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PROCEEDINGS

16th Symposium on Thermal Science and Engineering of Serbia

Sokobanja, Serbia, October 22-25, 2013

University of Niš, Faculty of Mechanical Engineering Niš
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Numerical Simulation of Friction Stir Welding

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Abstract: Friction stir welding is a solid-state welding technique that utilizes thermo-mechanical influence of the rotating welding tool on parent material resulting with monolith joint - weld. On the contact of welding tool and parent material, significant stirring and deformation of parent material appears, and during this process mechanical energy is partially transformed into heat. Generated heat affects the temperature of the welding tool and parent material so proposed analytical model for estimation of the amount of generated heat can be verified by temperature: analytically determined heat is used for numerical estimation of the parent material's temperature and this temperature is compared to the experimentally determined temperature. Numerical solution for analytical estimation of welding plates temperature is estimated using finite difference method - explicit scheme with adaptive grid, considering influence of temperature on material's conductivity, contact conditions between welding tool and parent material, material flow around welding tool etc.

Keywords: Numerical Simulation, Friction Stir Welding.

1. Introduction

In recent years, friction stir welding (FSW), which was invented at TWI in 1991 [1], has emerged as an excellent technique for joining aluminum structures that are difficult to be welded with the traditional fusion welding technique. This process uses a specially designed rotating pin that is first inserted into the adjoining edges of the blank sheets with a proper tilt angle and then moved all along the welding line. Such a pin produces frictional and plastic deformation heating in the welding zone; actually, no melting of material is observed in FSW. Furthermore, as the tool moves, material is forced to flow around the tool in a quite complex flow pattern.

Several studies were conducted to deeply understand the process mechanics [2], material flow [3], metallurgical aspects [4], and both static and dynamic strength [5]. Other researches have focused the attention to the weld residual stress. Peel et al. [6] investigated the influence of the tool feed rate on the residual stresses of FSW aluminum joints by using synchrotron X-rays measurement; the residual stresses were highlighted and found out that, in FSW, the weld zone is subjected to longitudinal (parallel to tool travel) and transverse (perpendicular to tool travel) residual stresses.

Staron et al. [7] and Prevéy et al. [8] used non-destructive technique for determining the residual stress in FSW butt-joints in order to investigate the possibility to modify the residual stress state in the joint by exerting external mechanical tensioning or low plasticity burnishing during the welding process. Fratini et al. [9] have also used the hole drilling technique to achieve the residual stress profiles for 6082-T6, 2024-T4, and 7075-T6 aluminum alloys. Although this residual stresses seems to improve the fatigue strength of the joint [10]; they can be considered an obstacle inhibiting the full application of the FSW process in manufacturing process since a detrimental bending and distortion is introduced.

Numerical model were also successfully used to predict the residual stresses in FSW butt joint. Chao et al. [11] for to stainless steel, Chen and Kovacevic [12] and Reynolds et al. [13] for aluminum alloys have developed thermal analyses, based on properly tuned analytical models, and subsequent mechanical ones to obtain the residual stress state due to the thermal input. A few consideration can be developed on the latter papers: first of all the local mechanical action of the tool, and in particular of the tool pin, is not considered. Just the subsequent thermal flux is taken into account and in this way a sort of macro effect of the process on the material is investigated.

What is more, the used thermal models, describing the heat flux due to the tool action, are always axial-symmetric: in other words no effect of the asymmetric material flow occurring in FSW processes is considered. As a consequence symmetric profiles of temperature, strain and strain rate are obtained with respect to the tool axis.

In the present paper the effects of the thermal and mechanical actions on the residual stress, occurring in FSW processes of AA7075-T6 aluminum alloy were investigated. Particularly, both numerical simulations and experimental tests were performed to highlight the occurring metallurgical phenomena and induced residual stress field in the FS welded blanks. The FSW process was simulated using a continuous rigid-viscoplastic FEM model with the DEFORM-3D^{TM} [14] software, previously developed by some of the authors to simulate the FSW process with a single block approach [15, 16]. Thus, the temperature history in each node of the FE model was extracted and transferred to a further FE model of the joint considering an elasto-plastic behavior of the AA7075-T6 material. The adopted model was developed with Abaqus/Standard [17] using the coupled temperature-displacement analysis option. As far as the experiments are regarded, the cut-compliance methodology described by Prime [18] was used to determine the profiles of residual stress; this provides extremely accurate measurements of the longitudinal and transversal residual stresses. Furthermore, the method enables the residual stresses at the crack tip to be determined, which play an important role in fatigue crack growth.

The performed analysis permitted to fully predict the residual stress distribution in the longitudinal, transverse and through-thickness directions.

2. Friction Stir Welding

Friction Stir Welding (FSW) is a solid state welding process predominantly used for welding of aluminium, aluminium alloys and other soft metals/alloys. This welding technique requires usage of specialized, cylindrical – shouldered tool, with a profiled threaded/unthreaded probe (Figure 1). Welding tool is rotated at a constant speed and fed at a constant traverse speed into the joint line between two welding plates (workpieces), which are butted together. The parts are clamped rigidly onto a backing plate (anvil) 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 is moved against the weld – joint line, or vice versa. While traveling, welding tool stirs, deforms and mixes the material of the workpieces into the monolith mixture that represents the weld.

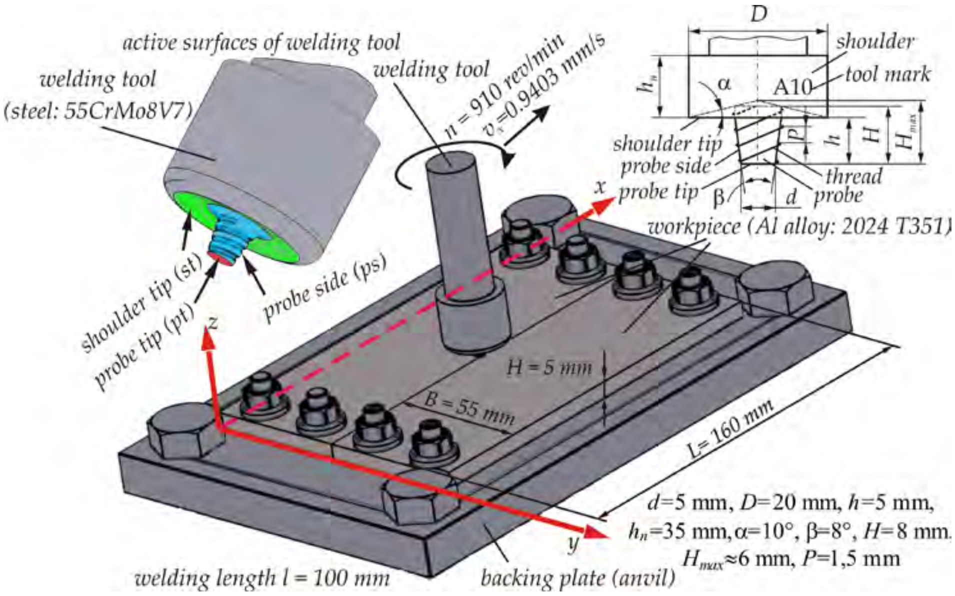

Figure 1. Principle of the FSW, welding tool and active surfaces of the welding tool

As a solid state welding procedure, FSW uses pure mechanical energy as welding process activation energy and distributes it from the welding machine to the base material (workpieces) over the 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 used for deformation and mixing of the particles chopped from workpieces during contact of the welding tool and workpieces, the rest of energy is transforming into heat and some of it is transformed in other types of energy (Figure 1).

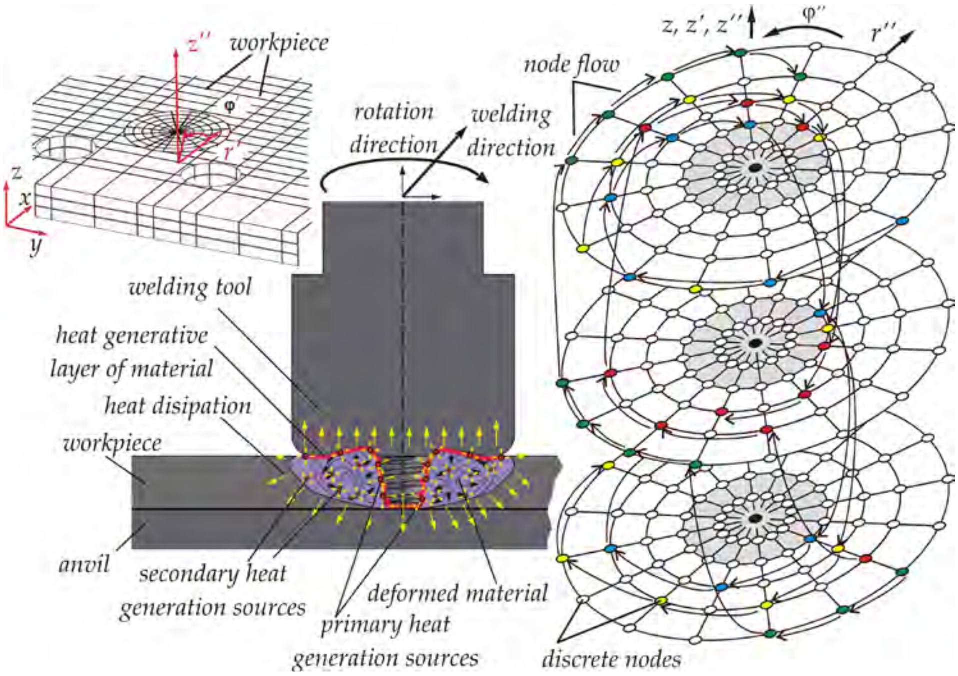

Figure 2. Space discretization, heat generation and material flow pattern - node substitution and replacement during FSW

Primary transformation of the mechanical power into heat happens on the intimate contact of the welding tool and workpieces or in a thin layer of the softer material (in this case it is the material of workpieces) near the welding tool (Figure 2). This layer represents primary heat generation sources. Secondary transformation of power into heat happens in the volume of deformed material of workpieces and moving particles of workpieces' material represent secondary heat generation sources.

3. Analytical model for estimation of amount of generated during FSW

Heat generation process at FSW has been partially investigated at the beginning of 2002 for the first time [3]. This happened 11 years after invention of the FSW.

Until present days, there are three (four) published analytical models for estimation and assessment of amount of heat generated during FSW [21, 25, 26]. All of them differently approach to the heat generation in FSW, however, all of them consider heat generation in FSW as a process tightly connected with the contact mechanics, tribology, plastic deforming and thermodynamics of deformable bodies. These models show that 60% to 100% of the mechanical power transform into heat during FSW.

Analytical model developed at Faculty of Mechanical Engineering Nis is the fourth published model for estimation of amount of heat generated during FSW [22, 23, 24]. As well as first three models, it relies on the conservation of mechanical energy postulate and starts from the assumption that in theory complete amount of mechanical energy delivered to the welding tool transforms into heat. In reality, one part of mechanical energy is used for other processes that appear during welding what gives that at most the rest of the mechanical energy can be transformed into heat. In order to estimate maximal possible amount of generated heat during FSW (for certain technological parameters of the process), this model takes into consideration influence of the welding tool to the process of welding, loads, tribological parameters, temperature of workpieces, material flow around the welding tool, heat generation mechanisms etc.

4. Numerical simulation of FSW

Estimation of the amount of generated heat during FSW is basing on analytical expressions that give the amount of heat generated on active surfaces of the welding tool. Due to the numerous parameters involving transformation of mechanical energy into heat, complex mutual dependences between these parameters, as well as the fact that heat generation in FSW is highly process-realization dependent phenomena, analytical estimation of amount of heat generated during FSW is iterative and discrete process. For example, temperature of workpieces is important for the FSW process and estimation of temperature requires solving heat equation. Heat equation is differential equation that has algebraic solutions for limited cases and usually is solved numerically. Even more complex challenge is estimation of heat transfer thru the workpieces initiated with the material flow around the welding tool: it is necessary to recognize material flow patterns, dependences between welding tool, technological parameters of welding process and material properties etc, and then to connect heat transfer with mass transfer.

Material flow in FSW was explained by many [19, 20, 26, 27, 28], however, there is no adequate mathematical model capable to fully describe it. Present works on FSW either neglect the influence of material flow or simplify the material flow patterns considering it purely rotational around the welding tool. Faculty of Mechanical Engineering in Nis has proposed a new numerical procedure for implementation of material flow pattern into numerical simulations of FSW. Procedure is called - node substitution and replacement [24] and uses experimental results, probabilistic theory, technological parameters of the FSW, geometry of the FSW tool etc. to estimate material flow pattern around the FSW tool. The main goal of the procedure was to improve accuracy of the numerical simulation.

All these procedures are numerical and when implemented in analytical model for heat estimation they are part of the numerical simulation of FSW that has a goal estimate amount of heat generated during FSW.

As process-realization dependent phenomena, heat generation during FSW influences analytical model for amount of generated heat estimation to use experimental data of FSW for proper precision (Figure 3). Table 1 shows some important parameters necessary for the numerical simulation.

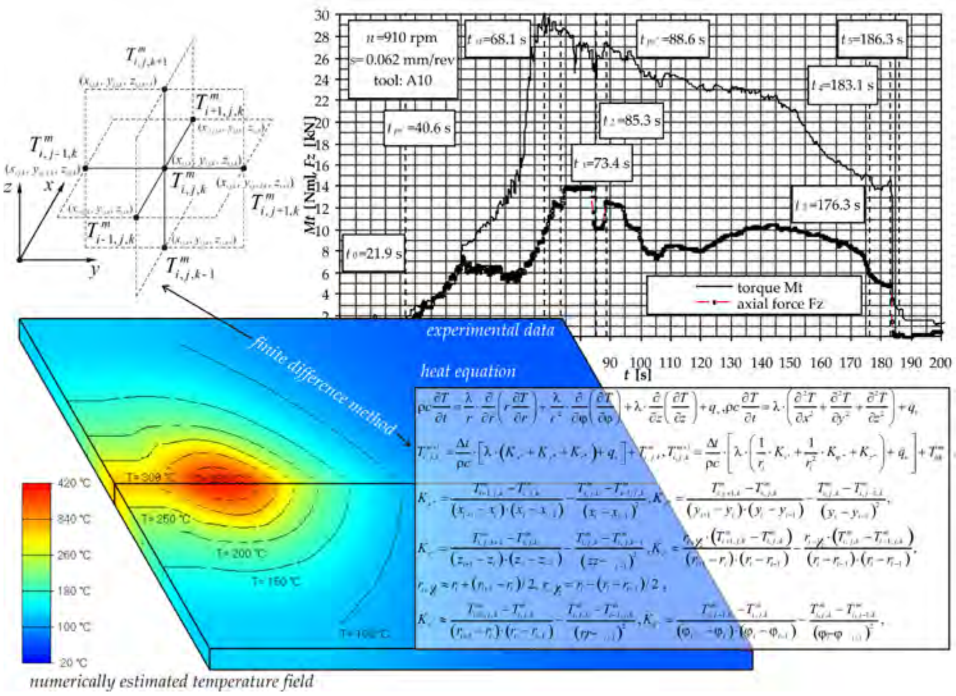

Figure 3. Numerical simulation of the FSW

Table 1. Simulation parameters

T, [°C]	24	100	149	204	260	316	371	400
σ_{yield}(T), [N/mm2] / no plastic strain	345	331	310	138	62	41	28	21
σ_{yield}(T, ε), [N/mm2] / plastic strain ε	483 / 0.18	455 / 0.16	379 / 0.11	186 / 0.23	76 / 0.55	52 / 0.75	34 / 1.00	25 / 1.00
Convection coefficient		α=10 W/(m^{2}K), α_{aprox}=1500 W/(m^{2}K)						
Nominal TP* of welding plates:		λ_{pt} = 121 W/(mK), ρ_{pt} = 2780 kg/m^3, c_{pt} = 875 J/(kgK)						
Nominal TP of welding tool:		λ_{wt} = 38 W/(mK), ρ_{wt} = 7840 kg/m^3, c_{wt} = 500 J/(kgK)						
Material and diameter of bolts:		S335 EN 10025, d_z=10 mm						
Nominal TP of bolts:		λ_{bt} = 43 W/(mK), ρ_{bt} = 7850 kg/m^3, c_{bt} = 420 J/(kgK)						
Important dimensions and material of anvil:		L_a=220 mm, B_a= 148 mm, H_a=16 mm, X5CrNi18-10						
Nominal TP of anvil:		λ_a = 18 W/(mK), ρ_a = 8030 kg/m^3, c_a = 500 J/(kgK)						
Minimal discretization dimensions / time step:		Δx_{min}= 3 mm, Δy_{min}= 1.5 mm, Δz_{min}= 1.5 mm; Δt= 0.0055 s						
Adaptive discretization parameters:		ε_x=-1, 1, 5/3, 7/2; ε_y= -4/3, 1, 5/3, 2, 10/3, 16/3, 20/3; ε_z=-1, 1;						
Convergence of FDM**:		$\lambda_{pt}\cdot\Delta t/(\rho_{pt}\cdot c_{pt}\cdot\Delta x_{min}^2)$=0.03<1/6=0.167 $\lambda_{pt}\cdot\Delta t/(\rho_{pt}\cdot c_{pt}\cdot\Delta y_{min}^2)$=0.122<1/6=0.167 $\lambda_{pt}\cdot\Delta t/(\rho_{pt}\cdot c_{pt}\cdot\Delta z_{min}^2)$=0.122<1/6=0.167						
Number of nodes/iterations:		n_{nod}=14160 / n_{iter}=28528						
Approximate calculation time		t_{calc} = 1283760 s (14 d 20 h 36 min) (processor: 2×2.30GHz)						

*TP – thermomechanical properties, **FDM - finite difference method

5. Discussion and conclusions

Analytical model for the estimation of amount of heat generated during FSW has shown that 60-100% of mechanical power delivered to the welding tool transform into heat. Median value of heat transformation is 86.58% (during plunging phase 79.27%, first dwelling 90.10%, welding 90.25%, second dwelling 90.94%, and pulling out 52.92%). Numerical simulation of FSW included well known finite difference method for numerical estimation of temperatures in discrete nodes of workpieces and accuracy of the simulation is improved by the innovative numerical method for material flow definition - node substitution and replacements. Proposed analytical/numerical model for temperature estimation gave numerically estimated temperature that varies up to 11% from experimentally estimated temperature (that is about 15 °C as absolute error). Maximal temperature on welding plates was numerically estimated T_{max}= 393,538 °C, what is about 80% of Al 2024 T351 melting point. Maximal temperature of the welding tool was experimentally measured T_{max} = 464 °C.

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