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SIMPLIFICATION POSSIBILITIES FOR ESTIMATION OF FSW PROCESS EFFICIENCY BY FEA

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ABSTRACT

Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminium alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be one of the most significant developments in metal joining in past decades. While the bulk of the information is still related to aluminium alloys, important results are also available for other metals and alloys. Among the most important ones are those relating to the process efficiency, which itself can be observed in two ways. One is strictly connected to the process parameters only, and influences heat input; the other one includes parameters like preparation time or necessity for filler material or post-weld heat treatment. Both are important from scientific and engineering point of view, influencing time and costs. This paper presents FEM simulation possibilities for estimation of process efficiency regarding heat input only. Modelling approach and model are explained, accompanied with comparison with experimentally achieved results.

Keywords: Friction Stir Welding, efficiency, numerical model, Finite Element Analysis

1. PREFACE

Joining processes are persistently developing, as human needs are growing. To achieve projected goals regarding design, functionality and efficiency of engineering structures, there are numerous welding and joining processes developed through years. Some of them are generally considered as “conventional”, and they are widely used in almost all aspects of manufacturing and production. These processes are usually based on use of electrical current as heat source, where either AC or DC is converted into heat, causing material to be softened or melt, hence creating weld. There are numerous problems associated with such approach to creating a weld, and lot of money, knowledge and energy is utilized to check whether welds made by fusion processes are correct.

On the other side, Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) are solid state processes, meaning that there is no melting of materials during welding. Therefore, there are no problems usually connected with fusion welding processes. FSW was invented at The Welding Institute (TWI) of UK in 1991, and it was initially applied to aluminium alloys. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. FSW is considered to be a “green” technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes less energy [1]. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar alloys and composites can be joined with equal ease. In contrast to the traditional rotational friction welding, which is usually performed on small axisymmetric parts that can be rotated and pushed against each other to form a joint, friction stir welding can be applied to various types of joints like butt joints, lap joints, T butt joints, and fillet joints.

A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint [2] (Figure 1). The tool serves two primary functions: (a) heating of workpiece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the workpiece and plastic deformation of workpiece [3,4].

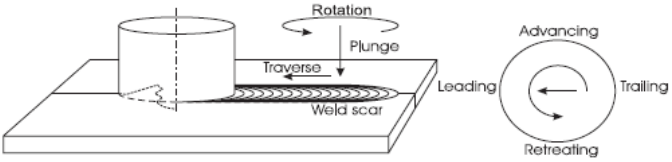

Figure 1. Schematic drawing of Friction Stir Welding [2]

2. MODELLING APPROACH

FSW results in intense plastic deformation and temperature increase within and around the stirred zone. An understanding of mechanical and thermal processes during FSW is needed for optimizing process parameters, controlling microstructure and properties of welds [1], as well as for estimation of heat transfer efficiency. For this, a detailed understand of heat generation mechanism is essential.

There are two different ways to define and describe heat generation. The first is based on direct way, with explicit expressions describing how amount of generated heat depends on rotational speed, geometry of tool and mechanical properties of material [5,6]. The second is reversed ("engineering") way, where temperatures are measured during the process of welding, and then relationships between certain factors (generated heat, friction coefficient, force, rotational speed etc.) and reached temperatures are calculated [7,8].

While in general is believed that direct approach yields more accurate results for estimation of heat generation (i.e. more accurate prediction of efficiency), it also involves a number of mutually dependent parameters which are hard to be known, or their relations to be mathematically described. Since this paper presents simplification possibilities, the reversed approach – for which is believed to be more simple both from modelling and computational point of view – has been chosen to describe heat generation (Figure 2).

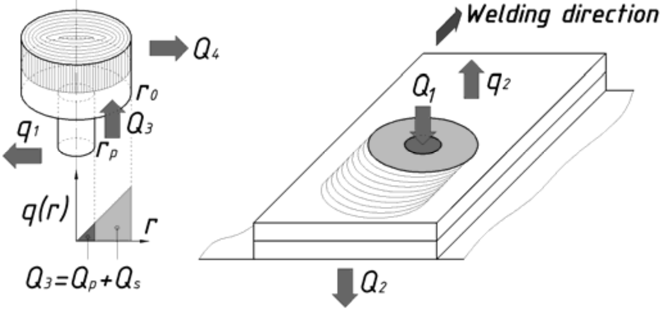

Figure 2. Heat transfer in tool and workpiece during FSW; radiation not shown [7]

Heat flow in the tool and the machine head involves Q_3, Q_4 and q_1, where Q_3 is the heat flux to the tool from the friction between the tool and the workpiece, q_1 is the heat lost from the surface of the tool to the environment through convection and Q_4 is the heat transferred to the machine head in which the tool is mounted. Energy balance requires:

$$Q_3 = Q_4 + q \tag{1}$$

It is assumed that maximum temperature in aluminium welds rarely exceeds 500°C, and radiation is neglected [9]. Since the machine head is very large relative to the tool, it serves as a heat sink and is modelled as a large body with constant ambient temperature 20°C on the outside surface. The guessed boundary conditions are adjusted to match with the measured temperatures. The set of the guessed values yielding the best fit to the measured temperatures is considered as the “actual” values. Energy balance at any time during the FSW requires:

$$Q_1 = Q_2 + q_2 + Q \tag{2}$$

Here Q_1 is the heat flux coming from the friction between the tool and the workpiece, Q_2 is the heat conducted from the bottom surface of the workpiece to the backing plate on the machine, q_2 is the heat lost from the surface of the workpiece to the environment through convection, and Q is the increase of the heat content in the workpiece. To simulate the heat generated from the friction between the tool shoulder and the workpiece [7], the rate of heat input to the workpiece is assumed to be:

$$q(r_i) = \frac{3Q_1 r_i}{2\pi r_0^3} \quad \text{for } 0 \le r_i \le r_0 \tag{3}$$

Here, Q_1 is heat input guessed, until measured temperatures match those from simulation, and r_0 is radius of shoulder. $q(r_i)$ is defined as function in FEA application as heat input function dependent on tool radius. Heat input due to plastic deformation is set to be 20% of Q_1, what is value assumed to be reasonable enough [5]. Boundary conditions of heat withdrawal have been set with best coefficient values possible to find at the moment, with radiation neglected [7], and material properties have been defined as temperature dependent.

3. EFFICIENCY CALCULATION

Total efficiency covers entire welding process (plunging, traveling and plunging out), and it is calculated as ratio:

$$\eta_{\text{total}} = \frac{Q_1}{Q_{\text{total}}} \tag{4}$$

Where Q_{total} is heat input from machine, and Q is total heat input used in simulation, guessed to match temperatures with measured ones, and equals Q_1. Since machine software is able to log spindle torque feedback [10,11], as well as spindle speed, Q_{total} can be calculated as:

$$Q_{\text{total}} = \int_0^{t_{\text{dwell end}}} M(t)\,\omega(t)\,dt \tag{5}$$

Here, $M(t)$ is torque (recorded by software), and ω is circular frequency. For efficiency ratio without plunging (covering only travelling), only data which lies inside dwell period has been considered, and in that case efficiency is:

$$\eta_{w/\,plunging} = \frac{Q_1}{Q_{dwell}} \tag{6}$$

The reason for calculate heat input and efficiency is to show that plunging has great influence on it. If you neglect plunging, efficiency rises.

It is expected that efficiency fall down with longer time of welding, because of heat generation due to friction. Longer time of welding causes changes of surface conditions, therefore changing heat generation and efficiency. Various welding times have been evaluated to confirm this.

4. RESULTS AND DISCUSSION

Figure 3 shows results of FEA simulation of FSW process. First graph shows how guessed value of Q_1 depends on dwell time. It is expected that Q_1 rise as dwell time extends, what is confirmed. However, calculations based on equations (4) and (6) shows decrease of efficiency as dwell time prolongs. As assumed, longer welding time induces lower efficiency ratio.

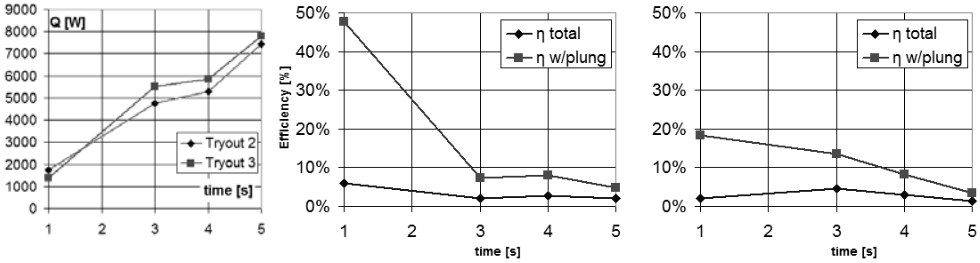

Figure 3. Calculations of heat input, and heat transfer efficiency (with and without plunging) for various welding times

Efficiency of heat transfer in FSW has been experimentally evaluated, and in general it is reported as very high [1]. Values shown in Figure 3 shows lacks of numerical model used for estimation of efficiency. While it seems that approach that uses guessed value of Q_1 works when predicting heat input, it is not as accurate as direct approach when predicting efficiency.

It is hard to believe that numerical model itself can cause this big error, but rather the way model is made and boundary conditions defined. Value Q_1 has to be considered as dependant on dynamic friction coefficient and stresses caused by plastic deformation. Approach presented in this paper also simplifies geometry of tool, what should not be done.

While indirect "engineering" approach could be used for rough estimations of energy consumption for FSW, it should not be used for calculations of heat transfer efficiency during FSW, due to numerous lacks of its accuracy.

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