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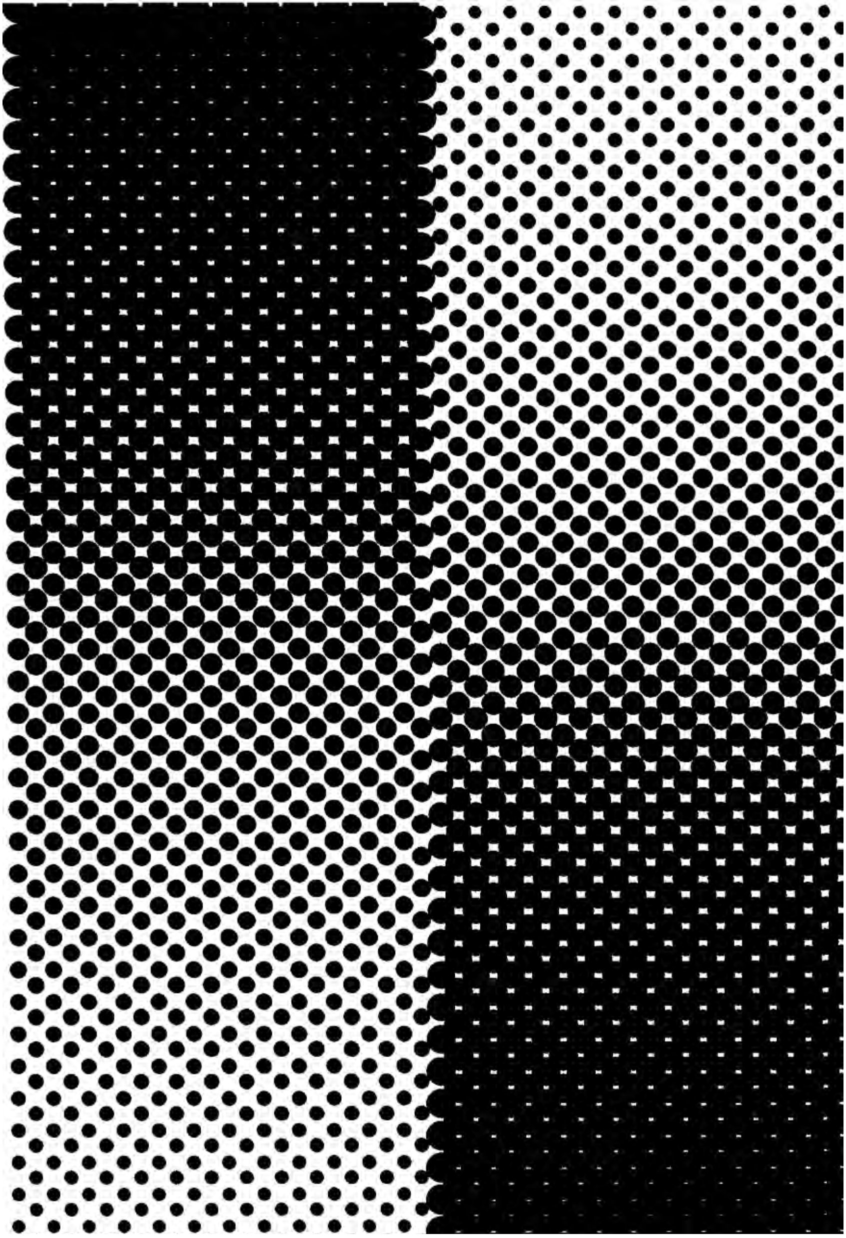

Journal of the Balkan Tribological Association is an International Journal edited by the Balkan Tribological Association for rapid scientific and other information, covering all aspects of the processes included in overall tribology, tribomechanics, tribochemistry and tribology.
The Journal is referring 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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Compiled by S. K. Ivanov, Zh. D. Kalitchin, J. P. Ivanova, M. I. Boneva, N. Evtimova and E. Tosheva.

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Friction welding

MATHEMATICAL MODEL FOR ANALYTICAL ESTIMATION OF GENERATED HEAT DURING FRICTION STIR WELDING. PART 2

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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 capable to precisely describe heat generation during FSW. 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.

This article is a direct follow-up of the article 'Mathematical Model for Analytical Estimation of Generated Heat during Friction Stir Welding. Part 1'.

Keywords: friction stir welding, heat generation.

FRICTION COEFFICIENT

Friction coefficient is a value easy to define but difficult to determine[1]. Friction stir welding (FSW) got the name because of the friction being the dominant (tri-

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* For correspondence.

bological) process during this type of welding. However, investigation of the friction coefficient in FSW has not been the primary area of researches in FSW in the past and in most of the investigations, friction coefficient has been proposed as a single, constant value.

Complexity of the friction during FSW showed several levels:

(a) Friction coefficient can be static and kinematic; when and how it changes its nature?

(b) Friction coefficient is not the same for every active contact surface.

(c) Friction coefficient depends on many other physical/tribological processes and it is difficult to follow all the dependences between them.

This brings all researches to the beginning: friction coefficient is very difficult to be determined analytically.

Kumar[2] has proposed a method to determine median value of the friction coefficient in FSW experimentally, without concern of the nature and complexity of friction. It bases on the main Colombo equation that makes a bond between the normal force F_n, applied on a body set on some realistic surface, and frictional force F_μ:

$$F_\mu = \mu F_n,\ \mu = F_\mu / F_n \tag{1}$$

where μ represents the median friction coefficient between the body and the surface.

In the case of FSW, welding tool plunges into the welding plates, with normal, plunging force $F_z(t)$. At the same time, welding tool rotates and delivers the torque $M(t)$, to the contact.

Following equation (1) and analysing contact mechanics, Galin[3] proposed a dependence between torque $M(t)$, friction coefficient $\mu(t,\dots)$ and normal force between two bodies (semi-rigid punch and elastic half space) in contact $F_z(t)$:

$$M(t) = \frac{1}{3}\mu(t,\dots)F_z(t)d(t) \tag{2}$$

where $\mu(t,\dots)$ represents the median value of experimental friction coefficient and $d(t)$ – the diameter of the punch (equation (3)), in this case active diameter of the welding tool (given and well explained in Part 1 (Ref. 4)):

$$d(t) = \begin{cases} \approx \dfrac{d-D}{t_{st}-t_1}(t-t_{st})+d, & t_{st} \le t < t_1 \\ D, & t_1 \le t < t_4 \end{cases} \tag{3}$$

Transformation of equation (2) gives the friction coefficient:

$$\mu(t,\dots) = \mu = \frac{3M(t)}{F_z(t)d(t)},\ t_0 \le t \le t_5. \tag{4}$$

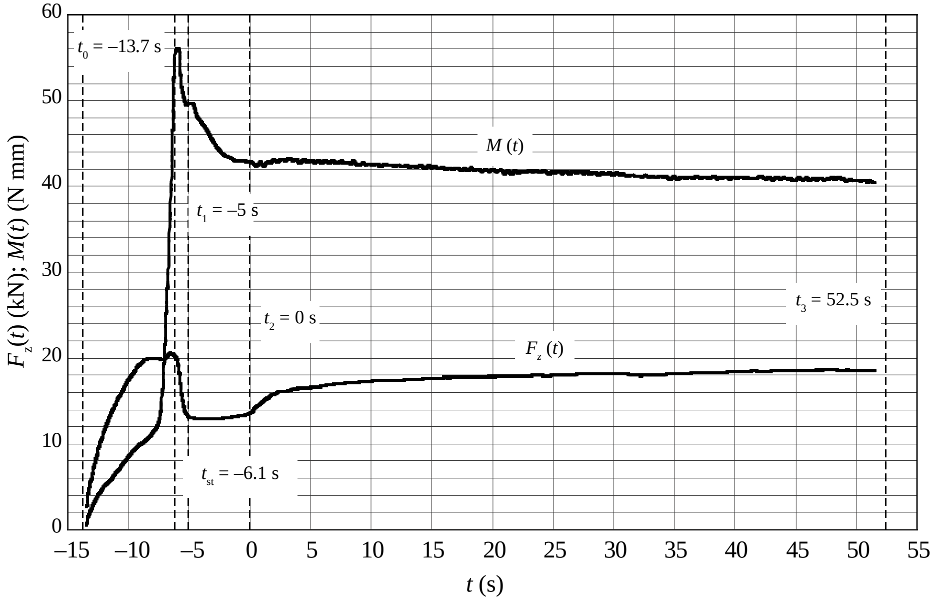

Fig. 1. Experimental torque $M(t)$ and plunging force $F_z(t)$

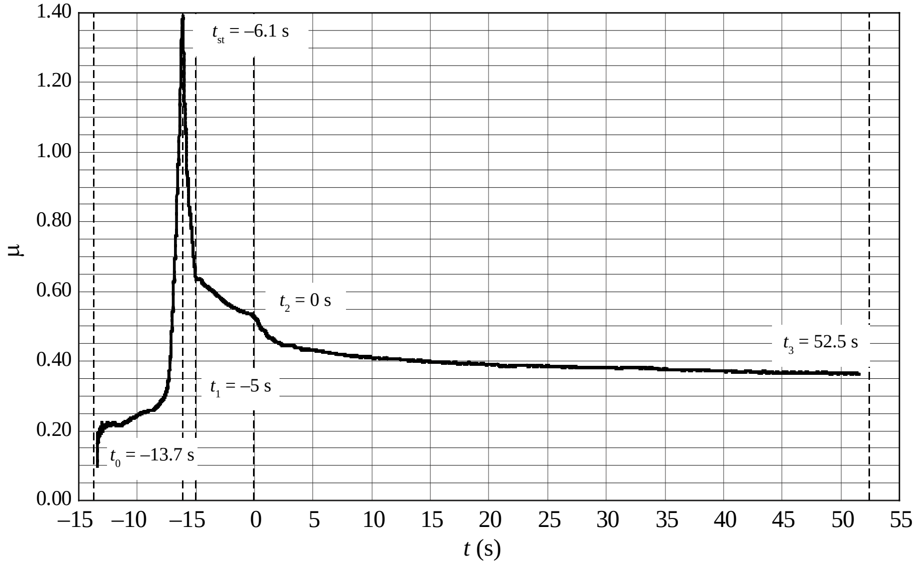

Fig. 2. Experimental value of friction coefficient μ

Schmidt[5] gave experimental results of the plunge force $F_z(t)$ and torque $M(t)$ (Fig. 1). The corresponding friction coefficient μ values are estimated using equation (4) and shown in Fig. 2.

TOTAL GENERATED HEAT

Total generated heat is a sum of heat generated on all active surfaces during time:

$$Q_{\text{total}}(t) = Q_{\text{pt}}(t) + Q_{\text{ps}}(t) + Q_{\text{st}}(t). \tag{5}$$

Concerning duality of heat generation, total heat generated on active surface is sum of sticking Q^{st} and sliding Q^{sl} component of heat, with respect on contact state variable δ[4], assuming that every active surface has different contact state variable, changeable during time – $\delta_{\text{pt}}(t)$, $\delta_{\text{st}}(t)$, $\delta_{\text{ps}}(t)$:

$$\begin{aligned} Q_{\text{pt}}(t) &= \delta_{\text{pt}}(t)Q_{\text{pt}}^{\text{st}}(t) + \left(1-\delta_{\text{pt}}(t)\right)Q_{\text{pt}}^{\text{sl}}(t), \\ Q_{\text{ps}}(t) &= \delta_{\text{ps}}(t)Q_{\text{ps}}^{\text{st}}(t) + \left(1-\delta_{\text{ps}}(t)\right)Q_{\text{ps}}^{\text{sl}}(t), \\ Q_{\text{st}}(t) &= \delta_{\text{st}}(t)Q_{\text{st}}^{\text{st}}(t) + \left(1-\delta_{\text{st}}(t)\right)Q_{\text{st}}^{\text{sl}}(t), \end{aligned} \tag{6}$$

what gives:

$$\begin{aligned} Q_{\text{total}}(t) &= \delta_{\text{pt}}(t)Q_{\text{pt}}^{\text{st}}(t) + \left(1-\delta_{\text{pt}}(t)\right)Q_{\text{pt}}^{\text{sl}}(t) + \delta_{\text{ps}}(t)Q_{\text{ps}}^{\text{st}}(t) \\ &+ \left(1-\delta_{\text{ps}}(t)\right)Q_{\text{ps}}^{\text{sl}}(t) + \delta_{\text{st}}(t)Q_{\text{st}}^{\text{st}}(t) + \left(1-\delta_{\text{st}}(t)\right)Q_{\text{st}}^{\text{sl}}(t). \end{aligned} \tag{7}$$

Sticking components of the total generated heat directly depends on the temperature history of the welding plates. Temperature of the welding plates influences the yield strength of the material and it is clear that total generated heat and temperature are directly influencing one to another, throughout of the FSW. It is necessary to use step-by-step approach to determine precise values of generated heat: total generated heat is calculated for initial conditions and temperatures of welding plates after influence of generated heat, these values become initial conditions for next time step. Procedure repeats until the end of the FSW process. Thermal history of welding plates is used for estimation of yield strength of welding plates.

Temperature of the welding plates during FSW can be modelled as a 3D heat transfer problem with a moveable heat source[6–9]. Problem of welding plate temperature history estimation starts with the following heat equation:

$$\rho c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{dQ_{\text{total}}}{dV}. \tag{8}$$

Explanation of heat equation parameters is given in Table 1. Derivation $\frac{dQ_{\text{total}}}{dV}$ is explained as 'volume heat of a moving source' – total generated heat distributed to the control volume[10].

Heat equation can be solved numerically, applying explicit scheme of finite difference method, what demands discretisation of welding plates volume, discre-

Table 1. Numerical solution of heat equation

Thermal history calculation	
Median density of 2024 T3	$\rho = 2700 \dfrac{\text{kg}}{\text{m}^3}$
Specific heat for 2024 T3	$c = 900 \dfrac{\text{J}}{\text{kg °C}}$
Thermal conductivity coefficient	$\lambda = 300 \dfrac{\text{W}}{\text{m °C}}$
Initial temperature	$T_0 = 20°\text{C}$
Convection heat transfer coefficient	$\alpha = 15 \dfrac{\text{W}}{\text{m}^2\ °\text{C}}$
Convection heat transfer coefficient	$\alpha_{\text{sim}} = 3000 \dfrac{\text{W}}{\text{m}^2\ °\text{C}}$
Time step	$\Delta t = 0.001$ s
Mesh	$\Delta x_{\min} = 2$ mm $\Delta y_{\min} = 2$ mm $\Delta z_{\min} = 1$ mm

Yield strength of 2024 T3		
T (°C)	σ_{yield} (N/mm^2) no plastic strain	σ_{yield} (N/mm^2) plastic strain
24	345	483 / 0.18
100	331	455 / 0.16
149	310	379 / 0.11
204	138	186 / 0.23
260	62	76 / 0.55
316	41	52 / 0.75
371	28	34 / 1.00
400	21	25 / 1.00

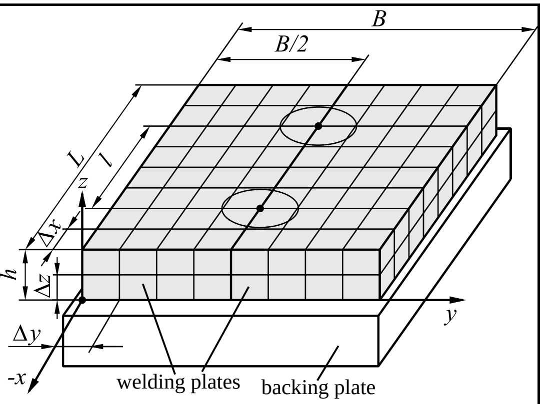

Fig. 3. Welding plates – mesh

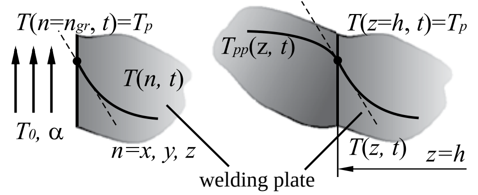

Fig. 4. Welding plates – boundary conditions

$$-\lambda\left(\frac{\partial T}{\partial x}\right)_{x=0|L} = \alpha\left(T_{p,x=0|L} - T_0\right),$$

$$-\lambda\left(\frac{\partial T}{\partial y}\right)_{y=0|B} = \alpha\left(T_{p,y=0|B} - T_0\right),$$

$$-\lambda\left(\frac{\partial T}{\partial z}\right)_{z=h} = \alpha\left(T_{p,z=h} - T_0\right),$$

$$-\lambda\left(\frac{\partial T}{\partial z}\right)_{z=0} = -\lambda_{pp}\left(\frac{\partial T_{pp}}{\partial z}\right)_{z=0}$$

$$-\lambda\left(\frac{\partial T}{\partial z}\right)_{z=0} = \alpha_{\text{sim}}\left(T_{p,\,z=0} - T_0\right)$$

tisation of time, with special care on solution convergence, and setting up initial and boundary conditions for the welding plates[10]. An approximation set to the numerical solution defines that all thermal coefficients, used during heat equation solving, are considered to be constant values. This approximation will not dramatically influence the precision of results as proper selection of discretisation parameters: time step Δt and finite difference step Δx, Δy and Δz (Ref. 10).

Numerical solution of the heat equation for the proposed initial and boundary conditions is a set of temperatures ($T_{\text{t,x,y,z}}$) in a specific, discrete moment of time (t), for discrete points in welding plate (Fig. 4) – coordinates (x, y, z), given in

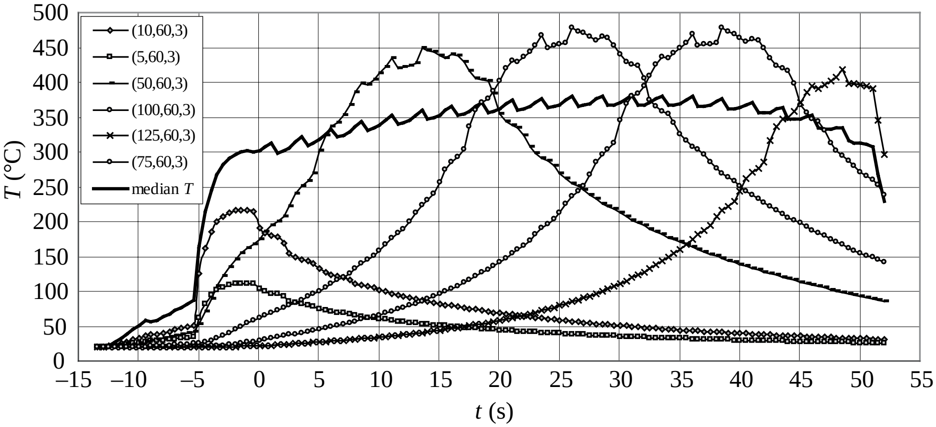

Fig. 5. Thermal history of welding plates

mm. Coordinates of points are in correspondence with the coordinate system and welding plates orientation given in Fig. 3. One piece of the welding plate thermal history is given in Fig. 5.

As it can be seen from Fig. 5, temperature varies from node to node and over time. This leads to variable yield strength of welding plates in different parts of welding plates, no matter how close they are one to another.

To obtain temperature usable for calculations, it is necessary to recognise the part of the welding tool where temperature has dominant influence on the yield strength and heat generation. Since deformational component of generated heat is greater on probe side than on any other active surface, it is suitable to recognise probe side; more precise explained: advancing side of the probe side, as active surface where temperature and yield strength should be analysed. Figure 6 schematically shows advancing side of the probe side and discrete nods on contact surface, where temperature of welding tool/welding plates is calculated.

To simplify the problem, it is easiest, but still precise enough, to consider temperature on the advancing side of probe side as median temperature of all nods on contact between advancing side of the probe side and welding plates:

$$\overline{T}\left(t,x,y,z\right)=\frac{\sum\limits_{s=1}^{s=n_{\mathrm{nod}}} T_s\left(t,x_s,y_s,z_s\right)}{n_{\mathrm{nod}}} \tag{9}$$

where $\overline{T}$ (t, x, y, z) is median temperature on advancing side of the probe side, dependable on time t and space (x, y, z), T_{s} (t, x, y, z) – the temperature of nod S: $(x_{\mathrm{s}}, y_{\mathrm{s}}, z_{\mathrm{s}})$ in moment of time t, n_{nod} – number of nods on advancing side of the probe side where temperature is calculated. Median temperature $\overline{T}$ (t, x, y, z) is calculated for complete duration of FSW process, with attention on position of the welding tool during welding process, and shown in Fig. 5 as dataset ‘Median T’.

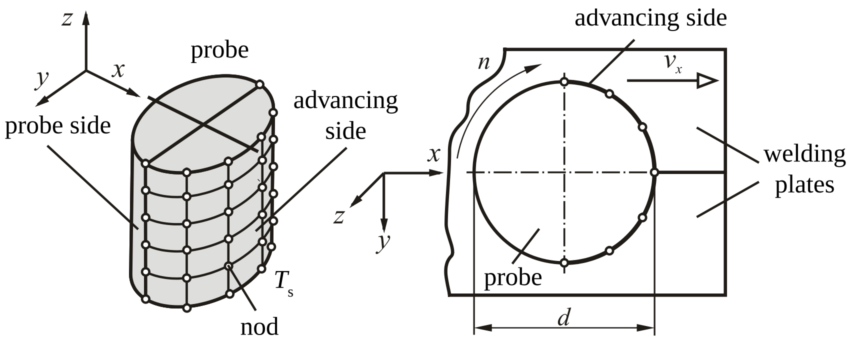

Fig. 6. Discrete nods on advancing side of the probe

Neglecting the plastic strain that appears around the probe side, this median temperature $\overline{T}\,(t, x, y, z)$ is used to define the value of yield strength $\sigma_{\text{yield}}\,(T)$ using the values given in Table 1.

EXPERIMENTAL POWER VERSUS ANALYTICAL GENERATED HEAT. DISCUSSION AND CONCLUSIONS

Finally, the generated heat is estimated for the conditions that were used in the experiment and compared to the experimentally monitored power. Figure 7 shows experimental power $P(t)$ given in experiment[5] and analytical generated heat $Q(t)$.

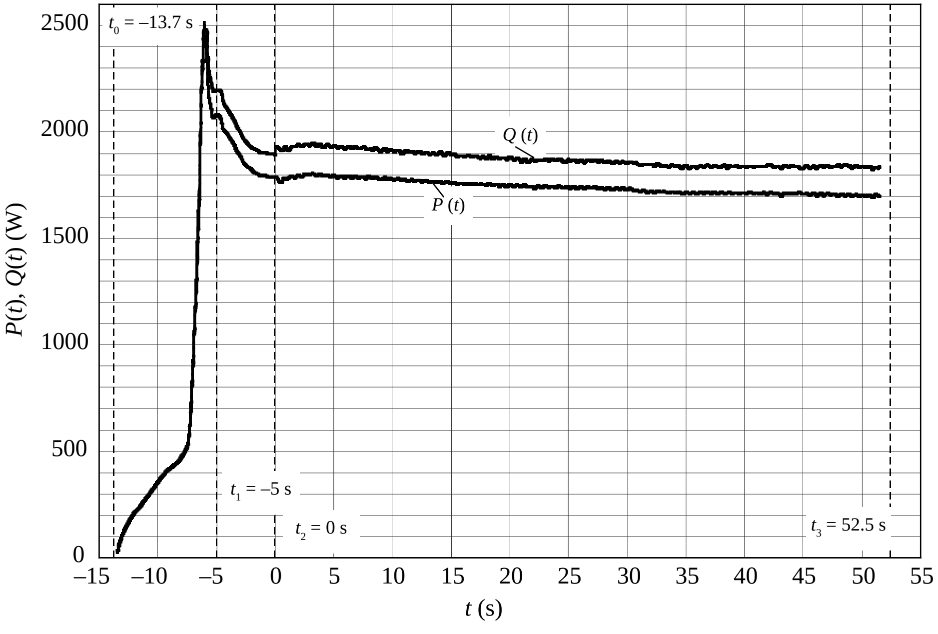

Fig. 7. Experimental versus analytical power

From the beginning of the plunging $t_0 = -13.7$ s until the moment when the shoulder tip touches welding plates $t_{st} = -6.1$ s, experimental and analytic values are almost identical (maximum difference $P(t) - Q(t) < 100$ mW). The main reason for such a coincidence between results might be found in fact that the heat is generated only at the probe tip, while probe side and shoulder tip have only minor or have no influence on heat generation.

Thus, the assumption that during pure sliding with minor deformations, during this time period dominates, has been proved. After t_{st} analytically estimated heat keeps the same trend as experimental power, but continuously has a 6÷12 % greater value until the end of the welding phase. Since this imperfection appears after the engagement of the shoulder tip, it can be concluded that the generated heat under shoulder tip is a bit smaller than it is estimated. This is proven by the fact that contact between shoulder tip and welding plates is purely sliding since the welding plates are softened after the period of plunging. On the other hand, the tilt angle is neglected in analytical estimation as well as the thread on the probe, what might result in shown difference.

Finally, it is shown that sliding component of the generated heat is dominant in total amount of heat during complete FSW process. During plunging phase, sliding is almost a 100% of the total heat, generated on the probe tip. Deformation component is far less, but still, it is not possible to neglect it in calculations. During welding phase, sliding still dominates but not as much as during plunging and first dwelling phase. Mathematical model proposed by this work is relied on numerous previous works, it summarises collected knowledge and uses all the results gathered by experiment proposed by Schmidt[9]. Algorithm for generated heat estimation given in this paper might be useful for following researches in area of heat generation in FSW.

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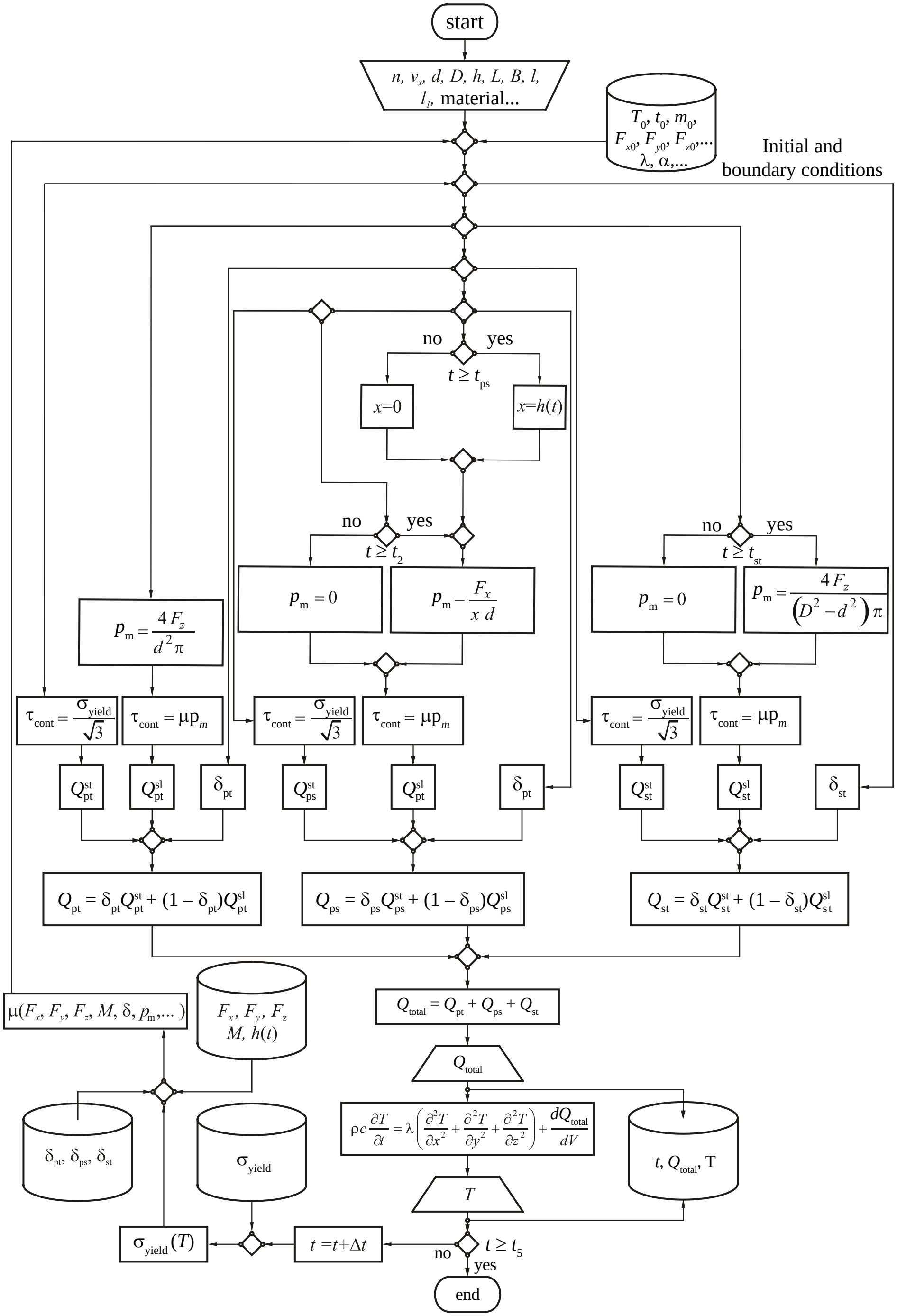
Appendix. Algorithm of heat generation estimation



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