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HEAT GENERATION DURING FRICTION STIR WELDING PROCESS

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Abstract: *Friction stir welding – FSW was a promising welding technology from the same moment of its existence because of its easy use, low energy costs, being ecology friendly process and with no need for filler metal. FSW works in the solid state of weld metals and basic goals of the process are to generate thermal energy by friction on contact of FSW tool and welding pieces, which will soften weld pieces and stir it with solid metal into weld. FSW process has five main phases: plunging into weld pieces, dwelling, moving along joint line for the weld creation, final dwelling and pulling out of the welding tool from the weld. Generated heat is in proportion with large number of parameters, but most significant are contact pressure between tool – weld pieces and speed. Significant thermal energy is generated during FSW and there is mathematical model which describe these stages but still there are several inaccuracies of the model that give some differences between theoretical and experimentally determined amount of heat.*

Keywords: *Friction Stir Welding, Technological Hole, Heat Generation.*

1. INTRODUCTION

Friction stir welding is non melting process of welding invented in 1991. From the early beginning of the application, this process showed good characteristics in welding pieces that have to keep unchanged their structure and properties as much it is possible. First application of the friction stir welding process was with aluminum and its alloys, but this technique is widely used with various types of metals nowadays. Welding is achieved with one tool that is in contact with weld pieces. This tool is cylindrical, mostly with a profiled threaded probe and it is rotated at a constant speed (*n*) and fed (inserted) at the constant traverse rate (v_x) into the joint line between two weld pieces which are rigidly clamped onto a backing plate and butted together. Backing plate prevents abutting of the joint faces from being forced apart [1-5].

2. PHASES OF THE FSW PROCESS; BASIC REVIEW

There are various shapes and design of welding tool, backing plate etc, but that does not affect basic friction stir welding process, without any concern on technology varieties, friction stir welding process can be separated to five phases: a) plunging, b) dwelling, c) welding, d) dwelling, and e) pulling out [5].

Figure 1 shows these phases of friction stir welding process. Last two phases are non productive phases and they only finalize the weld but they are unavoidable. During the first phase, the rotating welding tool is plunged vertically into the joint between the weld pieces – into the joint line (Figure 1, a) and it is the classical welding process.

In the case analyzed in this paper, weld pieces are previously prepared so that they have a "technological hole" and welding tool is plunged directly into the hole instead of making one during the first phase. Technological hole can ease welding process since there is no need for significant vertical force (in *z* direction) that is necessary in the case with plunging into pieces without the technological hole. The plunge phase is followed by the dwell phase, where the toll stays steady relatively to the welding pieces but still constantly rotating (Figure 1, b). The mechanical interaction, due to the velocity difference between the rotating tool and the stationary work piece, produces heat by frictional forces. This heat dissipates into the surrounding material – welding pieces, temperature of the material rises and it softens. After these two phases, the welding process is initiated by moving either the tool or the work piece relative to each other, traversal along the joint line (Figure 1, c).

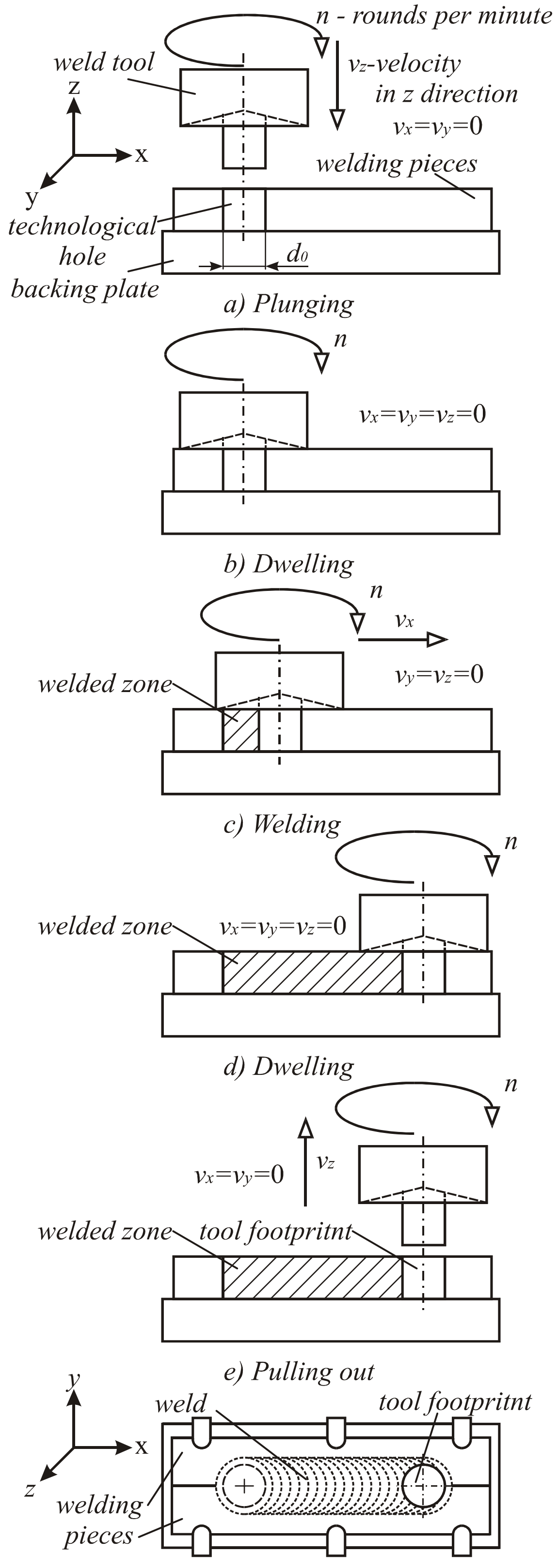

Figure 1. Phases of the friction stir welding process

Welding is processed until the welding pieces become connected along the planed weld distance. After welding phase traversal movement between tool and weld pieces stops but welding tool continues its rotation. This is the third phase or the second dwelling phase (Figure 1, d). There is no special need for this phase and if machine used for welding has ability to pull out the tool the same moment when traversal movement along the joint stops, this phase can be avoided. Final phase is pull out of the welding tool from the weld (Figure 1, e).

Friction welding tool or simply *tool* has two basic parts: the shoulder and the probe. Shoulder is massive cylindrical part that carries smaller cylindrical part – probe. Figure 2 shows the basic shape of the tool. New tool designs have special features on probe like multi-facets, threads, gear teeth and flutes which are manufactured to produce advantageous conditions in heat generation, stirring and to assist the joining process.

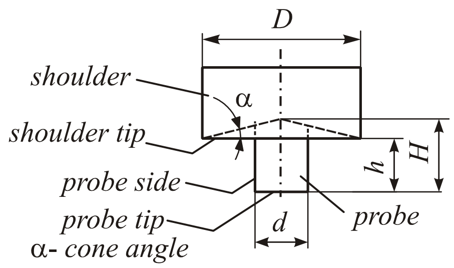

Figure 2. Basic shape of the friction stir welding tool

There are three surfaces of the tool that perform the heat generation by friction and enable joining of weld pieces. Probe has two surfaces that can generate heat – the tip and the side of the probe. The probe tip generates significant heat during plunging phase if there is no technological hole. But in any other case and in the following phases of welding its contribution to the heat generation is ignorant. The probe side surface is directly in the contact with the work pieces and this surface gives the greatest tribute to the heat generation. When welding pieces are previously prepared with technological hole with diameter d_0, it can be expected that diameter of the weld tool's probe d can be equal, smaller or greater than d_0. In theory contact [7] between cylindrical weld tool's probe and hole's cylindrical surface is:

- in one contact line, if $d<d_0$ and
- surface to surface, if $d \geq d_0$..

If we consider situation where $d<d_0$, real situation is slightly different than theoretical: traversal force of the tool, which is parallel to the joint line, forces tool's probe to contact surface of the technological hole in one contact line. Elastic deformations of the probe and the hole make this contact to spread from the linear to the contact in the surface, defined with contact angle θ (Figure 3). Elastic properties of the realistic materials do not allow linear contact between two cylindrical surfaces except in some special situations [7].

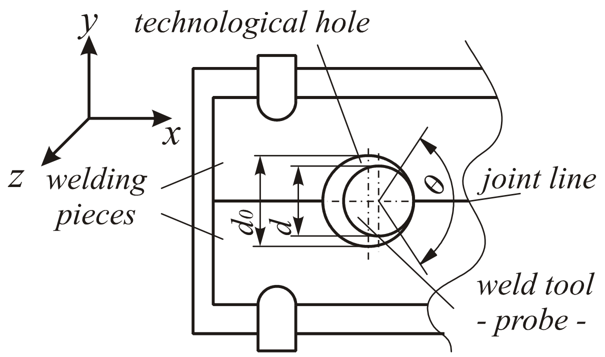

Figure 3. Contact angle θ between the probe and technological hole

The shoulder surface is the area where certain amount of heat is generated only if cone angle has a value of α=0°. In the case of α>0° this surface has relatively small contact surface with solid metal and generated amount of heat is slightly smaller. Coned part of the shoulder confines the underlying material of the weld so prevent formatting of porosity in the weld behind the probe. The conical tool shoulder helps establishment of the constant pressure under the shoulder necessary for the welding, but also acts as an escape volume for the material displaced by the probe during the plunge phase. The probe height is limited by the work piece thickness *h*. The probe tip must not contact, damage or penetrate the backing plate.

3. ANALYSIS OF THE TOOL-WELD PIECES CONTACT DURING WELDING PHASES

It is more than clear that heat, necessary for the welding, is generated by friction during active contact of at least two surfaces – one surface from the tool and front surface of the weld pieces. Number of contact surfaces, surface area and ability to generate heat vary from phase to phase of the welding and parameters of the welding process – rotation speed *n*, traversal speed v_x *etc.* Active contact is consequence of weld tool rotation and transverse movement of weld tool, weld pieces or both.

The simplest possible shape of the welding tool has cylindrical shoulder, with the cone on the shoulder tip, cone angle α and cylindrical tool probe (Figure 2). According to the assumed geometry of the tool (Figure 2) and weld pieces (Figure 1) heat can be generated during all phases of the welding on the following surfaces:

1) Plunging phase: dependable to the diameter of the tool *d* and diameter of the technological hole d_0, there are three possible situations:

1.a) $d<d_0$ – tool probe's pin surface has no contact with the weld pieces surface so there is no heat generation on these surfaces; tool probe's side surface has no contact with side surface of the technological hole and there is no heat generation on these surfaces.

1.b) $d=d_0$ – tool probe's pin surface has no contact with the weld pieces surfaces so there is no heat generation on these surfaces; tool probe's side surface has limited or no contact with side surface of the technological hole and there is expected small amount of heat generation on these surfaces, contact length between tool probe's side surface and weld rises from 0 to *h*.

1.c) $d>d_0$ – tool probe's pin surface has contact with the weld pieces surfaces so there is some heat generation on these surfaces; tool probe's side surface has contact with side surface of the technological hole and there is significant amount of heat generation on these surfaces, contact length between tool probe's side surface and weld rises from 0 to *h*.

2) Dwelling phase: tool probe's side surface is in contact along height *h* (*H*) with weld pieces and shoulder's tip surface is in contact with plate surface of the weld pieces.

3) Welding phase: tool probe's side surface is in contact along height *h* (*H*) with weld pieces and pushes forward along the joint line for weld creation; shoulder's tip surface is in contact with plate surface of the weld pieces.

4) Dwelling phase: tool probe's side surface is in contact along height *h* (*H*) with weld pieces and shoulder's tip surface is in contact with plate surface of the weld pieces.

5) Pulling out phase: toll probe's side surface generates heat from the contact with weld pieces; contact length between tool probe's side surface and weld decreases from *h* to 0.

From the aspect of welded joint heat treatment during welding, friction stir welding can be described in four phases:

1) Dwelling: the material is preheated by a stationary, rotating tool in order to achieve a sufficient temperature ahead of the tool to allow the traverse movement. This period includes the plunging of the tool into the work pieces at one point of the joint line.

2) Transient heating: when the welding tool begins traversal movement along joint line there is a transient period where the heat production and temperature around the tool rises until pseudo steady-state is reached.

3) Pseudo steady – state. Although fluctuations in heat generation will occur the thermal field and temperature around the tool remain effectively constant, at least on the macroscopic scale. Microscopic transformations are present on a high level.

4) Post steady – state. Near the end of the weld heat may "reflect" from the end of the weld

pieces and backing plate leading to additional heating around the tool.

Table 1. Friction stir welding phases and the contact areas between surfaces

Welding phase	Surfaces	Area
Plunging	Probe tip	$d < d_0 \quad A_{pt} = 0$ $d = d_0 \quad A_{pt} \approx 0$ $d > d_0 \quad A_{pt} = \frac{\pi}{4} \cdot \left(d^2 - d_0^2\right)$
	Probe side	$d < d_0 \quad A_{ps} = 0$ $d = d_0 \quad A_{ps} \approx d \cdot \pi \cdot dz$ $d > d_0 \quad A_{ps} = d \cdot \pi \cdot dz$ $dz = 0 \div h$
	Shoulder tip	$A_{st} = 0$
Dwelling	Probe tip	$A_{pt} = 0$
	Probe side	$d < d_0 \quad A_{ps} = \theta \cdot \frac{d}{2} \cdot h,$ $\theta = 0 \div \pi \quad rad$ $d \geq d_0 \quad A_{ps} \approx d \cdot \pi \cdot h$
	Shoulder tip	$A_{st} \approx 0$
Welding	Probe tip	$A_{pt} = 0$
	Probe side	$A_{ps} \approx \theta \cdot \frac{d}{2} \cdot H$ $\theta = 0 \div 2\pi \quad rad$
	Shoulder tip	$A_{st} \approx \frac{D^2 - d^2}{4} \cdot \pi$
Dwelling	Probe tip	$A_{pt} = 0$
	Probe side	$A_{ps} \approx d \cdot \pi \cdot H$
	Shoulder tip	$A_{st} \approx \frac{D^2 - d^2}{4} \cdot \pi$
Pulling out	Probe tip	$A_{pt} = 0$
	Probe side	$A_{ps} \approx d \cdot \pi \cdot dz$ $dz = H \div 0$
	Shoulder tip	$A_{st} = 0$

If we analyze surfaces involved in the heat generation, shown in Table 1, but it is completely clear that physical phases of welding process are not identical with phases that describe heat generation and heat flow within work pieces, weld tool and surrounding.

4. ANALITICAL METHOD FOR HEAT GENERATION ESTIMATION

All amount of generated heat can be assumed as a direct product of weld tool's rotation and it is coming as a product of the adhesion and the deformation of the material around the tool. Heat generated from the traverse movement is significantly smaller amount then from the rotation so it can be excluded from calculations.

$$Q = Q_{adhesion} + Q_{deformation}$$
$$Q_{adhesion} = Q_{sliding} \; ; \; Q_{deformation} = Q_{sticking} \qquad (1)$$

On the other hand, total amount of the heat Q generated by the cylindrical friction stir welding tool can be calculated as a sum of the energy generated on the tool probe's tip surface Q_{pt}, tool probe's side surface Q_{ps} and tool shoulder's tip surface Q_{st}.

$$Q = Q_{pt} + Q_{ps} + Q_{st} \qquad (2)$$

Some assumptions about heat generation [1] suggest that heat is generated predominately under shoulder tip's surface because of the great contact surface between tool and weld pieces. Newer experiments and analysis of the welding process have partially declined these assumptions and gave some explanation about influence of all contact surfaces in the heat generating [1, 2].

Heat is generated during two basic tribological processes that appear in the contact of the tool and weld pieces: *pure sliding* - adhesion and *pure sticking* - deformation. Pure sliding condition assumes shear in the contact interface and can be described as fully Coulomb friction condition. Assumption is that the contact pressure between tool and weld piece p and friction coefficient μ are constant or linearly dependable values from various variables. If contact shear stress has smaller value than the internal yield shear stress of the weld pieces, segment volume of the weld piece shears slightly to the elastic deformation where shear stress becomes equals to dynamic contact shear stress. Pure sticking assumes shearing in the layer of the material of weld pieces very close to the contact surface and uniformity of the shear stress τ. In this situation surface of the weld piece will stick to the moving tool's surface only if friction shear stress exceeds the yield shear stress of the weld piece. Segment of the weld piece material is being chopped and accelerate along the tool, until the equilibrium state is established between the contact stress and shear stress of the weld pieces. Unfortunately, real situation during welding process gives combination of the pure sliding and the pure sticking and it is absolutely correct to say that heat generating during friction stir welding is product of pure sliding, pure sticking and combination of sliding and sticking.

Basic equation for heat generation with infinitesimal surface in contact with the weld pieces is equal to

$$dQ = \omega \cdot dM \, [\mathrm{J}] \qquad (3)$$

where:

ω – tool angular rotation speed, rad^{-1}

dM – torque of the welding tool.

If torque is replaced as a product of the perimeter force *dF* and radial distance *r*, and perimeter force is replaced as a product of a shear stress τ and infinitesimal area of observed surface *dA*, equation for generated heat is

$$dQ = \omega \cdot r \cdot \tau \cdot dA . \quad (4)$$

Application of the equation (3) and consideration of sticking and sliding condition gives equations for the heat generating at the specific surfaces.

Shoulder tip surface:

sticking

$$Q_{st} = \frac{2}{3} \cdot \pi \cdot \tau \cdot \omega \cdot \left[\left(\frac{D}{2} \right)^3 - \left(\frac{d}{2} \right)^3 \right] \cdot (1 + \tan\alpha) \quad (5)$$

sliding

$$Q_{st} = \frac{2}{3} \cdot \pi \cdot \mu \cdot p \cdot \omega \cdot \left[\left(\frac{D}{2} \right)^3 - \left(\frac{d}{2} \right)^3 \right] \cdot (1 + \tan\alpha) \quad (6)$$

Tool probe tip surface:

sticking

$$\begin{aligned} d < d_0 \quad & Q_{pt} = 0 \\ d = d_0 \quad & Q_{pt} \approx 0 \\ d > d_0 \quad & Q_{pt} = \frac{2}{3} \cdot \pi \cdot \tau \cdot \omega \cdot \left[\left(\frac{d}{2} \right)^3 - \left(\frac{d_0}{2} \right)^3 \right] \end{aligned} \quad (7)$$

Sliding

$$\begin{aligned} d < d_0 \quad & Q_{pt} = 0 \\ d = d_0 \quad & Q_{pt} \approx 0 \\ d > d_0 \quad & Q_{pt} = \frac{2}{3} \cdot \mu \cdot p \cdot \omega \cdot \left[\left(\frac{d}{2} \right)^3 - \left(\frac{d_0}{2} \right)^3 \right] \end{aligned} \quad (8)$$

Tool probe side surface:

Sticking

$$Q_{ps} = \theta \cdot \tau \cdot \omega \cdot \left(\frac{d}{2} \right)^2 \cdot H , \; \theta = 0 \div 2\pi \quad (9)$$

Sliding

$$Q_{ps} = \theta \cdot \mu \cdot p \cdot \omega \cdot \left(\frac{d}{2} \right)^2 \cdot H , \; \theta = 0 \div 2\pi \quad (10)$$

In situation of the mixed state – what is the most usual situation, welding is done with combination of the sliding and sticking and it is necessary to define a contact state variable δ. This constant is ratio of velocity of contact points at the weld piece segment v_{cp} that are in contact with tool and velocity of the tool v_ω that comes from rotation of the tool.

$$\delta = \frac{v_{cp}}{v_\omega} \quad (11)$$

Pure sticking is defined for δ=1, pure sliding for δ=0 and combination of the sticking and sliding is assumed for values 0<δ<1.

Amount of the generated heat for combination of the sticking and sliding state is equal to:

$$Q = \delta \cdot Q_{sticking} + (1 - \delta) \cdot Q_{sliding} . \quad (12)$$

Shoulder tip's surface generates approximately 85% of the total amount of heat while probe generates about 15% when welding is applied without technological hole [1]. Technological hole changes ratio of the generated heat on surfaces and it is expected to get different values with than in [1].

5. DISCUSSION ABOUT UNCERTAINTIES WITHIN HEAT GENERATION IN THE FRICTION STIR WELDING PROCESS

Mathematical model describes geometrical conditions for heat generating and if statement that "heat generated from traverse movement of the welding tool has a minor value" [5, 8] is correct, value of analytically calculated heat has to be close to the experimentally measured value of the generated heat.

Experiments with heat generating during friction stir welding, conducted by various scientists in various laboratories with different expectations give completely different results. Some results have an excellent matching with theoretical (analytical) results, but huge number of experiments gives results incomparable with analytical results [9].

If we agree that mathematical model used to describe geometrical inputs to the friction stir welding process is adequate and precise enough, this suggests that there are some parameters, involved in mathematical model, which lead to uncertain or imprecise results.

If we exclude geometrical and machining parameters from total generated heat Q equation (13) we get parameters that might influence precision of the results: contact state variable δ, friction coefficient μ between tool and wield pieces, contact pressure between tool and weld pieces p and the shear stress τ of the wield pieces.

Contact state variable δ precisely define border conditions of welding: pure sticking or pure sliding. Condition involving both sticking and sliding remain uncertain and imprecise since there is huge variation of the variable δ. Contact state variable δ is directly influenced with tool's number of rotations per minute n and traversal speed vx and selection of those parameters will directly influence on value of δ. Still, there is uncertainty about intensity of weld piece segment velocity vcp since measuring requires complex tribological measuring system. Some authors [8, 9] give numerical values of the δ depending on materials and machining parameters, but still there are no mathematical models or experimental values that will cover complete palette of materials and machining parameters. Nowadays δ values are determined buy expert assessment or buy usage of artificial intelligence and neural networks. Fuzzy set theory has adequate mathematical tools that might solve this uncertainty in some specific cases.

Friction coefficient μ is tribological parameter that describes the ratio of the force of friction between two bodies and the force pressing them together. At the beginning of the welding process, weld tool – metal is in contact with weld pieces – metal so friction coefficient has regular and familiar value. During phases of welding, tool softens the surface of the weld pieces and it is clear that value of friction coefficient changes its value. It would be unwise to tell that value of friction coefficient increases/decreases. The most precise statement is that friction coefficient changes its value or that friction coefficient is function of at least two parameters – pressure p and traversal rate vx:

$$\mu = f\left(p, v_x, \ldots\right) \tag{13}$$

Some authors [2, 4] give boundaries for friction coefficient for metal – metal contact as μ=0,08÷1,4. Still no one gives functional dependency of friction coefficient for parameters in friction stir welding phases.

Contact pressure p between tool and weld pieces is considered as a value changing between 0 and maximal value of p so there is no issue with this parameter.

Finally, assumptions about constant values of the parameters like linearization of the values or uniformity are, have to be analyzed and adapted to the problem of friction stir welding. Certain amount of imperfections and assumptions must be changed with goal to get better precision of the results.

6. CONCLUSION

Friction stir welding process is relying on heat generating for weld joint creation. Parameters involving proper welded joint creation are just the same parameters involved in heat generation and this amount is directly dependable from the geometrical parameters of the tool, speed – rotational and traversal, pressure, shear stress and friction coefficient.

Determination of precise amount of heat generated during friction stir welding process is complicated since there are various uncertainties, assumptions and simplifications of mathematical model that describes welding process. Various experiments conducted around the planet, from the very beginning of the FSW method's application gave dispersive results about the generated heat. The analytical heat generation estimate correlates with the experimental heat generation, by assuming either a sliding or a sticking condition. For the sliding condition, a friction coefficient that lies in the reasonable range of known metal to metal contact values is used in order to estimate the experimental heat generation. Assuming the sticking condition yield shear stress, which is descriptive for the weld piece material at elevated temperatures, is used to correlate the values.

Main uncertainties about process are when welding condition is mixture of sliding and sticking. In this situation ambiguity of the value of the friction coefficient in every moment of the welding process, contact pressure between weld tool and weld pieces and shear stress are main reasons for difference between analytical and experimental results.

REFERENCES

[1] H Schmidt, J Hattel and J Wert: An analytical model for the heat generation in Friction Stir Welding, *Modelling Simul. Mater. Sci. Eng.* 12 No 1 (January 2004) 143-157.

[2] Song, M., Kovačević, R. Numerical and experimental study of the heat transfer process in friction stir welding. *Journal Engineering Manufacture*, vol. 217 Part B.

[3] Song, M., Kovačević, R. (2003) Thermal modeling of friction stir welding in a moving coordinate system and its validation. *International Journal of machine Tools & Manufacture*, 43, 605-615.

[4] Ulysse, P. (2002) Three-dimensional modeling of the friction stir-welding process. *International Journal of Machine Tools & Manufacture*, vol. 42, str. 1549-1557.

[5] Arbegast, J.W. (2006) Friction stir welding after a decade of development. *Welding Journal*.

[6] Stamenković D, Đurđanović M, Mitić D.: ZAVARIVANJE POSTUPKOM FSW, "Zavariva-nje i zavarene konstrukcije", godina LI, 2006, br. 2, st.59–66.

[7] Shigley, J.E., Mischke, C.R., *Mechanical Engineering Design*, Fifth Edition, McGraw-Hill, Inc, 1989, ISBN 0-07-056899-5.

[8] Thomas, WM; Nicholas, ED; Needham, JC; Murch, MG; Temple-Smith, P. Dawes, CJ.*Friction-stir butt welding*, GB Patent No. 9125978.8, International patent application No. PCT/GB92/02203, (1991).

[9] H. Schmidt, J. Hattel: Thermal modeling of friction stir welding *Scripta Materialia*, Volume 58, Issue 5, Pages 332-337.

[10] Wayne, M.T., i dr. (1995) Friction stir butt welding UP patent 5. 460 317