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On The Friction Stir Welding of Titanium Alloys: Experimental Measurements and FEM Model Fine Tuning

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Abstract. Friction Stir Welding (FSW) is a solid state welding process patented in 1991 by TWI; initially adopted to weld aluminum alloys, is now being successfully used also for magnesium alloys, copper and steels. Recently, research is focusing on titanium alloys thanks to the high interest that such materials are getting from the industry as welding of titanium alloys by traditional fusion welding techniques presents several difficulties due to high material reactivity resulting in bonding with oxygen, hydrogen, and nitrogen with consequent embrittlement of the joint. In this way FSW represents a cost effective and high quality solution. The study of the temperatures reached at the varying of the main process parameters allows a deeper knowledge of the process enabling the prediction of the microstructural evolutions occurring during the process and dramatically influencing the mechanical properties of the obtained joints. In the paper a 3D FEM model of the FSW welding process, based on a thermo-mechanical fully coupled analysis, is presented. In particular the model is tuned following an inverse identification approach starting from welding temperatures on the tool acquired during FSW experiments on the widely commercially diffused Ti-6Al-4V alloy. The inverse approach led to the identification of the most correct friction factor to be introduced in the numerical model. The obtained results permit to asses that the tuned FEM model of the FSW process can be utilized as an effective design tool.

Keywords: Friction Stir Welding, Temperature, FEM model

1. INTRODUCTION

Due to its high strength-weight ratio as well as its good corrosion resistance titanium and titanium alloys are applied widely in aerospace industry [1]. Currently titanium and its alloys are welded by gas tungsten arc welding (GTAW), gas metal arc welding (GMAW) as well as plasma arc welding and laser beam welding [2]. However, by using these traditional fusion welding techniques the development of brittle cast structures, large distortion and residual stresses cannot be avoided.Additionally such alloys can be easily contaminated by air, forming brittle compounds by absorbing oxygen, hydrogen and nitrogen. Friction Stir Welding (FSW) of titanium alloys can represent a cost efficient and high quality solution. The process, patented at the beginning of the nineties by TWI,as a solid state technique permits to over-comethe typical defects related to the phase transition of the materials from the melted state to the solid one [3-5]. The effectiveness of the obtained joint is strongly dependent on several operating parameters such as rotational and advancing speed and tool geometry [6]. In the most recent years several research works on FSW have been developed with the aim of highlighting its mechanics, the mechanical behavior of the joints and the influence of the most relevant process parameters on the effectiveness of the obtained joint [6, 7]. However, most of the results found in literature are referred to aluminum alloys.

Due to the elevated costs deriving from the welding material, the tool material and the fixture development, in order to carry out cost effective process engineering, the use of a numerical model represents a valuable solution. As a matter of fact, a FEM model of the whole process can be used to design both the process, in terms of selection of the main parameters, and the needed clamping fixture. In the recent past a few research activities have been developed on the numerical simulation of FSW processes, in order to develop a proper computer aided engineering of the process. Two main approaches have been followed: first thermal models, taking into account the heat generated by both friction forces work and the material deformation one, have been proposed [8, 9]with the aim to highlight the temperature distributions nearby the rotating pin. On the other hand, finite element thermo-mechanical models have been presented [10, 11] with the aim to investigate the stress and strain distribution during the FSW process. Some of the authors already presented a numerical model for FSW of aluminium alloys [12] and, more recently presented preliminary results of themodel customized for titanium alloys [13].
However the utilized numerical models have to be properly tuned in order to become effective devices in the design of FSW processes. First, correct and detailed material data,varying in proper ranges of temperature, strain and strain rate, have to be implemented; then, effective contact algorithms must be utilized in the thermo-mechanical FEM analysis in order to take into account the right heat generation due to friction forces work.

In the paper the results of an experimental and numerical campaign aimed to the fine tuning of the existing FEM model for FSW of titanium alloys is presented. An inverse approach was used in order to identify the proper friction factor to be utilized in the model. The temperature distributions and histories in the welding tool were acquired by ainfrared camera system during the experimental tests and compared to the calculated ones. Different numerical simulations were performed at the varying of both the process parameters, in order to reproduce the tests, and the friction factor. Finally an error function was built and minimized. The obtained friction factor value was used for an assessment simulation.

2. PROPOSED APPROACH

2.1. Experimental set up

Friction Stir Welding of butt joints is obtained inserting a rotating tool into the adjoining edges of the sheets to be welded and then moving it all along the butt joint. The

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shoulder of the rotating tool generates the heating of the material beneath the materials' melting point, the pin stirs the softened material while the tool moves along the butt joint under constant conditions. For welding a vertical machining center of the type Mazak Nexus 410A (Mazak) is utilized with an argon shielding around the tool. The experimental activity was aimed to obtain Friction Stir Welded butt joints. The utilized base material was Ti-6Al-4Vtitanium alloy in 3 mm thick sheets, characterized by a yield stress of 920 MPa and an ultimate tensile stress (UTSb) of 1050 MPa. The material showed a micro-hardness equal to 351 HV and two-phase alpha/beta microstructure. The sheets were reduced in rectangular specimens of 100 mm x 200 mm.A properly designed clamping fixture was built and utilized in order to perform the welds. In particular a 30mm wide tungsten insert was introduced in a pocket milled in the center of the backplate in order to assure the contact between tungsten and titanium at least close to the welding line, i.e. where temperature levels may lead to contamination problemswith the carbon present in the backplate steel.AW25Re tool with a 16 mm shoulder and a 30° conical pin, 2.6 mm in height and 5mm in major diameter, was utilized. A fixed external collar, sealed on the top surface and with a 20 mm hole on the bottom surface,was placed around the tool; argon was admittedfrom the lateral surface in order to create around the tool a ring shaped protection gas flow for the weld. No cooling media was utilized for the backplate or the tool. Additional details on the experimental set up can be found in [14].

The experimental fixture was completed by a data acquisition system made of aninfrared camerasystem. Process temperature of the tool was measured by an infrared camera system of the type FLIR SC7600, which was positioned towards the welding direction and perpendicular to the tool axis. The tool was coated with graphite to minimize thermal reflections. By comparison measurements an emission coefficient of 1.0 was determined for the coated surface. In figure 1 the sketch showing the layout of the experimental set up is shown.

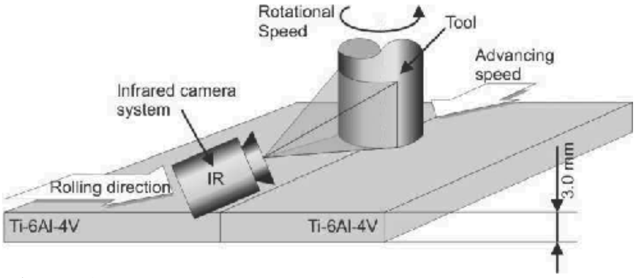

Figure 1. Sketch of the layout utilized for the experiments.

In order to develop the FEM model calibration four different FSW processes of butt joints were carried out at the varying of tool pin rotation speed R (300, 500, 700 and 1000 rpm): the tests performed with the last three values, i.e. 500, 700 and 1000 rpm, were utilized for the inverse approach. The last test, i.e. the one obtained with tool rotation speed equal to 300 rpm, was utilized for a final assessment of the model once carried out the fine tuning of the friction factor. Fixed nuting angle ($\theta = 0°$), tool sinking (equal to 2.85 mm) and welding speed ($v = 35$ mm/min) were selected for all the tests. Each experiment was repeated three times.

2.2. Numerical set up

The FWS process of butt joints was simulated by a fully three-dimensional thermo-mechanical model. In particular a "single block" model was taken into account in order to avoid contact instabilities due to the simultaneous contact at the sheet-sheet and sheet-tool interfaces. In other words just one single sheet metal was modeled and the tool pin, with its movement, opens and welds the crack in the material. In this way a process more similar to Friction Stir Processing (FSP) is simulated. It should be noticed that FSW and FSP produce in the sheets the same distribution of field variables for a given combination of process input parameters [8-12].The blank was meshed through about 22,000 tetrahedral elements with single edges of about 0.75 mm; in this way about four elements were placed along the sheet thickness. A non uniform mesh was adopted with smaller elements close to the tool. Arigid-plastic rate dependent and temperature dependent material model was considered; thermal conductivity and thermal capacity varied with temperature because of the large ranges of variation such parameters present for the considered material; convection phenomena with environment were considered. As far as the utilized W25 Re tool is concerned it was meshed, for the thermal analysis only, with about 6,000 tetrahedral elements. A sketch of the developed model is presented in figure 2.

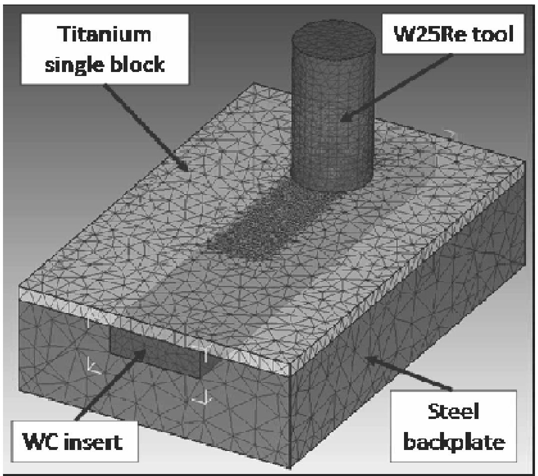

Figure 2. Sketch of the developed model.

Constant values, provided by the material supplier, were utilized for the thermal conductivity, equal to 58 $Ns^{-1}°C^{-1}$, and thermal capacity, equal to 16 $Nmm^{-2}°C^{-1}$. Additional details on the utilized material equations and thermal data can be found in [12, 13]. For the mechanical analysis the experimental clamping fixture, as well as the welding tool, was reproduced by rigid bodies. A thermal exchange coefficient with the sheet metal equal to 11 $Nmm^{-1}s^{-1}°C^{-1}$, was utilized for all the contacts between rigid bodies and the titanium sheet. Large deformation and material flow were treated with an adaptive remeshing finite element formulation. As far as the contact between the tool and the sheet metal is regarded a shear factor model was utilized. Three different friction factor values, equal to 0.12, 0.25 and 0.5, were considered for

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each experimental configuration. In this way a total of 9 simulations were performed.

It should be observed that the proposed numerical model is able to predict the distribution of the main field parameters, i.e. temperature, strain and strain rate as well as microstructure parameters as grain size in the sheets as shown in [12, 13]. Additionally the forces acting on the welding tool can be numerically calculated.

3. RESULTS

First, the results coming from the thermo-vision acquisition system were collected. In the next figure 3 the image acquired by the infrared camera after about 300 s from the beginning of the tool sinking stage is compared to the actual image of the weld for the case study characterized by a tool rotating speed of 500 rpm. In the picture the external collar and the argon intake, as described in the previous paragraph, are highlighted. It should be observed that at the bottom of the acquired image of the tool a damping effect due to the different emissivity coefficient of the titanium sheets is present. Such effect has been taken into account and eliminated in the building of the temperature curves reported in the following of the paper.

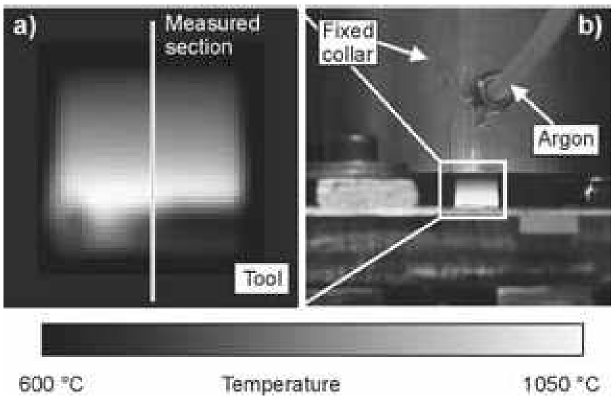

Figure 3. (a) acquisition from the thermo-camera compared to (b) actual image of the process – tool rotating speed 500 rpm.

As far as the numerical results are obtained, the temperature distribution in the tool was taken into account to be compared with the experimental measurements.

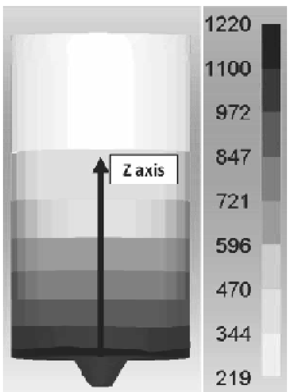

Figure 4. Temperature distribution around the tool as calculated by the FEM model – tool rotating speed 500 rpm, m = 0.5.

In figure 4 the thermal profile obtained after the process reached its steady state, i.e. after about 300 s from the beginning of the tool sinking stage is presented for the case study characterized by tool rotational speed equal to 500 rpm and friction factor m equal to 0.5. In the picture the z axis, i.e. the closest cylinder generatrix to the infrared camera, is highlighted. Although it can be observed that temperatures are over estimated with respect to the experimental data shown in the previous Figure 3, it should be considered that the shown result is obtained with the largest value of friction factor between the ones selected. In order to carry out a quantitative comparison between the numerically calculated and experimentally measured data, the temperatures along the z-axis were taken into account. In figure 5 the three curves calculated with the three simulations characterized by rotating speed of 700 rpm and the three different values of the friction factor m selected, as described in the previous paragraph, are shown together with the experimental curve.

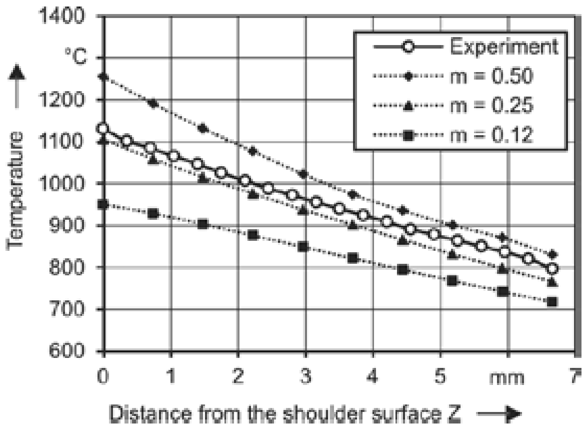

Figure 5. Experimental vs. numerical temperature along the z-axis at the varying of the friction factor - tool rotating speed = 700 rpm.

In order to carry out the proposed inverse approach, for each rotational value curves similar to the one shown above were built. Then, for each value of the friction factor, a pitch equal to 0.2 mm was selected on the z axis (the horizontal axis in the previous Figure 5) and the quadratic error between numerical and experimental temperature was calculated. The final result was the obtainment of an error function,depending just on the utilized friction factor, taking into account the $z_i$measurement points of each curve as well as the three rotation values (j),according to the following formula:

$$E(m) = \sum_j \sum_i \left(T_{exp} - T_{num}\right)^2 \qquad (1)$$

Figure 6 shows the obtained error curve permitting to identify the friction factor m* that minimizes the total error.

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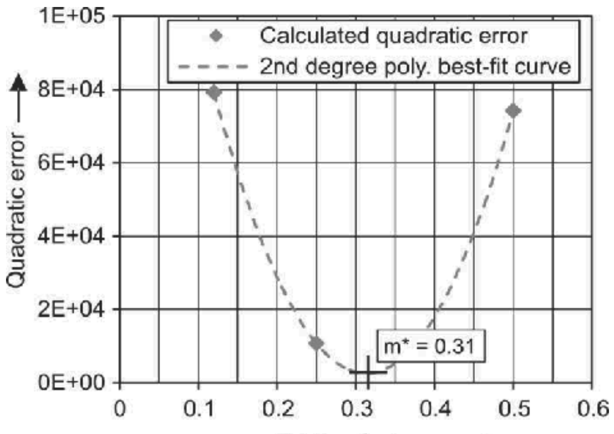

Figure 6. Total error curve vs. friction factor and curve minimization.

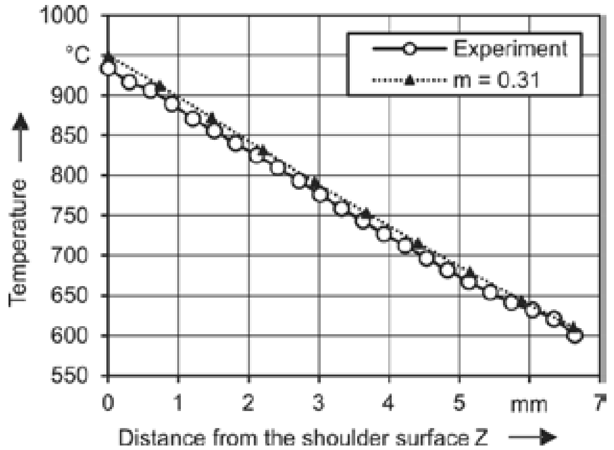

Figure 7. Experimental vs. numerical temperature along the z axis for the optimized friction factor - tool rotating speed 300 rpm.

As it can be seen from the figure, the parabola passing through the three points corresponding to the three rotational speed values taken into account has a minimum in correspondence of a m* value equal to 0.31. Such factor was utilized for a further simulation characterized by a tool rotating speed of 300 rpm. It should be noticed that this assessment test can give useful information for the effectiveness of the model as the considered case study is “out” of the boundary of the experiments used for the inverse approach phase. The comparison between the experimental temperatures and the correspondent numerical ones, calculated with the new friction factor value, are shown in figure 7.A very good matching is found, both for the maximum value and the curve slope, proving that the proposed approach, through quite simple, is also effective. In particular the good overlapping between the curves also denoted a correct modeling of the thermal parameters, namely thermal capacity and thermal conductivity, of the W25Re tool.

4. CONCLUSION REMARKS

In the paper a simple procedure based on an inverse approach was carried out in order to identify the proper friction factor for an already developed 3D lagrangian rigid-viscoplastic model for the FSW of titanium alloys. From the comparison between temperatures on the tool measured through an infrared camera and calculated with three different values of the friction factor an optimized friction factor was derived. The assessment test, although performed with process parameters “out” of the ones utilized for the presented approach, showed very encouraging results indicating the effectiveness of the developed procedure and of the utilized model.

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