials in manufacturing methods. Friction welding in the technique is one of the various application methods. The method has been in widespread use since 1950. The most important advantages of the method are its easy application, the savings on materials and energy. In the process, heat is generated by conversion of mechanical energy into thermal energy at the interfaces of the components during rotation under pressure. In this study, the relationship between mechanical and heat energy was carried out mathematically. AISI 1040 medium carbon steel, which is the example material, was used in the experiments and the models. The total heat energy, the heat loss and the temperature field in joints which depend on the welding time were examined on friction welding of various parts having various geometries. The examination was carried out using Quick-Field program due to the harmony with the experimental results and its easy application. As a result, different data were evaluated for obtaining material properties and operating conditions, and the obtained results were compared with previous studies. Then, the most suitable conditions for time, material and energy were acknowledged on the future applications of friction welding.

Toplinska evaulacija i modeliranje zavarivanja trenjem

Izvornoznanstveni članak

Zavarivanje se koristi za spajanje različitih materijala u proizvodnim procesima. Tehnika zavarivanja trenjem je također jedna od mnogih aplikacijskih metoda. Ta se metoda počela intenzivno razvijati od 1950. godine. Najvažnije prednosti te metode su jednostavna primjena, ušteda materijala i energije. Pri tom procesu se toplinu generira pretvorbom mehaničke u toplinsku energiju na dodirnoj površini komponenata koje rotiraju pod nametnutim tlakom. U ovom radu je izvedena matematička relacija koja povezuje utrošenu mehaničku i dobivenu toplinsku energiju. Kao ogledni materijal, pri eksperimentima, korišten je srednje ugljični čelik AISI 1040. Sveukupna toplinska energija, gubitci topline kao i temperaturno polje u spajanim (zavarivanim) materijalima, a koji ovise i o trajanju vremena zavarivanja, ispitani su pri zavarivanju trenjem za tijela različitih geometrija. Ispitivanje je izvedeno koristeći Quick - Field program obzirom na skladnost s eksperimentalnom rezultatima i s obzirom na njegovu jednostavnu primjenu. Kao rezultat, evaluirani su različiti podaci za određivanje svojstava materijala kao i uvjeta zavarivanja, i dobiveni su rezultati uspoređeni s rezultatima iz prethodnih studija. Na taj se način došlo do najboljih uvjeta za vrijeme, materijal i energiju koji bi se koristili u budućim primjenama procesa zavarivanja trenjem.

Keywords
FEM
Friction Welding
Modelling
Numeric Simulation
Temperature Variation

Ključne riječi
MKE
Modeliranje
Numerička simulacija
Varijacija temperature
Zavarivanje trenjem

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1. Introduction

As mentioned before, heat in friction welding is generated by conversion of mechanical energy into thermal energy at the interface of the work pieces during rotation under pressure. Generally, friction welding can easily be used to join components that have circular or non-circular cross sections. Friction time, friction pressure, forging time, forging pressure and rotation speed are the most interesting parameters in the friction welding method [1].

Continuous drive and inertia friction welding are the two main types of the friction welding process. Continuous drive friction welding was used to join the parts in this study.

In continuous drive friction welding shown in Figure 1, a rotating part is first brought up to a constant speed.

Symbols/Oznake

c	- specific heat capacity, J/(kg·K) - specifični toplinski kapacitet
λ	- thermal conductivity, W/(m·K) - koeficijent toplinske provodnosti
T	- temperature, K - temperatura
ρ	- density, kg/m^3 - gustoća
ω	- angular velocity, rad/s - kutna brzina
n	- rotational speed, min^{-1} - brzina vrtnje
P	- pressure, MPa - tlak
L	-length, m - duljina
r	- radius, m - polumjer
D	- diameter, m - promjer
t	- time, s - vrijeme
F	- force, N - sila
μ	- friction coefficient - faktor trenja
V	- linear velocity, m/s - brzina
T	- torque, N·m - moment uvijanja
q	- heat flux, W/m^2 - gustoća toplinskog toka
Q	- total heat flux, W - ukupni toplinski tok

While the speed of rotation is kept constant and when an unrotating part is pushed against the rotating part under a friction pressure (P_1), the welding starts. This is the heating phase. When the interface temperature reaches the forging (upsetting) range of the work-piece, the rotation is stopped in the shortest possible time. During the same time, a forging pressure (P_2) is applied to forge the parts together by upsetting. The welding is completed and the work piece can be removed after cooling. Parameters of the method are shown in Figure 2.

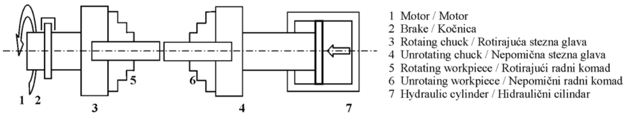


Figure1. Layout of Continuous Drive Friction Welding

Slika 1. Prikaz kontinuiranog zavarivanja trenjem

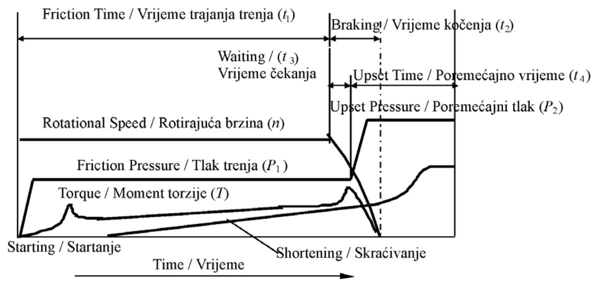


Figure 2. Parameters on Continuous Drive Friction Welding

Slika 2. Parametri kontinuiranog zavarivanja trenjem

Various research papers have been published in this area, and these were given below.

Vill, V. I. [1] made a study on the friction welding of metals.

An analytical temperature solution was presented in an article based upon a finite weld piece and ambient temperature chuck ends by Rich, T. and Roberts, R. [2]. They discussed the establishment of boundary conditions. They used the continuous drive method to join AISI 4140 steel tubes.

Imshennik, K. P. and Kragel' Skii [3] examined heating properties in friction welding.

Healy, J. et al. [4] made an analysis of the frictional phenomena in friction welding of soft steel.

Kinley, W. [5] made a study on the friction welding set-up.

Murti, K.G.K. and Sundaresan, S. [6] directed a study on parameter optimisation in friction welding of dissimilar materials.

Sluzalec, A. [7] developed a finite element model to simulate the temperature process.

Nentwig, A.W.E. et al. [8] investigated the cross section effect differences of the components on the joint quality of friction welding and started that friction pressure, upset pressure and rotation speed must be changed in the friction welding of different cross-sections.

Bendzsak, G. J. et al. [9] investigated the numerical model in friction welding.

Fu, By L. and Duan, L. [10] carried out analysis of the coupled thermo-mechanical problem during friction welding by using a finite element method, according to the constitutive relation of large elasto-plastic deformation and the principle of virtual work in their studies. Then, the heat flow and stress-strain process at the heating stage of friction welding were simulated, and the law of variation of temperature, stress and strain fields during friction welding were systematically investigated by authors.

Balasubramanian, V. et al. [11] carried out a study on the application of friction welding to 1045 steel welds.

Sahin, M. [12] investigated the effects of work-piece dimensions and plastic deformation on the friction welding method. Then, Sahin, M and Akata, H. E. [13] examined an experimental study on the application of friction welding on parts with different diameters and width. Investigations on the effect of dimensional differences in friction welding of AISI 1040 specimens were directed by the same authors [18]. D'Alvise, L. et al. [17] studied finite element modelling of the inertia friction welding process between dissimilar materials.

In this study, the aim is to support the development of the method and new knowledge on the literature of friction welding, which is a manufacturing method. Therefore, proper conditions on work-pieces, which are not produced in other manufacturing methods, are selected for material and energy use. Above all, two questions below were investigated in this study. Firstly, which material properties can be the highest quality reached for material properties and practice? Secondly, how are time and energy used in the manufacturing processes?

Finally, conditions were determined for more results than material properties and production quality by using new knowledge and technologies.

2. The experimental procedure

2.1. The experiment set-up

In the present study, an experimental set-up was designed and constructed as continuous drive method. The photo of the experiment set-up is given in Figure 3.

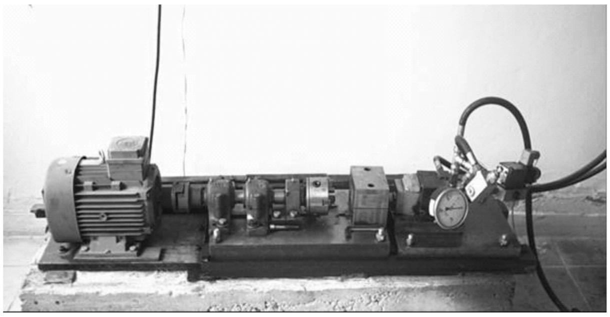


Figure 3. A photo on the experiment set-up

Slika 3. Fotografija uređaja za eksperiment

2.2. Material

Composition of AISI 1040 steel used in the experiments is given in Table 1.

Table 1. Chemical compositions of test material used in the experiments [14]

Tablica 1. Kemijski sastav materijala koji je korišten u eksperimentima

Material	% C	% P	% S	% Mn	% Si	% Ni	% Cr
AISI 1040	0,35 0,44	< 0,04	< 0,05	0,75	0,20	-	-

2.3. Geometry of parts

The experiment specimens were machined from AISI 1040 steel on geometry below. Geometry of parts is given in Figure 4.

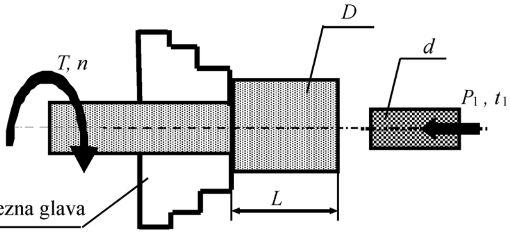


Figure 4. Part dimensions used in the experiments

Slika 4. Dimenzije tijela u eksperimentu

2.4. The experimental study

The experiments were carried out in a laboratory with a designed and constructed continuous drive friction welding set-up. Motor power of set-up is 4 kW, and revolution speed of motor is 1410 rpm.

Upset pressure and upset time were kept constant. However, friction time and friction pressures were changed in the experiments.

First of all, tests were conducted to determine the optimum parameters for a convenient joint. The optimum parameters were determined with 10 mm specimens having equal diameter [18]. Welding experiments were aimed at obtaining optimum friction time and friction pressures using upset time (20 s) and upset pressure (110 MPa). Hence, the optimum parameters were found (30 MPa) for friction pressure and (5 s) for friction time. Then, the parameters obtained were used to join parts having different diameters and widths [18].

Parameters used in the friction welding experiments are given in Table 2.

Table 2. Parameters used in the friction welding experiments [18]

Tablica 2. Parametri koji su korišteni u procesu zavarivanja trenjem

Length of rotating work-piece / Duljina rotirajućeg radnog komada *L,* mm	Diameter of rotating work-piece / Promjer rotirajućeg radnog komada *D*, mm	Diameter of axially sliding work-piece / Promjer aksijalno kliznog radnog komada *d,* mm	Friction time / Vrijeme trajanja trenja t_1, s	Friction pressure / Tlak trenja P_1, MPa	Upset time Poremećajno vrijeme t_4, s	Upset pressure / Poremećajni tlak P_2, MPa
15	10	10	5	30	20	110
	15					
	20					
	30					
	40					

Temperature measurement is of great importance at interfaces of parts because of friction in friction welding. Nevertheless, it is hard to predict measurements according to temperature time.

Sluzalec, A. [7] developed a finite element model to simulate this process and to represent the work pieces and surface contact conditions. Predictions of the temperature distribution, thermal expansion and thermo-plastic stresses obtained from this model. Comparison of the analytic results to test data were presented and discussed by the author.

Later, Balasubramanian, V., et al. [11] presented the results of a combined experimental and numerical study of continuous drive friction welding of 1045 steel. A new friction law was proposed for the estimation of the apparent coefficient of friction during direct drive friction welding. The temperature distributions were empirically and numerically predicted in the heat-affected zone that is formed during the direct drive friction welding of 1045 steel to 1045 steel. Temperature measurements were made at different locations using thermocouples. A finite element model was used to determine the appropriate coefficient of friction to fit the experimental data. Predictions of the coefficient of friction were in close agreement with the experimental results obtained from the direct drive friction welding trials on 1045 steel. The current results suggest that the new friction law may be used to determine the effects of friction welding parameters on friction coefficients in other material systems.

In this study, AISI 1040 material was used by considering similar properties of AISI 1045 material in the experiments. Moreover, the Quick-Field simulation program was used in this study as it is easy to make a study with the program, and it is suitable when it comes to comparing obtained knowledge from welding methods with the program, and the program gives close results for real values [15, 16].

2.5. Temperature dependent properties of material

In this study, AISI 1040 material was used considering similar properties of AISI 1045 material in the experiments [11].

Table 3. Temperature dependent properties of 1040 steel [11]

Tablica 3. Temperaturna ovisnost svojstava čelika 1040

Density / Gustoća kg/m³	7860									
Temperature / Temperatura °C	20	150	315	485	650	750	815	1000	1150	1300
Specific heat capacity / Specifični toplinski kapacitet J/(kg·K)	460	500	586	730	835	1250	840	670	630	630
Thermal conductivity / Toplinska provodnost W/(m·K)	52	48	46	43	34	33	32	43	48	60

3. Numerical simulation

3.1. Quick-field finite element analysis program

In many engineering situations today, it is a well-known fact that it is necessary to obtain approximate numerical solutions to problems rather than an exact close form solution. In recent years, the finite element method has rapidly become a very popular numerical analysis technique for obtaining an approximate solution to a wide variety of engineering problems. The finite element method envisions the solution region as being built up of many small, interconnected sub-regions or elements. The material properties and governing relationships are considered over these elements and expressed in terms of unknown values at element corners.

Quick-Field V 4.2T version can be downloaded from the internet free (www.quickfield.com/free.html). The program used is limited to 200 nodes. With this program, finding the heat distribution in any section below requirement would call for two dimensional calculations.

1- First of all, a drawing is required. This can be taken from other drawing programs such as AutoCAD in DXF format.

2- Thermal conductivity of solid body.

3- Surface boundary conditions (Convection, radiation or heat flux).

Suppositions given below were used in the quick field software program.

3.2. Suppositions

A theoretical formula on heat produced in the friction welding method was carried out in this study. Then, various experiments were made independently. Heat variations, during welding and after welding, in welded parts were determined according to certain boundary conditions by Quick-Field program. While doing this, friction coefficient for observed parts was taken constant as an average value in formulas. When we take the welding period obtained experimentally into consideration, the Coulomb friction coefficient, which is known in Physics and Mechanics branches, must be about two seconds. Total friction time is 5 s for welding of AISI 1040 steels in this study. Viscose friction takes place in an other 3 s time. Generally, rolling motion of molecules on each other occurs in zones of both parts having a few mm thicknesses and added to viscose friction by means of movement amount of welding parts over each other.

Suppositions for theoretical approaches are given below:

1. Forms of parts were not changed throughout welding stage.
2. Friction pressure was homogeneously spread at welding interface. However, in this welding method, there are two components. While one is an unrotated-part, the other one is a rotated-part. Linear velocity depending on part diameter changes over the welding surface between parts. However, heat flux which occurs due to friction of parts changes depending on part diameter. Friction pressure or friction force which requires friction is applied to work-pieces by a hydraulic piston. Then, the friction force was not changed at the start of melting and surface-deformation at friction-surfaces.
3. In general, forms of work-pieces were not changed at welding stage.
4. Chuck has a large-mass. Then, friction welding time occurs at 5-9 s in a short time. Therefore, it was foreseen that the temperature was kept constant on cross-section according to the surface-axis which is contacted of fixed chuck of rotated-work-piece.
5. There are different circumference-torsions and heat fluxes because of friction along the rotation-axis at interfaces of work-pieces.
6. The welding surface is the zone in which mechanical energy is converted into thermal energy under pressure, and it exposes to high temperature. Therefore, not surface friction but viscose friction similar to volume movement occurs at interface of parts. Two approaches can be used for friction coefficient on the friction type. The first approach is the fundamental background and the approach on viscose flow process based on Fluid mechanics. The second approach is to determine the friction coefficient by keeping constant or measuring all parameters in the formulas. Both approaches were considered for this study. Also, friction coefficient for viscose friction was accepted through observing similar studies ($\mu = 1$) [7].

3.3. Correlation between torque and heat energy

The mathematical expression between operating characteristics on friction welding and heat energy produced on account of friction welding can be found by observing suppositions. It was assumed that friction pressure is homogeneously spread on the interface of rotated and unrotated parts. The produced heat and its variation can be determined with respect to operating characteristics and dimensions of parts. Produced heat energy can be expressed as:

$$\mathrm{d}\dot{Q} = \omega \cdot \mathrm{d}T, \tag{1}$$

where ω is angular velocity, and dT is differential torque of circle at width dr, Figure 5, [2].

Then, torque dT can be expressed as:

$$\mathrm{d}T = r \cdot \mathrm{d}F_{\mathrm{fric}}, \tag{2}$$

where dF is a friction force over a circle at width dr, and r is radius of circle, Figure 5.

Then, it can be determined that friction force dF equals friction-coefficient multiplied by axial-force of pressure P over circle at width dr.

$$\mathrm{d}F = \mu \cdot P \cdot 2\pi r \cdot \mathrm{d}r. \tag{3}$$

By introducing equations (2) and (3) into equation (1), we obtain:

$$\mathrm{d}\dot{Q} = 2\pi \cdot \mu \cdot \omega \cdot P \cdot r^2 \cdot \mathrm{d}r. \tag{4}$$

It can be determined that total energy occurring at friction-surfaces is heat occurring over friction-surface with respect to distance r and thickness dr from rotation-axis in Figure 5.

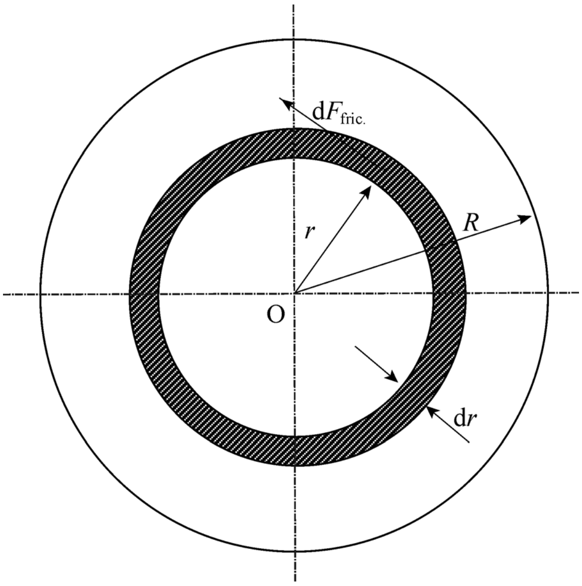


Figure 5. Friction surface and friction ring (dr)

Slika 5. Površina trenja i diferencijalni prsten trenja (dr)

We obtain heat occurring at welding surface by integrating with R of equation (4) as follows:

$$\int_0^R \mathrm{d}\dot{Q} = \int_0^R 2 \cdot \pi \cdot \mu \cdot P \cdot \omega \cdot r^2 \cdot \mathrm{d}r\,, \tag{5}$$

$$\dot{Q} = 2 \cdot \pi \cdot \mu \cdot P \cdot \omega \cdot \left.\frac{r^3}{3}\right|_0^R, \tag{6}$$

$$\dot{Q} = \frac{2}{3} \cdot \pi \cdot P \cdot \omega \cdot R^3\,. \tag{7}$$

We obtain total torque by integrating with R of equation (3) as follows:

$$T = \int_0^R 2 \cdot \pi \cdot \mu \cdot P \cdot r^2 \cdot \mathrm{d}r\,, \tag{8}$$

$$T = 2 \cdot \pi \cdot \mu \cdot P \left.\frac{r^3}{3}\right|_0^R, \tag{9}$$

$$T = \frac{2}{3} \cdot \pi \cdot \mu \cdot P \cdot R^3\,. \tag{10}$$

Then, when equation (7) is compared with equation (10), heat occurring in unit-time over welding surface is equal to total torque multiplied by angular velocity.

$$\dot{Q} = \omega \cdot T\,. \tag{11}$$

Heat flux occurring over any point at distance r from rotation-axis is equal to circle-area at width dr divided by equation (4).

$$\begin{aligned} \dot{q} &= \mathrm{d}\dot{Q} / (2 \cdot \pi \cdot r \cdot \mathrm{d}r) = \\ &= 2 \cdot \pi \cdot \mu \cdot \omega \cdot P \cdot r^2 \cdot \mathrm{d}r / (2 \cdot \pi \cdot r \cdot \mathrm{d}r). \end{aligned} \tag{12}$$

As a result, heat flux occurring over any point at distance r from rotation-axis can be expressed as:

$$\dot{q} = \pi \cdot \omega \cdot P \cdot r\,. \tag{13}$$

4. New approaches and results

Both temperature and heat flux variations were theoretically determined on rotated and unrotated parts, using starting and finishing of friction time. Therefore, the Quick-Field simulation program, which was given properties and principles in use under a special chapter, was used in this study.

Heat produced over welding-surface is theoretically proportional to linear-velocity. The linear-velocity increases as it removes from the rotation-axis. To predict this, heat produced at unit-area due to friction increases proportionally to part-radius as it moves from rotation-axis, symbolically shown in Figure 6.

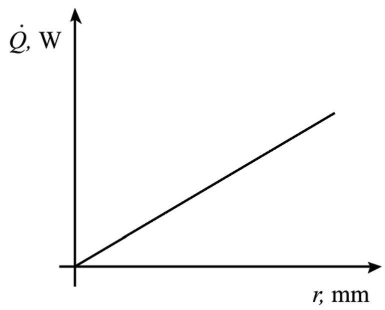


Figure 6. Symbolical energy variations according to part-radius over friction surfaces

Slika 6. Simbolički prikaz varijacije energije po polumjeru dodirne površine trenja

This work was carried out by referring to Balasubramanian et al. and Sluzalec [7,11], and is theoretical and experimental. In their studies, temperature over welding surface is 920 – 930 ^{o}C for similar material and dimensions using experimental methods in parts having equal diameter. Therefore, the obtained 927 ^{o}C temperature value using Quick-Field program is an acceptable value. Graphics (Figures 7 and 8) were found referring to the value in this study.

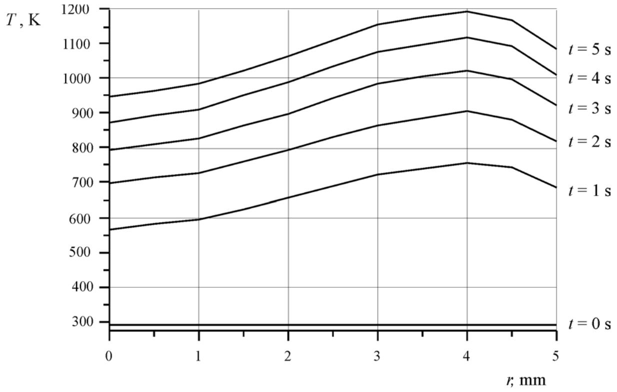


Figure 7. Temperature variations according to time over friction surfaces

Slika 7. Vremenska promjena temperature po polumjeru dodirne površine trenja

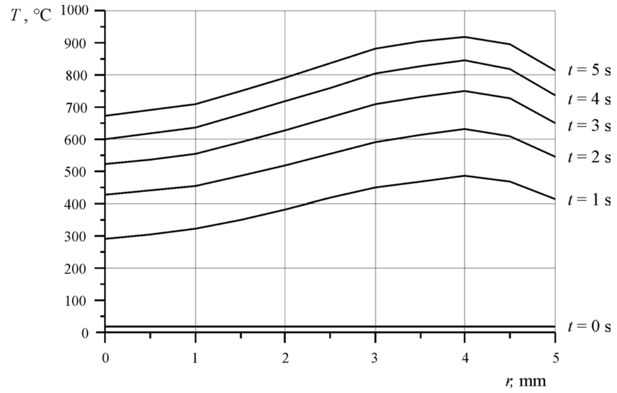


Figure 8. Temperature variations according to time over friction surfaces

Slika 8. Vremenska promjena temperature po polumjeru dodirne površine trenja

As can be seen in Figures 7 and 8, temperature variations over the friction surfaces of the parts having equal diameter increase as time is increased.

Then, D=20 mm and d=10 mm joints were selected for parts having different diameter as model (Figure 9). Mesh points of parts having different diameter (Figure 10), temperatures at friction surfaces of the parts, surface temperatures over outer surfaces of parts having big and small diameter and the heat flux vectors and temperature variations at times 1, 2,5 and 5 s of the model were investigated using Quick-Field program (Figures 11, 12, 13 and 14).

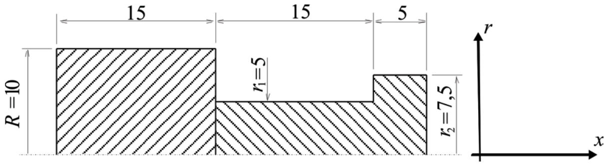


Figure 9. Welded parts and their dimensions (Chucks are not shown in this figure)

Slika 9. Zavarivana tijela (dijelovi) i njihove dimenzije (stezne glave nisu prikazane na slici)

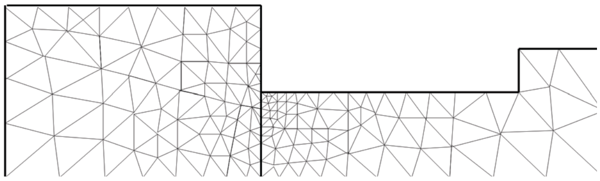


Figure 10. Mesh points at determined zone of temperature variation

Slika 10. Točke mreže u određenoj zoni za koje se računa temperatura

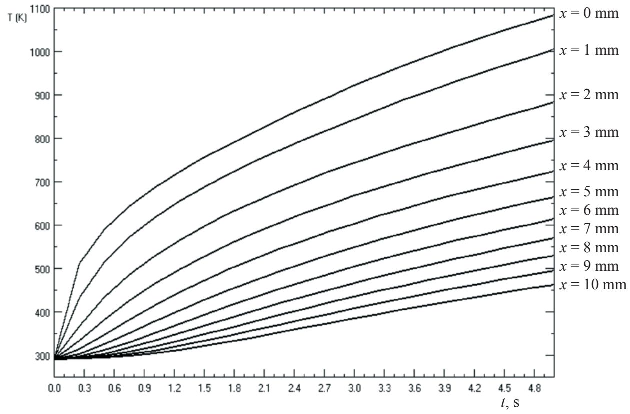


Figure 11. Temperature variations according to time over outer-surface of small part

Slika 11. Varijacija temperature s vremenom vanjske površine malog tijela

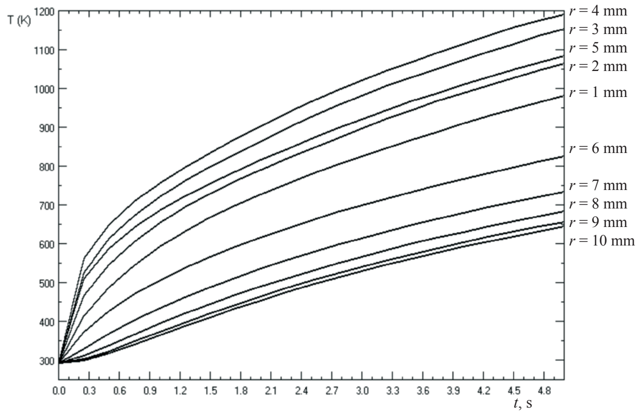


Figure 12. Temperature variations according to time over welding-surface of big part

Slika 12. Varijacija temperature s vremenom dodirne (površine zavarivanja) velikog dijela

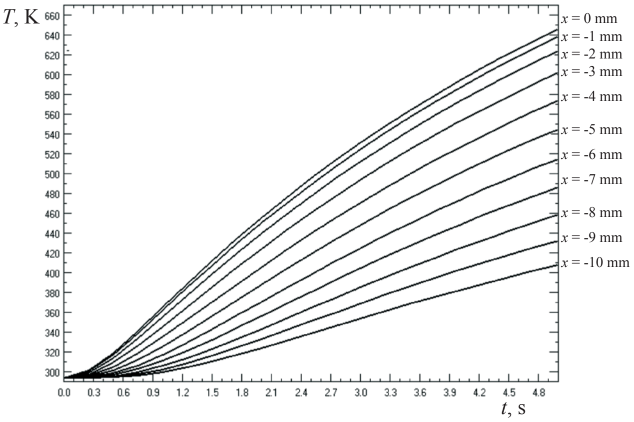
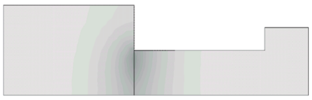


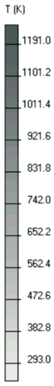
Figure 13. Temperature variations according to time over outer-surface of big part

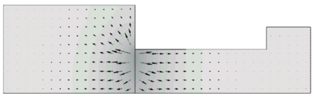
Slika 13. Varijacija temperature s vremenom vanjske površine velikog dijela

As can be seen in Figures 11 and 13, temperature variations over outer-surface of the small part are bigger than those of the big part. Then it is shown that temperature variations over the welding surface of the big part increase according to time in Figure 12.

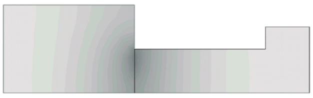


a) Temperature variation at $t = 1$ s
Temperaturno polje u vremenu $t = 1$ s

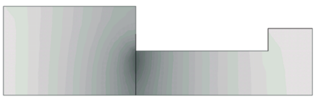




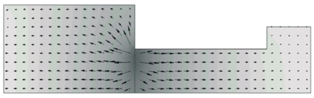
b) Heat flux vectors and temperature variation at $t = 1$ s
Vektori gustoće toplinskog toka i temperaturno polje u vremenu $t = 1$ s



c) Temperature variation at $t = 2,5$ s
Temperaturno polje u vremenu $t = 2,5$ s



d) Temperature variation at $t = 5$ s
Temperaturno polje u vremenu $t = 5$ s



e) Heat flux vectors and temperature variation at $t = 5$ s
Vektori gustoće toplinskog toka i temperaturno polje u vremenu $t = 5$ s

Figure 14. Heat flux vectors and temperature variations at times 1, 2,5 and 5 s

Slika 14. Gustoća toplinskog toka i temperaturno polje u vremenima 1, 2,5 i 5 s

Temperature variations and heat flux vectors of the model part are shown belonging to times 1, 2,5 and 5 s in Figure 14. Then the temperature-scale at the upper-right corner can be used to determine the temperatures at various points of the part.

5. Conclusions

Heat transfer by conduction from welding surface to the centre of a part in small work-pieces is much more than that in big ones. Then there is high-temperature average over the circle of the part. Therefore, heat transfer at surface is higher than other places because of temperature-difference.

While heat variation of a work-piece having the small diameter is faster than that of the big one, heat capacity of work-pieces having the small diameter is lower than that of the big one. Therefore, heat transfer of small work-pieces disperses fast and more temperature-variation occurs in the small work-pieces.

Outer-sections of parts which are melted are deformed due to friction and upset pressures at interface of work-pieces. Besides, the deformation affects manufacturing-quality. In this study, it was assumed that the pressures were homogeneously spread for calculations over the welding surface. However, there is not any homogeneity. Sections of work-piece friction-surfaces, which were first of all melted in work-pieces, were deformed by mutual-pressures. Consequently, although total compression-force is unchanged, the pressures increase at centre-sections of work-piece friction-surfaces. Moreover, while heat energy increases at zones having high-pressure, it decreases at zones having low-pressure. Nevertheless, real heat–variation is different from obtained heat-variation with calculations, and the heat-variation is not homogeneous as in calculations.

Therefore, the knowledge obtained from our numerical calculation study is valuable to the development of the fundamental theory and engineering application research of friction welding.

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