University of Niš
Faculty of Mechanical Engineering

THE INTERNATIONAL CONFERENCE

Mechanical Engineering in XXI Century

PROCEEDINGS

Niš, Serbia, 25 - 26 November 2010.

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TRIBOLOGICAL ANAL   SIS OF CONTACT BETWEEN WELDING TOOL AND BASE METAL AS FUNCTION OF HEAT GENERATION WITHIN FSW PROCESS

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Abstract: *Friction Stir Welding – FSW is relatively new and still not completely theoretically described welding process. Parameters involved in weld creation during FSW are numerous.   owever,   uality of the weld, beside other parameters, directly is dependable from the amount of the generated heat and stirring of the base metal. Developed mathematical models do e plain FSW process with significant precision, but they include numerous appro imations and assumptions in order to overcome lack of understanding of tribological aspects of FSW – friction coefficient on the contact of welding tool and base metal, adhesion, cohesion, contact pressure, wearing etc.*

Key words*: tribology, friction stir welding, heat generation*

1. INTRODUCTION

Friction Stir Welding (FSW) is exclusively used for welding sheet parts and represents the typical example of indirect friction heat generation usage. FSW is patented in 1991 and during 1992 the industrial application of the process has started. Basic principle and scheme of the process is given in the Fig. 1. Welding pieces (1) and (2) are fixed above the backing plate (3) and positioned one to another along the joint line (7).   eat generation and welding is achieved with special cylindrical welding tool that consists of a shoulder (4) and a threaded probe (5). Shoulder has greater diameter than a probe and probe is mostly left threaded. Contact surface between shoulder and a probe is flat or cone surface called shoulder tip (6).

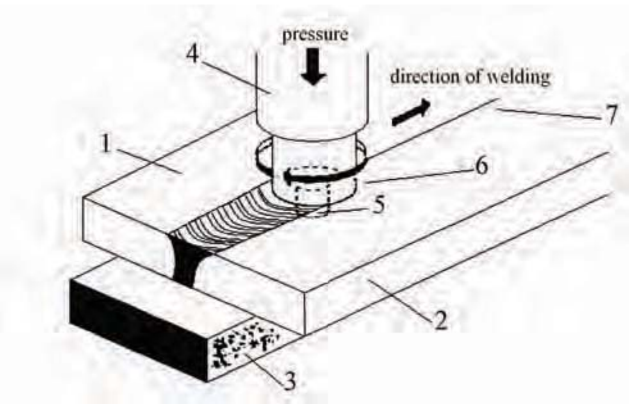

Fig. 1: Principle of the FSW: 1 and 2-weld pieces 3-postolje 4-shoulder 5-probe 6-shoulder tip 7-weld joint line

At the beginning of the welding process, welding tool is mounted above the backing plate and welding pieces and its main axis is perpendicular with the joint line (7). In that position welding toll starts to rotate and translator movement down. Weld probe (5) plunges into both of the welding plates in a start point on the joint line, friction between probe and the welding plates initiates heat generation, welding plates soften and thread on a probe stirs the material of the welding plates constantly. When shoulder tip (6) touches the welding plates, and probe tip is very close to the backing plate, translator movement of the tool down stops and tool starts transversal (horizontal) movement along the joint line. Moving along the joint line, weld tool's probe heats new layers of the welding pieces, stirs them, and creates a layer of mixed and plasticized metal which softens and creates monolith connection between welding pieces – weld. Shoulder tip (6) confines upper surface of the weld and backing plate (3) does the same to the lower surface of the weld. Welding process is finished with end of translation of the welding tool and pulling out from the weld pieces.

Very important kinematical characteristic of the FSW is that welding tool always has main rotational movement and in most of the cases it has both translator auxiliary movements. Analyzing the kinematics, in order to analyze the process easily, complete technological cycle of the FSW can be separated into five basic phases (Fig. 2).

  eat generated during FSW is a product of two mutually dependable physical processes:

– Active surfaces of the welding tool slide over base metal
– Base metal around the welding tool is deformed.

During all phases of the FSW, welding tool and base metal have mutual contact over at least one active surface of the welding tool [4]. Active surface of the welding tool is area on welding tool directly involved in welding process.

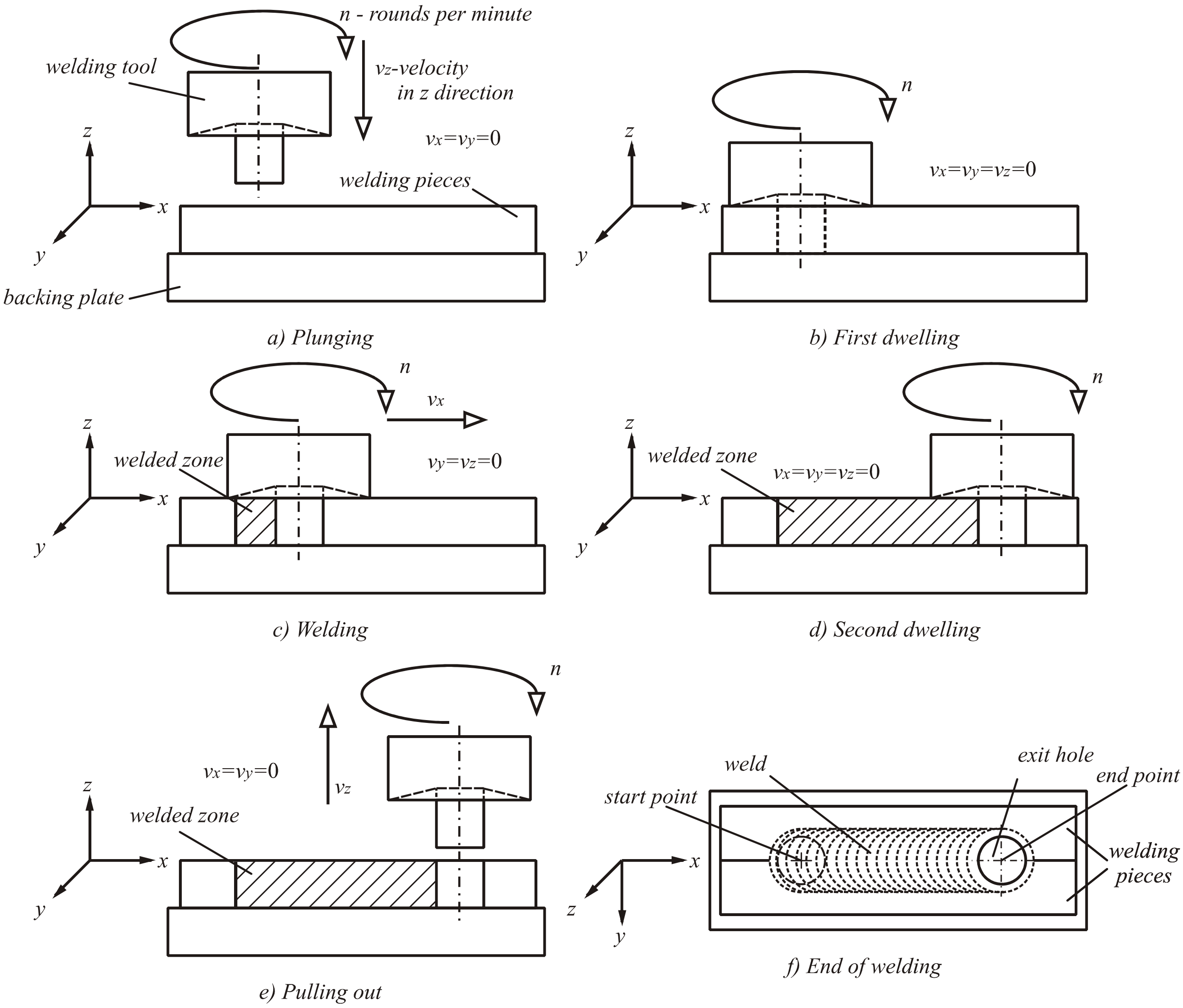

Fig. 2 Phases of the FSW

It influences the base metal on several different ways and makes welding possible. All used welding tools have at least 3 active surfaces: probe tip, probe side and shoulder tip (Fig. 3).

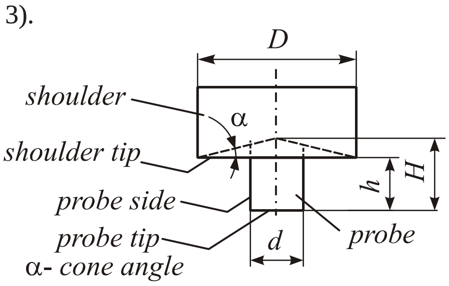

Fig. 3: Basic shape of the friction stir welding tool and basic active surfaces [4].

Variations and complexity of welding tools make possible to have more than mentioned 3 active surfaces on the welding tool or these surfaces can be slightly greater.

2. SLIDING CONDITION

Active surfaces of the welding tool are significantly harder than any surface of the base metal and material of the welding tool is stronger than base metal. Since contact between any two moving solid bodies inflicts appearance of new physical (tribological) processes – friction, wear, adhesion etc., [2], rotating and translating welding tool and base metal are in dynamical relationship. Constant sliding among surfaces can be explained over change of energetic status of the welding tool. One part of mechanical energy of the welding tool is transformed into heat on the sliding contacts between active surfaces and base metal. This heat increases the temperature of welding tool and base metal, they soften and change their mechanical properties and contact pressure between them, as well. Contact conditions between welding tool and base metal change and FSW process reaches some other pseudo – steady state.

3. DEFORMATION CONDITION

Besides pure sliding, constantly present physical process in FSW process is deformation. Since welding tool is harder and more wear resistant than base metals, contact between active surfaces and base metal results in constant transition of base metal's particles. Adhesion forces, which appear on contact, chop softened particles of base metal, stir them and move along the path of the welding tool's rotation or translation. This transition of material is called deformation.

Chopped, deformed and moved particles of base metal travel with the tool until they return to the relatively stabile state, stick to the base metal again and stop further movement. While being deformed particles transform mechanical energy of the welding tool into the heat and changes mechanical properties of base metal and welding tool, too.

4. REAL TRIBOLOGICAL CONTACT CONDITION

Sliding and deformation appear constantly during tribo – contact between welding tool and base metal. They appear one at a time, both at the same time, one by one etc. It is almost impossible to isolate just one of the processes and explain it partially. Real tribological contact assumes that there is pure sliding contact condition, pure sticking (deformation) condition and combination of both [3][4].

Active surfaces of the welding tool are not involved in welding all at once or fully during complete welding process. For example, probe tip is involved in welding process only during plunging phase. During all other phases probe tip is minimally or completely not involved in welding process. Probe side is successive involving in welding process during plunging phase and actively is involved in welding during all phases until the end of the pulling out phase. The largest active surface – shoulder tip is involving in welding process at the end of the first plunging phase or at the beginning of the dwelling phase. Shoulder tip has no active contact with the base metal from the end of the welding phase.

Table 1 show (descriptively) when and for how long active surfaces are involved in welding process (during phases of welding).

Table 1 Active surfaces involving in welding and heat generation during phases of FSW

Phase of FSW → / Active surface ↓	Plunging	First Dwelling	Welding	Second Dwelling	Pulling Out
Probe Tip	→ ...→				
Probe Side	→			. ..	...→|
Shoulder Tip	→			.. ...→|	

. AMOUNT OF GENERATED HEAT

Generated heat during FSW is a product of physical intercourse between active surfaces and base metal. At the same time generated heat softens base metal and eases the welding process – welding tool easier stirs the base metal and creates weld.

Analyzing contact surfaces, applying the tribological momentum of friction equations [2][3][4], it is easy to get equations capable to calculate heat generated on basic active surfaces – probe tip (Equation 1), probe side (Equation 2) and shoulder tip (Equation 3).

Probe tip:

$$_{pt} = \frac{2}{3} \cdot \pi \cdot \omega \cdot \tau_{cont} \cdot \left(\frac{d}{2} \right)^3 . \qquad (1)$$

Probe side:

$$_{ps} = 2 \cdot \pi \cdot \omega \cdot \tau_{cont} \cdot \left(\frac{d}{2} \right)^2 \cdot h . \qquad (2)$$

Shoulder tip:

$$_{st} = \frac{2}{3} \cdot \pi \cdot \omega \cdot \tau_{cont} \cdot \left[\left(\frac{D}{2} \right)^3 - \left(\frac{d}{2} \right)^3 \right] \cdot \left(1 + \tan \alpha \right) . \qquad (3)$$

where:

ω – angular rate of the welding tool $\left[\frac{\text{rad}}{\text{s}} \right]$,

d – diameter of the probe [mm],

D – diameter of the shoulder [mm],

h – height of the welding plates [mm],

α – cone angle [°],

τ_{cont} – contact tangent shear stress $\left[\frac{\text{N}}{\text{mm}^2} \right]$.

When analyzing pure sliding, contact tangent shear stress is:

$$\tau_{cont} = \mu \cdot p \qquad (4)$$

where:

μ – friction coefficient between welding tool and welding metal [–],

p – contact pressure (normal stress at the contact of welding tool and welding pieces) $\left[\frac{\text{N}}{\text{mm}^2} \right]$.

When analyzing pure sticking, contact tangent shear stress is:

$$\tau_{cont} = \tau \qquad (5)$$

where:

τ – tangent shear stress of the softer material (in this case: base metal) $\left[\frac{\text{N}}{\text{mm}^2}\right]$.

. TRIBOLOGICAL PARAMETERS OF THE FSW

Analyzing Equations 1, 2 and 3, it is obvious that tribological parameters involved in heat generation are: friction coefficient (μ), contact pressure (p), tangent shear stress (τ). Analyzing the fact that heat is generated during sliding and sticking, it can be said that other tribological parameters are: adhesion, cohesion, wear, lubrication etc.
It is clear that generated heat ( ) is:

$$= f\begin{pmatrix} \mu, p, \tau, adhesion, cohesion, \\ wear, lubrication, ... \end{pmatrix}. \quad (6)$$

All of these parameters are present during every phase of FSW, but difficulty is that all of them are in relationship with other parameters:

$$= f\begin{pmatrix} \mu(p,\tau,...), p(\mu,\tau,...), \\ \tau(\mu, p,...), adhesion(\mu, p,\tau,...), \\ cohesion(\mu, p,\tau,...), wear(\mu, p,\tau,...), \\ lubrication(\mu, p,\tau,...),... \end{pmatrix}. \quad (7)$$

It is difficult to superpose influence of any tribological parameter and to explain complete process after such a superposition. For example, friction coefficient is having static nature, at the beginning of the FSW, but the moment after, some particles of the base metal are heated, softened, stirred from the matrix and act as lubricant for the welding tool – base metal contact. Friction coefficient becomes kinetic. Fact that friction coefficient changes its nature, deliver different distribution of the contact pressure, what results in stability of the wearing process. Wear of the base metal becomes more intense and stirring (deformation) becomes dominant process. Welding tool increases its temperature as well and cohesive/adhesive forces increase. Softened particles of base metal stick to active surface of welding tool and travel along the joint line.
Example is more than enough to explain how difficult is analysis of the FSW with ambiguity of tribological parameters of the process.

. CONCLUSION

FSW is process 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, 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. Recognizing the nature and changes of these tribological parameters, some might theoretically describe FSW in precise and unique way.

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