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ABOUT THE INFLUENCE OF FRICTION COEFFICIENT ON HEAT GENERATION DURING FRICTION STIR WELDING

Miroslav Mijajlović¹, Dušan Stamenković¹, Miroslav Đurđanović¹, Dragan Milčić¹

¹ Faculty of Mechanical Engineering Niš, Serbia

mijajlom@masfak.ni.ac.rs; dusans@masfak.ni.ac.rs; djurdjan@junis.ni.ac.rs; milcic@masfak.ni.ac.rs

Abstract: Friction Stir Welding uses mechanical energy and heat as welding process's activation energy. Mechanical energy is given to the welding tool by welding machine and great portion of that energy is consumed in heat generation on or near the contact between welding tool and base metal. Many studies on FSW processes imply duality of generated heat appearance: it is a direct product of sliding and sticking processes that happen during FSW. Moreover, it is shown that frictional processes dominate in all processes included in heat generation. Almost 20 years after first application of FSW, friction remains unclear and hard to explain tribological phenomenon. Serious studies on FSW point out the necessity of friction demystification as a need for heat generation explanation. Paper gives brief state of the art analysis on influence of friction to the FSW, especially on heat generation process. Numerous studies propose contact and boundary conditions of processes that appear during FSW but very few loudly propose explanations of frictional processes. Since heat and friction are depending and changing one from another, paper will give ideas and experimental researches that show the dependency of heat and friction and might help in further work on heat generation explanation.

Keywords: Friction Stir Welding, Friction Coefficient, Heat Generation

1. INTRODUCTION

As a solid state welding procedure, Friction Stir Welding (FSW) [1] uses pure mechanical energy as welding process activation energy and distributes it from the welding machine to the base material (welding plates) over a specialized, profiled welding tool. However, only one part of the mechanical energy is used directly as a mechanical energy while the rest of it is transformed in other types of energy: into heat, light, electricity, radiation etc. Researches, experience and engineering practice have shown that, as a result of any kind of energy transformation, direct or indirect product of energy use is transformation of input energy into heat, partially or almost completely. This is a phenomenon that appears during the FSW process as well: mechanical energy given to the welding tool is dominantly transforming into the heat, some of it stays mechanical and the rest of it is transformed in other types of energy (Figure 1).

Transformation of power happens on the intimate contact between welding tool and welding plates or in a thin layer of the softer material (in this case it is the material of welding plates).



Figure 1. Power transformation during FSW

Recognizing the fact that almost all mechanical power given to the welding process (input power) transforms into the heat¹, also assuming:

¹ The common phrase that explains transformation of the mechanical power into heat is "heat generation".

- heat generated by rotation of the welding tool (Q_{rot}) is far greater than the heat generated by translation of the welding tool (Q_{tran}) and translation heat is equal to the $Q_{tran} \approx 0$ W,
- contact condition between welding tool and welding plates can be defined as pure adhesion, pure deformation and partial adhesion – deformation²,

Colegrove [2] and Schmidt [3] have proposed equations for estimation of generated heat on a contact surface of the welding tool, influenced by rotation, $Q_{surf, rot}$:

$$Q_{surf,rot} = \omega \cdot S_{surf} \cdot \tau_{contact}, \qquad (1)$$

where:

 ω [rad/s] – angular speed of the welding tool,

 S_{surf} [m³] – voluminous constituent of the generated heat, dependable from the shape of the contact surface (probe tip, probe side, shoulder tip, basic active surfaces on the FSW welding tool [4]), For example, voluminous constituent of the generated heat for the probe tip – *pt* (Figure 4) surface of the welding tool [4] can be defined as:

$$S_{pt} = \frac{2}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3, \qquad (2)$$

d [m] – diameter of the probe on the welding tool [4], and

 $\tau_{contact}$ [N/m²] – shear stress on contact between welding tool's surface and welding plates.

Angular speed of the welding tool ω and voluminous constituent of the generated heat S_{surf} are pure technological and geometrical parameters of the FSW process and their influence on amount of the generated heat is not so complicated to explain: the greater values of ω and S_{surf} are, the greater value of the generated heat $Q_{surf, rot}$ is. However, there is indirect influence of these parameters on other parameters that involve heat generated heat, defined as shear stress on contact between welding tool and welding plate $\tau_{contact}$ is, in fact, describing the true nature of the generated heat by describing the contact condition.

2. CONTACT CONDITION

While rotating and moving along the joint line in the welding phase of FSW [4] welding tool induces contact pressure and contact shear stress in the layer of welding plates [2, 4]. Based on assumed dual nature of the contact condition (adhesion – deformation what is terminologically equal to sliding – sticking), contact shear stress can be estimated as:

$$\tau_{contact} = \begin{cases} \mu(t, p, T, \omega...) \cdot p_m(t) & -\text{ sliding} \\ \tau_{yield}(T, \varepsilon) = \frac{\sigma_{yield}(T, \varepsilon)}{\sqrt{3}} & -\text{ sticking} \end{cases}$$
(3)

where:

 μ (t, p, T, ω ...) = μ – friction coefficient on the contact of the welding tool's surface and welding plates,

t [s] – time,

 $p [N/m^2]$ – contact pressure,

 $T [^{\circ}C]$ – temperature,

 p_m (t) [N/m²] – time dependent median contact pressure,

 τ_{yield} (*T*, ε) [N/m²] – temperature and strain dependent yield shear strength of welding plates, ε [-] – strain rate,

 σ_{yield} (*T*, ε) [N/m²] – temperature and strain dependent yield shear strength of welding plates.

This means that heat is generated while welding tool presses and slides over the material of welding plates and while deforms the particles of welding plates; these heat generation processes happen mutually, simultaneously, and dependable one from another.

3. INFLUENCE OF THE FRICTION COEFFICIENT ON HEAT GENERATION

Equation 3 shows that the friction coefficient on contact μ (*t*, *p*, *T*, ω ...) influences the contact shear stress $\tau_{contact}$ when pure or partial sliding condition appears. Sliding is a dominant contact mechanism and it is always present in contact problems, when relative movement appears [2, 4]. Basically, friction coefficient is always influencing the contact condition between welding tool and welding plates.

However, relationship between contact condition – friction coefficient – heat generation is not purely one sided nor single parametrically influenced. For example, if some analyze only previously mentioned tribo – parameters (e.g. p, T, ω , $\tau_{contact}$) and neglect all other tribo – parameters (surface hardness, surface roughness, surface corrosion, lubrication, cleanness etc.) that might influence heat generation or friction coefficient, graph of mutual relationships between parameters will get a bit difficult to follow (Figure 2).

For example, following the graph given in Figure 2, and symbolic representation of influences and relationships between parameters³, S_{surf} is

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² Also can be found as pure sliding, pure sticking and partial sliding – sticking.

³ Relationship between parameters ① and ② can be:

directly influencing μ but μ is not influencing S_{surf} ; μ is directly influencing p and p is directly influencing μ ; μ is directly influencing $\tau_{contact}$ and $\tau_{contact}$ is directly influencing Q_{surf} , rot, so μ is indirectly influencing Q_{surf} .



Figure 2. Graph of mutual relationships between some of the tribo – parameters

Analyzing the graph in Figure 2, one can say that friction coefficient μ is directly depending from the most of FSW parameters (technological, geometrical or/and tribological) and indirectly depending from all other (tribological) parameters. This conclusion returns the analysis to the beginning: friction coefficient is a tribological parameter whose value is relatively easy to measure but whose nature is difficult to explain." [5].

When researchers from TWI [1] patented the Friction Stir Welding as a novel welding procedure they were fully aware of the importance of the "friction" processes / phenomena in application of their patent so they used it for name of the procedure. With such a great number of influencing parameters, with complex relationships between parameters and still present ambiguity of the FSW process itself, friction coefficient in FSW is not at all a value easy to measure and even more hard to explain. Without any doubt, TWI researchers had no idea what a challenge will they make to the FSW researches around the globe with the word "friction" in FSW.

Early researches on the FSW were based on the "try and error" principle and aimed to the optimal geometry of the welding tool retrieval, technological parameters (speed and rotation of the machine) selection and proper materials usage (as well for the welding tool, as well for the welding plates). When usable results were found, researches have extended to the increase of weld's quality,

stress and strain analysis, and material flow, thermal influences on welding plates and welding tools, heat generation during FSW etc. At the beginning, friction coefficient was not of interest in researches. However, when researches aimed into FSW modelling (heat, temperature fields, stress and strain, material flow, residual stresses etc.), friction coefficient became interesting and necessary to be estimated. As one of the pioners in this area, Schmidt et al [3, 6, 7] has researched analytical thermomechanical model in FSW with a goal to understand material disposal during rotation of the welding tool in a qualitative manner. Friction coefficient was a necessity for the analysis made in ABAQUS / Explicit software used in this work, and authors have used the value of 0.3 for the complete process. In the following works, friction coefficient was mentioned as an important parameter that takes values from 0.3 to 0.4 for the welding phase of the FSW [6]. Results were not confirmed analytically or experimentally – they were predicted due to the experimental setup of conducted experiments [3].

Chen et al. [7] used a theoretical approach on friction coefficient estimation and calculated that the coefficient of friction cannot be greater than 0.577 in FSW. Duffin et al. [9] experimentally determined the friction coefficient exceeds 0.57 during friction welding processes (not FSW), and reported the coefficient of friction to be 1.5, 1.9, 2.1 and 2.7 for the welding of mild steel. Similar results were reported by Reid [10] for the welding of pure copper. Heurtier et al. [11] has modelled material flow around the welding tool and showed thermal history of the flown material with application of the friction coefficient of 0.2 to 0.9. Values of the friction coefficient were assumed.

Numerous authors [6 - 25] have experimentally and analytically worked on problems of heat generation during FSW, thermal modelling, stress distribution, deformation and material flow and they have suggested that friction coefficient in FSW varies from 0.1 to 1.6 dependably on contact pressure, temperature, materials etc. However, none of them has experimentally measured friction coefficient or analytically estimated the value of friction coefficient. Furthermore, no one has suggested that friction coefficient changes its value. All of the mentioned results were assumptions due to the results from similar researches, guesses or analogies with the machining processes – milling, drilling etc.

Summarization of the friction coefficient: it varies from 0.1 to 2.7 in friction welding processes (FSW and other frictional welding processes, for welding of aluminium, steel, copper etc.).

There are only few works that have reported experimental estimation of the friction coefficient.

[&]quot; $\mathbb{O} \rightarrow \mathbb{O}$ " what means: \mathbb{O} is influencing \mathbb{O} , no vice versa effect; " $\mathbb{O} \leftrightarrow \mathbb{O}$ " what means: \mathbb{O} is influencing \mathbb{O} and vice versa, " \mathbb{O} \mathbb{O} " what means: no relationship between \mathbb{O} and \mathbb{O} .

Main reasons for such a lack of researches on friction coefficient lays in complexity of the process, difficult measuring task and ambiguity of the process itself.

However, Kumar et al. [26] reported experimentally estimated values of the friction coefficient during plunging and the first dwelling phases of the FSW welding process. Experiment is based on the well known equation for the friction coefficient:

$$\mu = F_t(t) / F_n(t). \tag{4}$$

To determine friction coefficient μ , it is necessary to measure tangential force $F_t(t)$ and normal force $F_n(t) = F_z(t)$ that appear during experiment.

Experimental setup that measures normal and tangential forces applied on the welding tool is given in Figure 3.



Figure 3. Scheme of the experimental setup for friction coefficient estimation during plunging and first dwelling phases of the FSW process

Following the Equation 4 and analyzing contact mechanics, Galin [27] proposed a dependency between torque M(t), friction coefficient μ and normal force $F_z(t)$ between two solid bodies (semi-rigid punch and elastic half space) in contact:

$$M(t) = \frac{1}{3} \cdot \mu \cdot F_z(t) \cdot d(t)$$
(5)

where: d(t) [m] – is diameter of the punch, value dependable on time t and the phase of the FSW

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process [28]. Transformation of the Equation 5 gives the friction coefficient:

$$\mu = \frac{3 \cdot M(t)}{F_z(t) \cdot d(t)} = \frac{3 \cdot F_t(t) \cdot L_t}{F_z(t) \cdot d(t)}.$$
(6)

Kumar has proposed results for a set of conducted experiments where he changed value of contact pressure (normal force), angular rotation of the welding tool and plunging time. Friction coefficient varied from 0.2 to 1.6 (during phases of the FSW and for different technological parameters of the FSW process) [25]. His results are comparable with the results of other presented works.

However, despite the relatively simple construction of monitoring system and excellent results that can be used for further researches Kumar's model has some flaws:

- it can be used only for the first two phases of the FSW process – plunging and first dwelling phases, due to the rigidity and immovability of the monitoring system;
- friction coefficient calculated according to the Kumar's model has to be treated as approximate since Galin's equations [27] are usable only for

the punch (in this case: probe tip of the welding tool) not for the side of the punch. During these experiments probe side (punch side) is actively involved FSW process and this influences the accuracy of Equations 5 and 6.

3) Kumar's model does not recognize active surfaces of the welding tool [4] nor active surface engagement (ASE, Figure 4) in FSW. Active surfaces of the welding tool are in contact with the welding plates and they generate heat, convey weld, stir and depose material etc. and how much they involve in FSW depends on the ASE. Without concern on the ASE, friction coefficient in FSW by Kumar can be considered only as median value, what is, in most of the cases satisfactory.



Figure 4. Active surfaces of the welding tool and active surface engagement (ASE) during FSW welding process

4. CONCLUSIONS

Two decades away from the first application of the FSW in industry, friction process stays the least investigated parameter / phenomenon of the FSW process. All published researches about the FSW imply the importance of the friction in every aspect of this welding process's application but do not provide adequate experimental background or mathematical models that will take the influence of the friction (coefficient) in the process of frictional welding. Friction phenomenon or simply – the friction coefficient is considered to be a single value (in most of the researches), mostly from 0.3 to 0.7.

Furthermore, the influence of the friction coefficient to the heat generation process(es) is very poorly investigated or not investigated at all.

Generally speaking, increase of the friction coefficient increases the amount of the generated heat, what implies that mechanical power delivered to the welding tool by machine has to increase. Decrease of the friction coefficient delivers decrease in heat generation and decrease in power consumption during welding process. Problem is simple: friction coefficient is not some technological parameter (such angular rotation is) which can be altered manually / automatically for the purpose of process improvement. So, influence of the friction coefficient on heat generation is in relationship with all other parameters of the FSW and they have to be investigated in depth and mutually.

Understanding the nature of friction coefficient and its relationships with other parameters / phenomena in FSW process is a difficult task and requires in – depth analysis of all parameters that influence friction.

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