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ON MODELLING OF THE HEAT GENERATION DURING FRICTION STIR WELDING USING COMBINED DISCRETE/FINITE ELEMENT APPROACH

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Abstract

The concept of combining the latest finite element (FE) and discrete element (DE) multiscale numerical technologies for modelling of the tool/workpiece interface during high shear processing is described. The potential of FE tools and techniques merged with DE based transient dynamics is highlighted. The described numerical approach combines the DE transient dynamics used for meso- level modelling with FE analysis used for macro- level simulation. The transfer processes are described by the system of diffusion and motion equations including contact detection and interaction solutions for particles integrated in time. As an example of the application, modelling of the tool/workpiece interface including heat generation during friction stir welding (FSW) is considered.

Key words: friction stir welding; multiscale numerical analysis; combined finite-discrete element method; combined mechanical and heat transfer problem; heat generation

1. INTRODUCTION

Friction stir welding (FSW), as a solid state welding process invented and patented by TWI in 1991, has been subject to intensive research during the last years. The process is particularly applied to aluminium and titanium alloys in various fields of automotive and aerospace industries due to the demands for lightweight parts and environment protection (Mishra & Ma, 2005; Nandan et al., 2008). Increasing utilisation of FSW, as a joining process, requires current research activities of its influence on these alloys with different additions, for instance Zr and Sc, that can stabilize the microstructure during hot working operations, inhibit recrystallization during heat treatment and significantly improve residual properties following FSW (Threadgill et al., 2009; Kalemba et al., 2010).

An important aspect in the friction stir welding (FSW) development is study and understanding of the heat transfer process that can be helpful in predicting the material flow, thermal cycles and the hardness in the weld zone, and also, in evaluating the weld quality. However, a thermal model alone cannot predict the temperature/history without prior knowledge of the heat generation. The fundamental mechanisms of FSW are not part of a pure thermal model and most often, a constant heat flux input from the tool shoulder/workpiece interface is assumed (Song & Kovacevic, 2003). Modelling of heat generation and flow during the FSW can be considered as the basis of all other models of the process, be these microstructural, computational fluid dynamics (CFD) or thermomechanical (TMM) (Deng & Xu, 2001; Xu & Deng, 2002; Buffa et al., 2010; Schmidt & Hattel, 2008). However, modelling

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of the heat input from the tool pin is fraught with difficulties because of the continuous stir process. The material in front of the rotating tool is deformed and stirred back to the trailing edge of the pin during the welding. Such relocation of the material makes it very difficult to determine the temperature distribution assuming that the tool pin is both no consumable during the welding process and moving. This problem is supposed to be overcome by applying the combined finite element (FE) and discrete element (DE) numerical approach. The essential need is for knowledge regarding the material response for different alloys. It is the purpose of the present paper to explain these concepts and to illustrate their potential applications for modelling of the tool/workpiece interface during high shear processing and particular for heat generation during FSW process.

2. MODELLING APPROACH

To reflect the three main stages of the process, such as the tool penetration period, the welding and the pulling out of the tool, a model of the FSW process effectively should be a 3-D either TMM or CFD model. In order to demonstrate the possibility of the approach, the following assumptions were made at this stage of the development (figure 1).

First, the transfer processes at the tool pin/workpiece interface are considered in the plane perpendicular to the tool pin axis during the welding stage. Second, the heat generated by the tool pin is produced mainly by plastic deformation, by frictional contact and intermixing taking place at the tool/workpiece interface, similar to as it was indicated elsewhere (Schmidt & Hattel, 2008; Colegrove & Shercliff, 2004).

The meso-model consists of the combined FE and DE parts. The FE part of the model is discretised with finite elements. Then, depending on the choice, the material can follow the mesh, Lagrangian reference frame, or it can flow through the mesh, as in the case of the Eulerian one. The solid material of the DE part is represented with large number of bodies that interact with each other in the normal and tangential directions. In this particular example, the discrete elements are introduced into the model as a set of rigid bodies. However, they can also be deformable and are discretised into finite elements to analyse deformability, diffusion or heat conductance (Munjiza, 2004). The translational and rotational motion of each element i is governed by Newton's law:

$$m_i \ddot{u}_i = F_i + F_i^{damp}, \qquad I_i \dot{\omega} = T_i + T_i^{damp} \tag{1}$$

where u is the element centroid displacement in a fixed coordinate frame; ω is the angular velocity; m is the element mass; I is the moment of inertia. The contact forces between two blocks are decomposed into normal and tangential components and obtained using a constitutive model formulated for the contact. A quasi-static state of equilibrium of the assembly of blocks is achieved by application of non-viscous type damping necessary for kinetic energy dissipation:

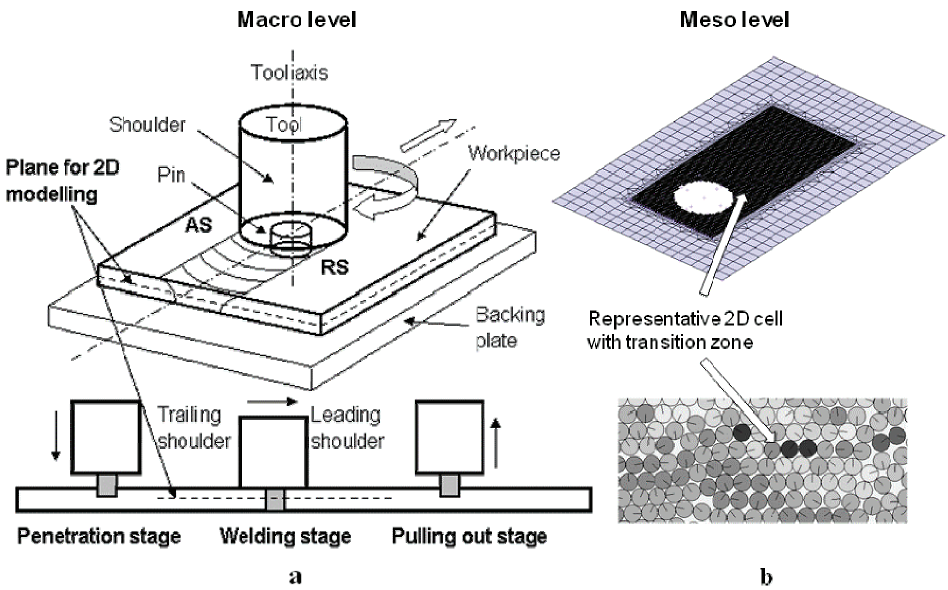

Fig. 1. *Schematic representation of the macro- (a) and meso- (b) model set up for the tool/workpiece interface in friction stir welding.*

$$F_i^{damp} = -\alpha^t \|F_i\| \frac{\dot{u}_i}{\|\dot{u}_i\|}, \quad T_i^{damp} = -\alpha^r \|T_i\| \frac{\omega_i}{\|\omega_i\|} \quad (2)$$

where α^t and α^r are the damping constants for the translational and rotational motion respectively. Initial bonding for the neighbouring particles is also assumed.

The main assumption of the FE analysis is that continuum domain is discretised with finite elements. Then, depending on the choice, the material can follow the mesh, Lagrangian reference frame, or it can flow through the mesh, as in the case of the Eulerian one. Similar to the case of contact between two spheres, the contact force between the sphere and the external edge of a finite element is decomposed into normal and tangential components and generally can include cohesion, friction, damping, heat generation and exchange (Oñate & Rojek, 2004). To obtain continuity in transferring mechanical and physical variables between discrete and finite element zones, a transition zone can also be introduced between those domains. The idea of the transition zone is that the domain is discretised and governed by both DE and FE methods (Tang & Xu, 2006). The location of the discrete elements is constrained by the location of the relative FE nodes in this zone allowing the continuity of the displacements, strains and stresses in the domain. The algorithm for the transient dynamic problem involving both DEs and FEs includes cyclic consecutive computation of the nodal velocities, the nodal displacements, the nodal pressures, updating the nodal coordinates, checking the frictional contact forces and updating the residual force vector. It is realised using both MSC Marc and ELFEN commercial software. The critical time step for the entire calculation is taken assuming the critical time step for the DE analysis, which is much smaller than the one for the FE analysis.

3. MODELLING OF THE COMBINED MECHANICAL AND HEAT TRANSFER PROBLEM AT THE MESO- LEVEL

The surface layer of the material near the rotating tool stock is characterised by severe deformation and wear due to the interaction between significantly harder imperfections of the tool and softer material undergoing the FSW process. In this case the energy produced by sliding is dissipated by combination of plastic deformation of the surface layer, by shearing, failure and mechanical intermixing taking place within the welded material near the tool surface. These mechanical effects significantly complicate the heat and mass transfer in the area. The developed DE approach allows for modelling of combined transfer problems in the surface layer of the material, such as coupled mechanical mixing and heat transfer or diffusion. There are several ways for modelling of these phenomena at the meso- level.

The DE formulation for the combined mechanical and heat transfer problem has been simplified by assuming that the temperature difference within a DE is small. Hence, the heat transfer between the DE is restricted to the contact surfaces and is due to convection. Both internal and external sources of energy are assumed (figure 2).

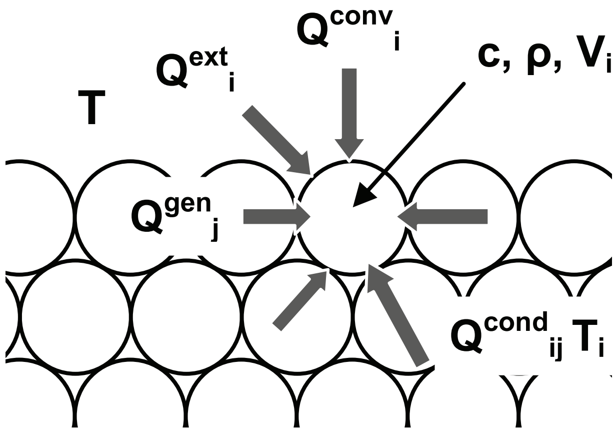

Fig. 2. Schematic representation of the heat balance between rigid discrete elements at the meso-level.

The heat balance for the DE formulation is given by the following equations:

$$\rho V_i c \dot{T}_i = Q_i$$

$$Q_i = \sum_{j=1}^{n_c} Q_{ij}^{cond} + Q_i^{ext} + Q_i^{gen} + Q_i^{conv} \quad (3)$$

where ρ is the density and V_i is the volume of the element i, c is the heat capacity, T_i is the temperature of the element i, Q_i is the combined heat flux at the ith element, Q_{ij}^{cond} is the conductivity component of the heat flux between i^{th} and j^{th} elements, Q_i^{ext} is the external component of the heat flux into the i^{th} element, Q_i^{gen} is the heat generation component of the heat flux into the i^{th} element, Q_i^{conv} is the convection component of the heat flux into the i^{th} element, n_c is the number of elements in contact with element i. The conductivity component of the heat flux between i^{th} and j^{th} discrete elements is determined by the following equation:

$$Q_{ij}^{cond} = -\bar{C}^{cond} (T_i - T_j) \quad (4)$$

where $\bar{C}^{cond}$ is the interface heat transfer coefficient between i^{th} and j^{th} discrete elements. It has to be mentioned here that the interface heat transfer coefficient between discrete elements depends on the apparent area of the heat transfer interface between the elements that is related to the configurations of the elements (Luding, 2004). The coefficient should be determined and verified to allow the heat transfer within the discrete body to be the same as within continuum body.

The heat generation Q_i^{gen} is a function of the element motion, u_i and w_i, and the temperature constraint, $\tau(T)$:

$$Q_i^{gen} = f\left[u_i, w_i, \tau(T)\right] \quad (5)$$

where T is the material temperature and τ is the yield stress. The constraint is based on the experimental evidence that the yield stress significantly decreases near the solidus temperature. As a consequence, the material close to the tool/workpiece interface reduces its heat generation when it approaches the solidus temperature recovering its strength. Thus, the temperature is set at the level below the solidus temperature due to the self stabilizing effect. Ideally, the strain rate dependence should be also included into the consideration. However, at this stage the temperature dependent yield stress is used as the driver for the heat source, similar to how it was proposed elsewhere (Schmidt & Hattel, 2008). This combined heat generation induces a heat flow both into the workpiece and into the tool, which is dependent on the FSW conditions such as the material properties of the components, surface state of the tool, for instance roughness, the controlling thermal boundaries due to different tool geometries, etc. The essential need is for knowledge regarding the material response for different alloys.

4. RESULTS AND DISCUSSION

Preliminary results from the new modelling approach for modelling the heat generation during FSW and some experimental data leading towards its experimental verification are presented beneath.

The DE meso model includes several parameters that have been assumed and require some verification. Thus, it is difficult to assess predictive abilities of the heat generation model at this stage of the research. The thermal properties of the material have been taken from the literature (Metals Handbook, 1990; Hot Working Guide, 1997). The heat flux predicted at the thin layer in front of the tool-pin surface at the leading shoulder is different from the one generated in front of the trailing shoulder (figure 3). This is due to the different displacement and temperature conditions at the areas. It is also seen that the maximum heat is generated at the workpiece area situated in about 0.5-1mm distance from the tool-pin surface at the trailing shoulder region. In majority of thermal models of FSW process the heat generation from both frictional and plastic dissipation is modelled via a surface flux boundary condition at the tool/material interface. In this approach, the heat is generated from modelling of both frictional and plastic dissipation by combination of plastic deformation of the surface layer, by shearing, failure and mechanical intermixing taking place within the welded material near the tool surface. From this point of view, the description of the heat generation can be considered as the basis of any thermal model of FSW process including the underlying physics of the process, the material flow producing heat generation by plastic dissipation in the shear layer and frictional contact at the tool/workpiece.

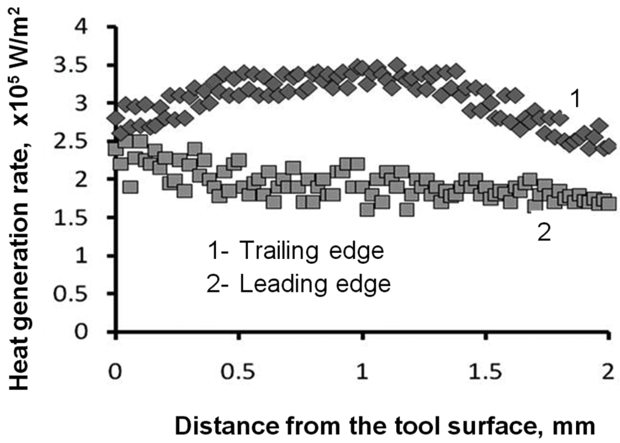

Fig. 3. *Heat flux rate predicted in the plane perpendicular to the tool pin axis during the welding stage of the friction stir welding process.*

Tests are being carried out for experimental verification of the numerical approach. The weld macrostructure from butt welded Ti-6Al-4V plate, for instance, provides valuable information about the peak temperature distributions in the weld (figure 4). The weld macrostructure is characterised by the light region in the centre, where welding temperatures have exceeded the beta transformation temperature

(~995°C ±5°C). The boundary of this region shows the location of this isotherm.

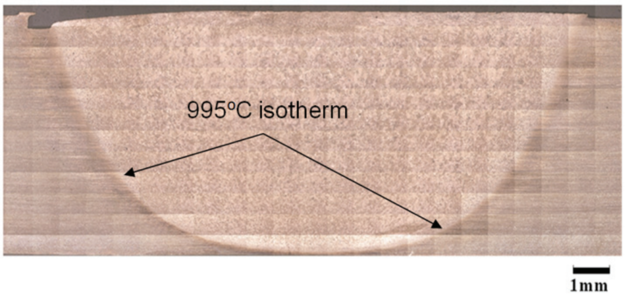

Fig. 4. Macrostructure from welded Ti-6Al-4V plate used for verification of the modelling results.

Although the illustrated results are only the first preliminary step towards development a numerical tool for establishment the predominant mechanisms of heat generation during the friction stir welding process, they show that the approach can give the possibility for linking technological parameters of the process, such as rotational and transverse welding speed, for instance, or the tool surface profile from one side, with the fine mechanisms taking place within the surface layer at the meso- level from another side, such as churning and mechanical mixing coupled with the heat transfer.

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MODELOWANIE GENEROWANIA CIEPŁA PODCZAS PROCESU FSW Z ZASTOSOWANIEM KOMBINOWANEJ METODY ELEMENTÓW DYSKRETNYCH I SKOŃCZONYCH

Streszczenie

W pracy opisano koncepcję wieloskalowego połączenia metod elementów skończonych (FE) i elementów dyskretnych (DE) i zastosowania tego podejścia do modelowania powierzchni styku narzędzie-materiał w procesie intensywnego ścinania. Przedstawiono korzyści jakie wynikają z połączenia możliwości obliczeniowych metody elementów skończonych w skali makro z opisem dynamiki stanów przejściowych przez metodę elementów dyskretnych w skali mezo. Procesy przepływu ciepła i masy opisane są przez układ równań dyfuzji i ruchu, włączając identyfikację powierzchni styku oraz wzajemne oddziaływanie integrowanych cząstek w czasie procesu. Jako przykład zastosowania opracowanego modelu pokazano symulację zjawisk w powierzchni styku narzędzie-materiał w procesie FSW (ang. friction stir welding).

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