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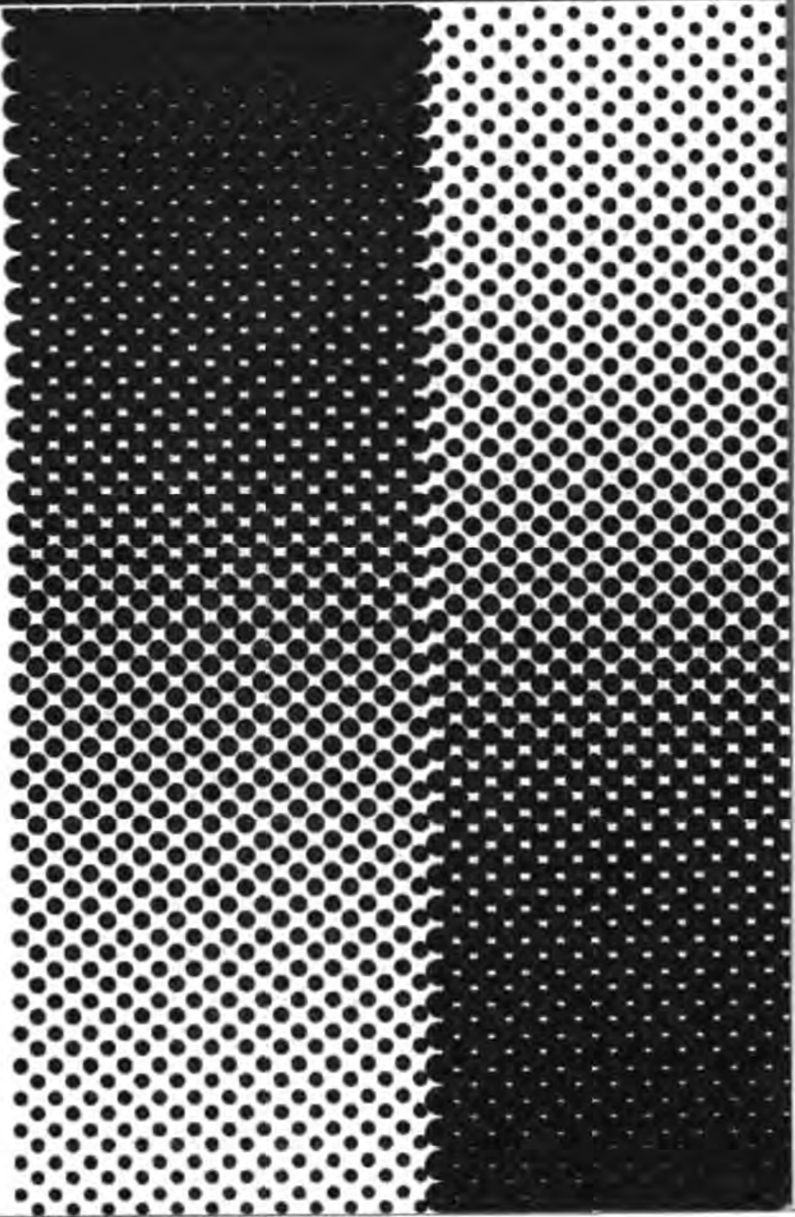

Journal of the Balkan Tribological Association is an International Journal edited by the Balkan Tribological Association for rapid scientific and other information, covering all aspects of the processes included in overall tribology, tribomechanics, tribochemistry and tribology.
The Journal is referring in Chem. Abstr. and RJCH (Russia).

Aims and Scope

The decision for editing and printing of the current journal was taken on Balkantrib'93, Sofia, October, 1993 during the Round Table discussion of the representatives of the Balkan countries: Bulgaria, Greece, Former Yugoslavian Republic of Macedonia, Romania, Turkey and Yugoslavia. The Journal of the Balkan Tribological Assosiation is dedicated to the fundamental and technological research of the third principle in nature – the contacts.

The journal will act as international focus for contacts between the specialists working in fundamental and practical areas of tribology.

The main topics and examples of the scientific areas of interest to the Journal are:

(a) overall tribology, fundamentals of friction and wear, interdisciplinary aspects of tribology;
(b) tribotechnics and tribomechanics; friction, lubrication, abrasive wear, boundary lubrication, adhesion, cavitation, corrosion, computer simulation, design and calculation of tribosystems, vibration phenomena, mechanical contacts in gaseous, liquid and solid phase, technological tribological processes, coating tribology, nano- and microtribology;
(c) tribochemistry – defects in solid bodies, tribochemical emissions, triboluminescence, tribochemiluminescence, technological tribochemistry; composite materials, polymeric materials in mechanics and tribology; special materials in military and space technologies, kinetics, thermodynamics and mechanism of tribochemical processes;
(d) sealing tribology;
(e) biotribology – biological tribology, tribophysiotherapy, tribological wear, biological tribotechnology, etc.;
(f) lubrication – solid, semi-liquid lubricants, additives for oils and lubricants, surface phenomena, wear in the presence of lubricants; lubricity of fuels;
(g) ecological tribology; the role of tribology in the sustainable development of technology; tribology of manufacturing processes; of machine elements; in transportation engineering;
(h) management and organisation of the production; machinery breakdown; oil monitoring;
(j) European legislation in the field of tribotechnics and lubricating oils; tribotesting and tribosystem monitoring;
(k) educational problems in tribology, lubricating oils and fuels.

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MATHEMATICAL MODEL FOR ANALYTICAL ESTIMATION OF GENERATED HEAT DURING FRICTION STIR WELDING. PART 1

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ABSTRACT

Heat generation controlling is a prerequisite for a high-quality welds creation during friction stir welding (FSW) processes and it is important to have an adequate mathematical model that is capable of estimating heat generation during FSW with satisfying accuracy. There are numerous models that do explain heat generation and give results with various degrees of accuracy, but these models include numerous approximations and neglect some key parameters for heat generation. The main objective of this work is to provide an accurate mathematical model for heat generation estimation. Mathematical model given in this work describes/defines contact condition, contact pressure, friction coefficient, thermal history of the welding plates and points out the dual nature of heat generation process in FSW – adhesion and deformation component in total heat generation. Generated heat, estimated by the mathematical model, is compared with the experimental power. It is concluded that this new algorithm for heat generation estimation gives applicable results and furthermore that adhesion component of total generated heat dominates though deformation component should not be neglected in the estimation of the generated heat.

Keywords: friction stir welding, heat generation.

AIMS AND BACKGROUND

Friction stir welding (FSW) is a solid-state welding process predominantly used for welding of aluminium, aluminium alloys and other soft metals/alloys[1]. This

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* For correspondence.

welding technique requires usage of specialised, cylindrical-shouldered tools, with a profiled threaded/unthreaded probe. Welding tool is rotated at a constant speed and fed at a constant traverse speed into the joint line between the two welding plates that are butted together. The parts are clamped rigidly onto a backing plate in a manner that prevents the abutting joint faces from being forced apart. The length of the probe is slightly less than the weld depth required and the tool shoulder should have contact with the work surface. The probe can be moved against the weld – joint line, or vice versa.

FSW is patented in 1991 and during 1992 the industrial application of the process has started[1]. At the beginning, application of FSW was based on 'try and error' principle. Previous works on modelling the FSW process included analytical thermal models, finite element (FE)-based solid thermal and thermomechanical models, fluid dynamic models, stress and strain conditions of the welding plates. Some of these models include heat generation from the FSW tool and assumptions are made regarding the interface condition, which all have their drawbacks and limitations. Santiago et al.[2], has introduced a model of the FSW process, using finite element based program with reproduction of the temperature field and volume flow. Gould et al.[3] developed an analytical heat transfer model for FSW based on the Rosenthal equation[4]. Chen and Kovacevic[5,6] carried out thermo-mechanical finite elements analyses based on a heat source model without considering heat generated by plastic flow. Song et al.[6] investigated the influence of the preheating period on the temperature fields and used an effective friction coefficient and experimental plunge force in the heat source expression. Ulysse[7] gave 3D modelling of FSW using fully coupled thermomechanical viscoplastic flow models. This kind of modelling was done by Colegrove et al.[8] using the CFD package FLUENT. Nandan et al.[9,10] reported results of stainless steel FSW simulation. Chao et al.[11] proposed a model where the heat generation comes from the assumption of sliding friction, where the Coulomb law is used to estimate the shear or friction force at the interface. The pressure at the welding tool-welding plates contact is assumed to be constant, with heat flux distribution as a representation of the friction heat generated by the tool shoulder, while neglecting heat generated by the probe. Frigaard et al.[12,13] has modelled the heat input from the tool shoulder and probe as fluxes on squared surfaces at the top and sectional planes on a 3D model and control the maximum allowed temperature by adjustment of the friction coefficient at elevated temperatures. Russell et al.[14] based the heat generation on a constant friction stress at the interface, equal to the shear yield stress at adequate temperature. Colegrove uses an advanced analytical estimation of the heat generation for tools with a threaded probe and a thorough presentation of analytical estimates of heat is included[15,16]. Xu et al.[17] introduced a 2D solid mechanical FE model using ABAQUS Explicit and a 2D CFD model using Fluent with the main objective to reveal the material flow around the probe. The FE model includes two different sub-models with different contact conditions at the probe/material interface: the sliding interface and the frictional contact model. The material surrounding the probe is exposed to a temperature field obtained from an experiment, with calculation of yield stress for the thermal material response. Khandkar et al.[18] introduced a torque based heat input model, where the torque/power known from experiments is used in the expression for the heat source. Shi et al.[19] uses the experimentally observed mechanical power as input in a 3D FE model. It investigates the influence of tool loads (torque and plunge force) on the residual stresses. Kumar et al.[20] proposed a model for friction coefficient estimation during FSW for different technological parameters of the process.

The aim of this work is to propose more precise mathematical model for estimation of generated heat during FSW process. It is based on the previous work on this problem, detailed geometric-kinematic dependences between parameters, numeric simulations and logical assumptions. Mathematical model is tested by comparing the analytically determined generated heat with the experimental results given by Schmidt et al.[21]

WELDING PLATES

Welding plates have to be positioned one to another along joint line and rigidly clamped to backing plate to disable dislocation during welding process. There is no need for any kind of preparation of joint line before welding.

Welding process starts at the 'start point', when welding tool firstly touches welding plates and finishes in 'end point', when welding tool leaves welding plates (Fig. 1). Scheme and basic data about welding plates used in experiment[21] are shown in Table 1.

Table 1. Scheme and basic data about the welding plates

Base metal – welding plates	
Length	$L = 150$ mm
Width	$B = 2 \times 60 = 120$ mm
Plate thickness	$\Delta = 3$ mm
Joint length	$l = 105$ mm
Start point	$l_1 = 15$ mm
Material of welding plates	2024 T3

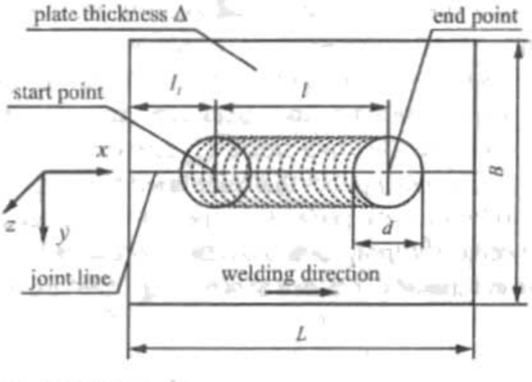
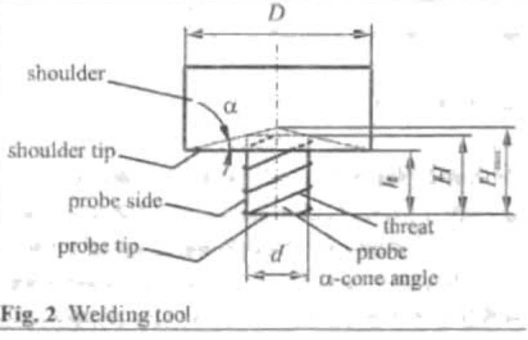


Fig. 1. Welding plates

WELDING TOOL

Tool used for FSW is special, cylindrically shaped part, usually made of high strength steel resistant to wear. It consists of two main parts: tool shoulder and probe. The shoulder is usually flat or internal-coned cylinder larger than a probe. The probe is directly involved in welding process. It is cylindrical or conical, mostly left threaded with a flat or rounded probe tip. Welding tool that is used in experiment was with the threaded probe, flat probe tip and with cone 'reservoir' for material in shoulder tip (Fig. 2). Geometry of used welding tool is shown in Table 2. For analytical estimation of generated heat thread on the probe and influence of the tilt angle (between vertical line and rotation axis of the welding tool) are neglected.

Table 2. Scheme and basic data about the welding tool

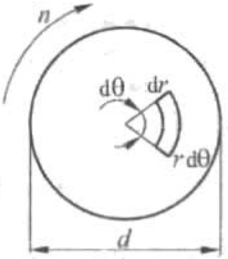
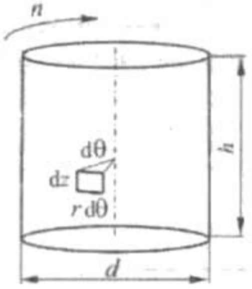
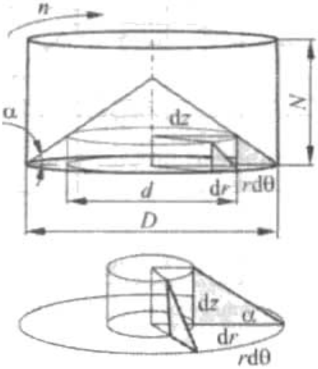
Welding tool used in experiment		
Probe (diameter)	$d = 6$ mm	 **Fig. 2.** Welding tool
Shoulder (diameter)	$D = 18$ mm	
Maximal probe height	$H_{max} \approx 6$ mm	
Probe height	$H \approx 5$ mm	
Effective probe height	$h \approx 3$ mm	
Cone angle	$\alpha = 10$ °	
Thread pitch	$P = 0.8$ mm, left	
Material	steel, no details	

ANALYTICAL EXPRESSIONS FOR HEAT GENERATION

Djurdjanovic[22] proposed analytical expressions for heat generation estimation during standard friction welding process (e.g. spin welding, linear friction welding). These expressions have evolved from friction momentum equation of contact between rotating punch and semi-half space[23]. Schmidt et al.[21] used the same principle to propose analytical expressions for heat generation during FSW basing it on contact shearing stress τ_{cont} between welding tool and welding plates.

Considering fact that simplified welding tool has 3 active welding surfaces[24] – probe tip (pt), probe side (ps) and shoulder tip (st), shown in Figs 3, 4 and 5, respectively, proposed analytic expressions[21] (equations (1), (2) and (3)) for the estimation of generated heat during FSW are given in Table 3.

Table 3. Analytical expressions for heat generation on active surfaces

$Q_{pt} = \int_0^{2\pi}\int_0^{\frac{d}{2}} \omega r^2 \tau_{cont}\, \mathrm{d}\theta\, \mathrm{d}r$ $Q_{pt} = \frac{2}{3}\pi\omega\tau_{cont}\left(\frac{d}{2}\right)^3$ (1)	 **Fig. 3**. Probe tip
$Q_{ps} = \int_0^{2\pi}\int_0^{h} \omega r^2 \tau_{cont}\, \mathrm{d}\theta\, \mathrm{d}z$ $Q_{ps} = 2\pi\omega\tau_{cont}\left(\frac{d}{2}\right)^2 h$ (2)	 **Fig. 4**. Probe side
$Q_{st} = \int_0^{2\pi}\int_{\frac{d}{2}}^{\frac{D}{2}} \omega r^2 \tau_{cont} (1+\tan\alpha)\, \mathrm{d}r\, \mathrm{d}\theta$ $Q_{st}\ \frac{2}{3}\ {}_{cont}\left[\left(\frac{D}{2}\right)^3\ \left(\frac{d}{2}\right)^3\right](1\quad \tan\quad)$ (3)	 **Fig. 5**. Shoulder tip

PHASES OF FSW

Physical phases of the FSW (Fig. 6) have been explained very well in literature[24], but for the completeness of analysis it is important to point them out again: welding procedure starts with the plunging of the welding tool into the material of the welding plates – plunging phase; when plunging stops, welding tool only rotates for a while in place – first dwelling phase; welding tool starts translation and creates weld – welding phase; welding stops and tool rotates in place – second dwell-

Table 4. Phases of the FSW and experimental data

Machine	CNC milling machine
Rotation speed	$n = 400\ \frac{\text{rotations}}{\text{min}},\ \omega = 41.87\ \frac{\text{rad}}{\text{s}}$
Welding speed	$v_x = 2\ \frac{\text{mm}}{\text{s}}$
Duration – plunging	$t_0 = -13.7$ s to $t_1 = -5$ s, $t_{pl} = 8.7$ s
Duration – dwelling	$t_1 = -5$ s to $t_2 = 0$ s, $t_{dw} = 5$ s
Duration – welding	$t_2 = 0$ s to $t_3 = 52.5$ s, $t_w = 52.5$ s
Duration – dwelling	$t_3 = 52.5$ s to $t_4 = 57.5$ s, $t_{dw} = 5$ s, no experimental data
Duration – pulling out	t_4 to t_5, no experimental data
Tilt angle	$\psi = 1°$
Effective plunge depth	$p_1 = 0.2$ mm

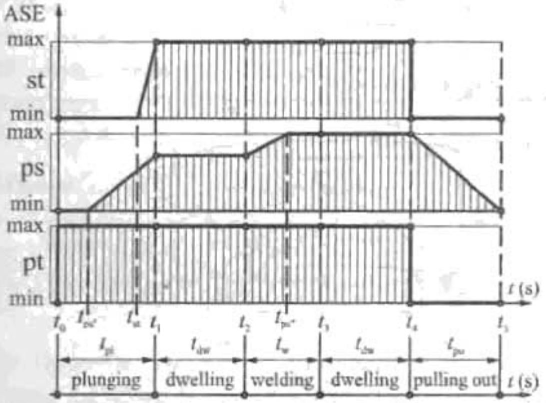


Fig. 7. Active surface engagement (ASE) during FSW welding process

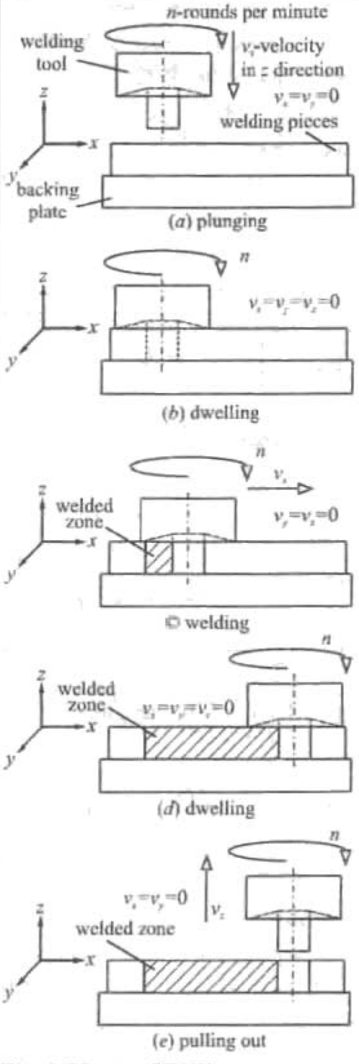


Fig. 6. Phases of FSW

ing phase; welding toll is taken away from the weld – pulling out phase. From the very start of the plunging phase until the end of the pulling out, welding tool and welding plate have contact on one or more active surfaces[24] while active surfaces involve in contact and in heat generation one by one or all of them at once, depending on welding phase. Engagement of active surfaces can be explained over active surfaces engagement (ASE) during FSW process shown in Fig. 7.

Probe tip is in contact with the welding plates from the beginning of plunging (t_0) until the end of second dwelling (t_4). Engagement of the probe tip in heat generation is maximum during complete duration. Probe side starts engagement when probe tip penetrates the matrix of the welding plates ($t_{ps'}$). This moment is directly connected with the contact pressure on the probe tip and will be explained in following chapters. Engagement of the probe tip increases until it reaches some value at the beginning of dwelling (t_1). It keeps this value until the end of the first dwelling phase (t_2). Further engagement increases to maximum when the welding process stabilises ($t_{ps''}$) – when welding tool reaches steady welding speed v_x. Engagement of the probe side drops to minimum at the end of the pulling out phase (t_5). Shoulder tip engages in heat generation when it starts to press the accumulated material on welding plates that was pushed up from the matrix during plunging (moment of time t_{st}). Maximum engagement happens when shoulder tip reaches top surface of welding plates (t_1) and it lasts until the end of the dwelling phase (t_4) when shoulder tip leaves the contact.

Relevant technological parameters of the experiment and durations of phases are given in Table 4.

PROCESS OF HEAT GENERATION

Heat generation can be defined as transformation of mechanical energy into thermal energy[22, 24]. During FSW this transformation happens while welding tool and welding plates relatively move one to another and active surfaces of welding tool have intimate contact with material of welding plates.

DUAL NATURE OF HEAT GENERATION. CONTACT CONDITION

Intimate contact between two moving bodies results to adhesion and deformation processes on both bodies. These processes appear on contact surface or in layer of material, close to contact surface, and dominantly influence the softer body[7, 9, 21, 22, 24–26].

Furthermore, contact condition in FSW is separated (from adhesion and deformation[22, 25]) to pure sticking, pure sliding and mixture of sliding/sticking[21]. Sliding condition appears when material of welding plates is capable to maintain the matrix consistent and tool slides over it without deformation – contact shear stress is in equilibrium with internal matrix shear stress. Sticking condition appears when welding tool deforms the matrix and particle from the matrix accelerate with the rotating welding tool – contact shear stress is greater than the yield strength of welding plate material.

Yield strength (elasticity limit) is a property of material that is not dependable from loads (e.g. pressure) but it changes its value when temperature and plastic strain rate of material change. As mentioned earlier, welding tool rotates while plunging into the welding plates and friction contact transforms significant part of mechanical energy into heat. Heat changes the temperature of the welding plates and value of the yield strength of welding plates changes in the contact area, as well. If one analyses the pure elastic and/or elasto-plastic contact condition, yield strength is in a functional dependency only with the temperature (T) of the material in contact area[21, 27]:

$$\sigma_{\text{yield}} = \sigma_{\text{yield}}(T). \tag{4}$$

Otherwise, when material is under plastic contact condition, yield strength depends on the temperature (T) and plastic strain (ε), as well:

$$\sigma_{\text{yield}} = \sigma_{\text{yield}}(T, \varepsilon). \tag{5}$$

Combination of pressure and rotation of welding tool induces shear stress in welding plates in the layer of material near the contact surface[21,25]. Considering the von Mises yield criterion in an uniaxial tension[27] and pure shear, yield shear strength τ_{yield} can be estimated as follows:

$$\tau_{\text{yield}} = \frac{\sigma_{\text{yield}}}{\sqrt{3}} \tag{6}$$

which, finally, gives that contact shear stress can be estimated as:

$$\tau_{\text{cont}} = \begin{cases} \mu(t, p, T, n, \ldots)\, p_m(t) & \text{– sliding condition} \\ \tau = \tau_{\text{yield}}(T, \varepsilon) = \dfrac{\sigma_{\text{yield}}(T, \varepsilon)}{\sqrt{3}} & \text{– sticking condition} \end{cases} \tag{7}$$

for both contact conditions; where T represents temperature in the layer of material near the contact surface and n – number of rotations per minute of the welding tool.

CONTACT STATE VARIABLE

One can expect a mixed contact condition state between the welding tool and welding plate during FSW: welding tool slides over plates (sliding condition) and deformed particles of welding plates stuck to the welding tool due to the work of adhesion forces (sticking condition). In this mixed state, the particle accelerates to a velocity smaller than the tool surface velocity, where it stabilises. The equilibrium establishes when the 'dynamic' contact shear stress equals the internal yield shear stress due to a quasi-stationary plastic deformation rate. This is referred to as the partial sliding/sticking condition. It is convenient to define a contact state variable δ, which relates the velocity of the contact points at the particles surface relative to the tool point in contact. This parameter is defined as follows:

$$\delta = 1 - \frac{\dot{\gamma}}{\omega r} = \frac{v_{\text{particle}}}{\omega r}, \; \dot{\gamma} = \omega r - v_{\text{particle}} \tag{8}$$

where $\dot{\gamma}$ is the slip rate, ωr – the position dependent tool velocity and v_{particle} – the translation velocity of the particle.

Contact state variable can be defined as follows:

(1) $\delta = 0$: contact condition is close to the pure sliding;

(2) $\delta = 1$: contact condition is close to the pure sticking;

(3) $0 < \delta < 1$: contact condition refers partial sticking and partial sliding.

Present works do not give mathematical background of the contact state variable and it is necessary to make some logical assumptions:

1. Probe tip is in contact with welding plates during complete FSW process (from t_0 to t_4) and it slides over the welding plates material; contact state variable can be assumed to be $\delta_{pt} = 0 \div 0.1$;

2. Probe side is in contact with welding plates from $t_{pt'}$ to t_5, it partially slides over material and partially deforms the material; contact state variable can be assumed to be $\delta_{ps} = 0 \div 0.5$;

3. Shoulder tip is in contact with welding plates from t_{st} to t_4 and it mostly slides over the welding plates; contact state variable can be assumed to be $\delta_{st} = 0 \div 0.1$.

CONTACT PRESSURE

Contact pressure within FSW is a tribological process that must follow any kind of contact between two solid bodies. In many tribological systems, contact pressure is considered as undesirable, however, it is always present and appears on every active surface, following the ASE of every single one.

At the beginning of FSW, probe tip touch the upper surface of welding plates and pushed by the plunging force $F_z(t)$ contact pressure $p_m(t)$ (equation (11)) appears on contact. It is important to mention that intensive plunging of the welding tool into the material of welding plates does not happen immediately when plunging phase starts, it happens when median contact pressure exceeds critical value[25, 28]:

$$p_m(t) > k\sigma_{\text{yield}}(T), \; k = 1.5 \div 3. \tag{9}$$

If this happens at time $t_{pt''}$, the critical value of the plunging force, when the intensive plunging begins, can be characterised as:

$$F_z(t_{pt''}) > \frac{1}{4} d^2 \pi k \sigma_{\text{yield}}(T). \tag{10}$$

Table 5. Contact pressure on active surfaces

$$p_{\mathrm{m}}(t)=\frac{4F_z(t)}{d(t)^2\pi},\ d(t)=d$$

$$t_0 \le t < t_{\mathrm{st}},\ 0 \le r \le \frac{d}{2} \tag{11}$$

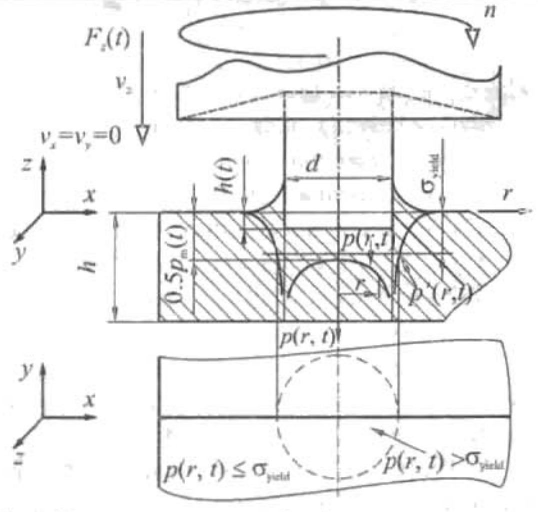


Fig. 8. Contact pressure on probe tip

$$p_{\mathrm{m}}(t)=\frac{4F_z(t)}{d(t)^2\pi},$$

$$d(t)=\begin{cases}\approx\dfrac{d-D}{t_{\mathrm{st}}-t_1}(t-t_{\mathrm{st}})+d, & t_{\mathrm{st}}\le t<t_1\\ D, & t_1\le t<t_4\end{cases} \tag{12}$$

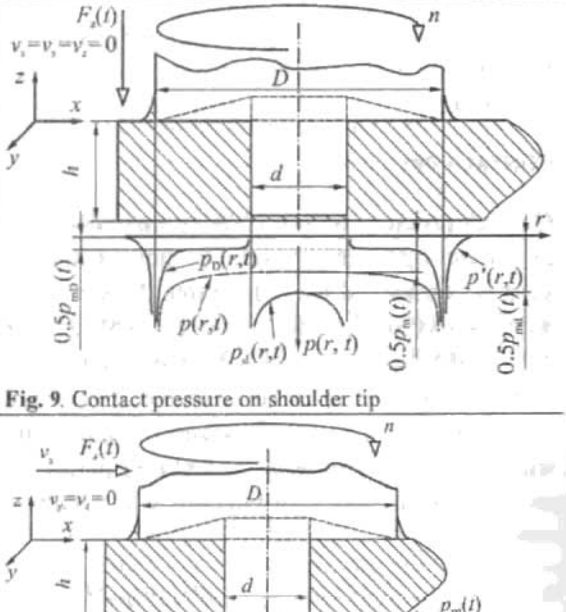


Fig. 9. Contact pressure on shoulder tip

$$p_{\mathrm{m}}(t)=\frac{F_x(t)}{dx},$$

$$x=h(t),\ t_{\mathrm{pl}}\le t<t_5 \tag{13}$$

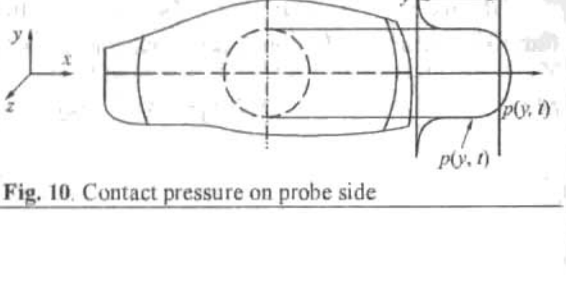


Fig. 10. Contact pressure on probe side

When shoulder tip touches the welding plates (in a moment of time t_{st}), contact pressure caused by the plunging force is calculated as shown in equation (12).

It can be considered that the initial contact between shoulder tip and welding plates appears when the plunging depth reaches $h(t) \approx 2/3h$. During the experiment, this happened at $t_{st} = 6.1$ s (Ref. 21).

Contact pressure (equation (13)) between probe side and welding material gets a notable value when welding phase starts and welding tool accelerates to the stationary, constant speed (in a moment t_{pt}). However, welding force $F_x(t)$ does not reach significant values (in the proposed experiment[21] it reaches maximal value of $F_{x\max} = 0.5$ kN) and heat generated by the probe side under sliding condition can be neglected (generated heat is less than 1 W).

Values of the plunging force $F_z(t)$ and welding force $F_x(t)$ have been obtained experimentally[21].

CONCLUSIONS

To predict or estimate the amount of generated heat during the friction stir welding process, it is necessary to recognise dominant contact condition between welding tool and base material, to determine contact pressure and recognise the engagement of the welding tool in heat generation. These are the main and needed prerequisites for the generated heat estimation. Further work on this topic will be given in Part 2 of this article.

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REFERENCES

1. W. M. THOMAS et al.: Friction Stir Butt Welding International Patent Application No PCT/GB92/02203 (1991); THOMAS W. M. et al.: Friction Stir Butt Welding GB Patent Application No 9125978.8 (1995); THOMAS W. M. et al.: Friction Stir Butt Welding UP Patent No 5460317 (1995).

2. D. SANTIAGO, U. SANTIAGO, G. LOMBERA, L. D. VEDIA: 3D Modeling of Material Flow and Temperature in Friction Stir Welding. Soldag. insp. (Impr.), **14** (3), 248 (2009).
3. J. E. GOULD, Z. FENG. Heat Flow Model for Friction Stir Welding of Aluminum Alloys. J. Mater. Process. Manu., 7 (1998).
4. D. ROSENTHAL, R. SCHRMERBER: Thermal Study of Arc Welding. Welding J., **17**, 208 (1938).
5. C. M. CHEN, R. KOVACEVIC: Finite Element Modeling of Friction Stir Welding – Thermal and Thermomechanical Analysis. Int. J. Mach. Tool. Manu., **43**, 1319 (2003).
6. M. SONG, R. KOVACEVIC: Thermal Modeling of Friction Stir Welding in a Moving Coordinate System and Its Validation. Int. J. Mach. Tool. Manu., **43**, 605 (2003).
7. P. ULYSSE: Three-dimensional Modeling of the Friction Stir-welding process. Int. J. Mach. Tool. Manu., **42**, 1549 (2002).
8. P. A. COLEGROVE, H. R. SHERCLIF: 3-Dimensional CDF Modelling of Flow Round a Threaded Friction Stir Welding Tool Profile. J. Mater. Process. Tech., **169**, 320 (2005).
9. R. NANDAN et al.: Numerical Modelling of 3D Plastic Flow and Heat Transfer during Friction Stir Welding of Stainless Steel. Science and Technology of Welding and Joining, **11**, 526 (2006).
10. R. NANDAN et al.: Three-dimensional Heat and Material Flow during Friction Stir Welding of Mild Steel. Acta Materialia, **55**, 883 (2007).
11. Y. J. CHAO, X. QI: 1st Int. Symp. on Friction Stir Welding, Thousand Oaks, CA, USA, 1999.
12. O. FRIGAARD, O. GRONG, O. T. MIDLING: A Process Model for Friction Stir Welding of Age Hardening Aluminium Alloys. Metall. Mater. Trans. A, **32**, 1189 (2001).
13. O. FRIGAARD, O. GRONG, B. BJORNEKLETT, O. T. MIDLING: 1st Int. Symp. on Friction Stir Welding. Thousand, Oaks, CA, 1999.
14. M. J. RUSSELL, H. R. SHERCLIFF: 1st Int. Symp. on Friction Stir Welding. Thousand Oaks, California, USA, 1999.
15. P. COLEGROVE: 2nd Int. Symp. on Friction Stir Welding. Gothenburg, Sweden, 2000.
16. H. R. SHERCLIFF, P. A. COLGROVE: Modelling of Friction Stir Welding. Math. Modelling Weld. Phenom., 6, 927 (2002).
17. S. XU, X. DENG, A. P. REYNOLDS: Sci. Technol. Weld. Joining, **6**, 191 (2001).
18. M. Z. H. KHANDKAR, J. A. KHAN, A. P. REYNOLDS: Sci. Technol. Weld. Joining, **8**, 165 (2003).
19. Q. SHI, T. DICKERSON, H. R. SHERCLIFF: 4th Int. Symp. on Friction Stir Welding. Park City, UT, USA, 2003.
20. K. KUMAR, C. KALYAN, KAIAS, V. SATISH, T. S. SRIVATSAN: An Investigation of Friction during Friction Stir Welding of Metallic Materials, Materials and Manufacturing Processes, **24** (4), 438 (2009).
21. H. SCHMIDT, J. HATTEL, J. WERT: An Analytical Model for the Heat Generation in Friction Stir Welding. Modeling Simul. Mater. Sci. Eng., **12** (1), 143 (2004), PII: S0965-0393(04)69225-4, http://iopscience.iop.org/0965-0393/12/1/013/
22. M. DJURDJANOVIC: The Calculation of the Heat Power Generation during the Formation of the End of Cylindrical Tube by Friction. Tribology in Industry, **19** (2), 72 (1997).
23. L. A. GALIN: Contact Problems. The legacy of L. A. Galin, Series: Solid Mechanics and Its Applications. **155** (Eds L. A. Galin, G. M. Gladwell), Original Russian edition published by Nauka, Moscow, Russia, 1953, 1980, 2008, XIV. 318 p.

24. M. DJURDJANOVIC, M. MIJAJLOVIC, D. MILCIC, D. STAMENKOVIC: Heat Generation during Friction Stir Welding Process. Tribology in Industry, (1–2), 2009, Serbia, Kragujevac, Faculty of Mechanical Engineering Kragujevac, May, Journal, **31** (1–2), 8 (2009).
25. F. P. BOWDEN, D. TABOR: Friction – An Introduction to Tribology. Anchor Press / Doubleday. Reprinted 1982, Krieger Publishing Co., Malabar, 1973.
26. H. SCHMIDT, J. HATTEL: Thermal Modeling of Friction Stir Welding. Scripta Materialia, **58** (5), 332 (2008).
27. K. HEDRIH (STEVANOVIC): Some Chapters in Theory of Elasticity. Faculty of Mechanical Engineering Nis (Izabrana poglavlja Teorije elasticnosti, Masinski fakultet Nis), 1976 and 1988 (in Serbian).
28. D. TABOR: A Simple Theory of Static and Dynamic Hardness. In: Proc. of the Royal Society of London. Series A, Mathematical and Physical Sciences, **192** (1029), 247 (1948). The Royal Society, Stable URL: http://www.jstor.org/stable/98140
29. G. ILIC, N. RADOJKOVIC, I. STOJANOVIC: Thermodynamic II – Fundamentals of Heat Propagation. Vranje, Yugoslavia, 1996 (Termodinamika II – Osnove prostiranja toplote, Vranje, Yugoslavia) (in Serbian).

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