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An Optimization Procedure for the Friction Stir Welding FEM Model of Corner Fillet Joints

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Abstract. Friction stir welding (FSW) is an energy efficient and environmentally "friendly" (no fumes, noise, or sparks) welding process, during which the sheets are welded together in a solid-state joining process. FSW is mature for simple configurations but a significant lack of knowledge is found when dealing with different designs such as T-sections, box sections and corner welds. Although the latter joint morphology has traditionally been considered unfeasible for the process, it seems to have a great potential to be used also for T-joint configurations, a recurrent design pattern in transport applications. A specific tool has been developed and a set of experimental welds has been produced with it. In this paper, experimentally measured and numerically calculated thermal histories were compared and a response surface approach was applied in order to model the behavior of the error functions taken into account. Once the conflicting trend of the selected indicators was observed, a constrained minimization approach was developed. The numerical results, obtained utilizing the numerical parameters from the optimization procedure, showed a very good matching with the experimental evidence. According to the obtained results, the proposed model is able to represent a useful design tool for the process.

Keywords: T Joints, Friction Stir Welding (FSW), FEM model, Response surface methods (RSM)

1. INTRODUCTION

FSW has experienced a significant and constant diffusion since its invention in 1991 by TWI because of its ability to produce effective joints in terms of metallurgical and mechanical properties compared to both traditional and innovative fusion-based techniques. Among the advantages the process offers the elimination of the arc, absence of fumes, low geometrical distortion of parts and absence of inclusions and porosities are the most relevant. However, the key of the success the process has experienced in the last years is the ability to join light alloys usually considered “unweldable” or “difficult to weld”: 2xxx, 5xxx, 6xxx and 7xxx series aluminium alloys as well as magnesium and titanium alloys, which are frequent in the transport industry, represented the main driver for the intensive research activity that the process has attracted. Certainly, welded structures are usually considered to offer cost and weight savings. Up to date, it can be said that the development of FSW joints is being been vastly focused on straight butt configuration of either similar or dissimilar sheets for most common aluminium alloys [1-2]. More complex joint configurations such as overlap, tailored butt or most dissimilar butt have been achieved only to a certain degree and basically under laboratory conditions [3-4]. Results on any additional configuration are rare up to date. Only a few papers are found in literature on FSW of T-joints [5-6]. In these papers T joints are obtained by introducing the tool on the horizontal sheet in the surface opposite to the vertical sheet. Although through such technique T joints can be obtained in one weld pass, L shaped joints cannot be obtained. For this reason, a study about the feasibility of a corner fillet geometry using FSW has been carried out showing a great potential for producing T-joint configurations, a recurrent design pattern when considering transport applications [7]. The main problem pending to be solved is how to avoid the formation of a tunnel defect in the weld centre line due to a suck effect of the tool on the stirred material. In this way a properly tuned numerical model can represent a useful design tool for the process. In the recent past, some of the authors proposed a 3D continuum based FEM model able to highlight the FSW mechanisms and to show local values of the field variables, which was based on a “single block” approach: no actual bonding between different blanks was modelled. The model was also used to investigate the possibility to weld T joints and blanks of different thicknesses [8]. Finally a preliminary modeling of the FSW of corner joints was presented in [9]. In order to build a reliable numerical model it is often necessary to identify a lot of input parameters, the most common are related to: material constitutive, heat transfer and friction models. In order to obtain the right parameters calibration some physical experiments have to be carried out and then the results have to be compared with the ones obtained FEM simulation. Subsequently, the considered numerical parameters can be updated until a good agreement between experimental and numerical results is reached. This problem is known as an inverse problem and can be treated as an optimization problem in which the objective function to minimize is the gap between the experimental and numerical results, while the numerical parameters are the variables to optimize. It is worth pointing out that a trial and error approach is often ineffective and time consuming.

In order to reduce the number of numerical simulations to reach the right parameters configuration it is possible to integrate the numerical simulation with optimization algorithms. A preliminary modelling phase is necessary to build up the objective function to optimize, in other words, it is necessary to create mathematical definition of the difference between the numerical and the experimental results. In literature several inverse approach are applied to properly tune the numerical mode of different manufacturing processes.

Ponthot and Kleinermann [11] proposed several optimization approaches based on different non linear gradient based optimization methods; the aim of such research is finding the most robust and accurate method for metal forming inverse approach problems. Yvonnet et al. [12] propose an optimization approach based on an iterative Newton Raphson procedure to identify both the heatflux flowing into the tool through the rake face and the heat transfer coefficient between the tool and the environment during a typical orthogonal cutting process.

Lin et al. develop an inverse approach based on Levenberg–Marquardt method to identify the material strength constant and the strain hardening coefficient based on the experimental upsetting load [13]. Endel and Dancker[14]t propose an inverse approach method to identify friction coefficients and hardening parameters in sheet metal forming processes. Once the inverse approach has been modelled as an optimization problem, different optimization techniques can be applied; some of the authors have applied both gradient based algorithms [15] and response surface methods [16] to design different forming processes, experiencing the advantages and the disadvantages of each technique. In the present work a constrained minimization approach was implemented by utilizing the response surface method to calibrate a numerical simulation by determining the best values of friction coefficient and convection coefficient.

2. EXPERIMENTS AND METHODS

2.1. FSW tests

In order to develop the corner fillet joints a specific tool, consisting of a conical rotating pin and a stationary prismatic shoulder, was designed and patented [10]. The pin, inclined by 45°, has the primary function to produce the needed heat and stir the material while a forging force is exerted by the shoulder. It is worthy notice that in this way a smaller heat flux is generated with respect to conventional FSW processes. As a consequence, higher rotational speeds are needed for the welding tool and particular attention must be given to the monitoring of the actual temperature distributions in order to obtain sound joints. Figure 1 shows a sketch of the process as well as the developed tool.

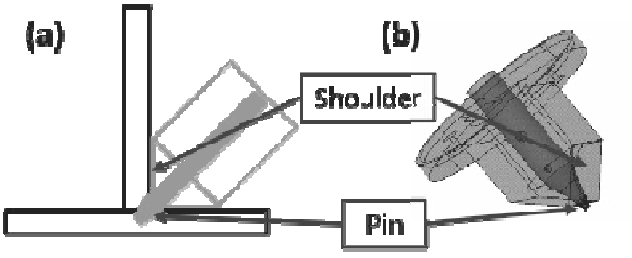

Figure 1. (a) sketch of the FSW of corner joints and (b) CAD image of the developed tool.

The pin has been made of MP159®. As far as the experiments are regarded welds have been produced in commercial AA2024-T351: 120x240 sheets, 6mm in thickness, were welded to 8mm thick 240mm square plates. Adequate fixtures have been designed and fabricated in order to clamp the plates. A tool rotating speed equal to 2000 rpm and a feed rate of 1210 mm/min were selected for the experiments. Temperature measurements have been taken during the tests by embedding thermocouples in both the straightening and the base plate at 1 mm from their top surfaces and 10mm from the weld centre line. In figure 2 the position of the two thermocouples is highlighted together with the main dimensions of the welded joints.

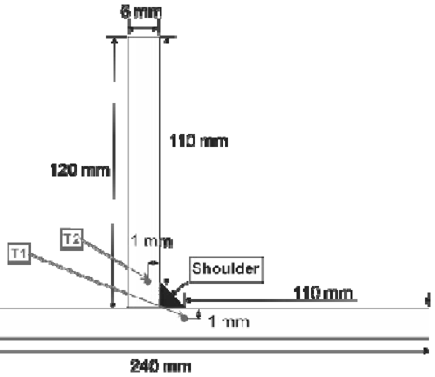

Figure 2. Dimensions of the welded joints and position of the two thermocouples.

2.2. FEM model

The commercial FEA software DEFORM-3D^{TM}, Lagrangian implicit code designed for metal forming processes, was utilized to investigate the process. The tool was modelled as two rigid bodies – i.e. the rotating pin and the fixed shoulder - and meshed, for the thermal analysis, with about 3,000 tetrahedral elements each. The components of the clamping fixture were taken into account by proper boundary conditions. A “single block” continuum model (T shaped sheet blank without a gap) was used to model the workpiece in order to avoid contact instabilities due to the intermittent contact at the sheet-sheet interfaces. The sheet blank was meshed with about 23,000 tetrahedral elements with minimum single edges of about 0.5mm. A non-uniform mesh with adaptive re-meshing was adopted with smaller elements close to the tool and a moving re-meshing referring volume was identified. Both the sinking stage and the welding stage were simulated in order to obtain a temperature distribution as close as possible to the experimental one. Figure 3 illustrates the utilized model with close-ups of both the shoulder and the pin

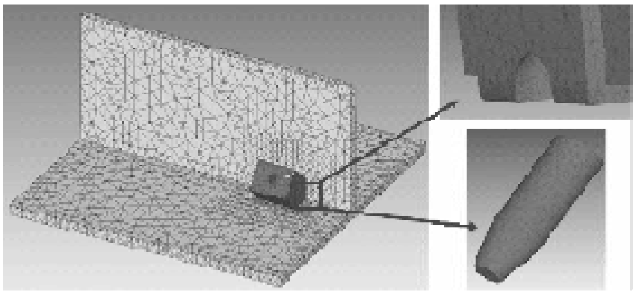

Figure 3. sketch of the utilized model highlighting tool and shoulder details.

As far as the thermo-mechanical characteristics of the considered aluminium alloy are regarded, a temperature, strain and strain rate dependant flow stress was considered; details can be found in [9]. The contact conditions between tool and blanks were simulated through the Tresca shear model. Finally, the heat exchange with environment was taken into account by a proper coefficient h. In particular three different values were selected both for the friction factor m and the heat exchange coefficient h as it will explain in the following paragraph.

3. OPTIMIZATION PROCEDURE

In this paper the inverse approach has been managed as an optimization problem and the response surface method (RSM) was applied to find the optimum. The RSM consists of the approximation of a given objective function to be optimized on the basis of a properly defined set of points (Design Of Experiments, DOE), belonging to the variation domain of the independent variables the function itself depends on. The approximation lead to the obtainment of the explicit function linking optimization variables and the objective function, the optimum can be found out by minimizing the obtained function. Such procedure can be eventually iterated over a zooming design space with an iterative optimum calculation.

As the design of experiments is regarded a 2^3 orthogonal factorial one at the varying of the friction coefficient (*m*) and the convection coefficient (*h*) was developed. Table 1 reports the values of the numerical parameters analyzed at the varying of the considered levels.

Table 1. Values of the numerival parameters.

Variable	Level -1	Level 0	Level 1
m	0,4	0,6	0,8
h	0,1	1	2

As already mentioned, in order to handle an inverse approach trough the optimization techniques, it is necessary a preliminary modelling phase to build up the objective function to optimize. In particular, in the present work, in order to model the gap between the experimental and numerical results two different error functions were developed. A classic least–square error formulation was calculated to control the global gap between the numerical temperature path and the experimental one, such error indicator will be indicated in the following as T_{distr}.

In order to check also the maximum temperature value predicted by the numerical simulation, the absolute difference between the maximum temperature values obtained in the experiments and in the numerical simulations (T_{max}) was collected. Once the modelling phase was developed, the inverse approach was managed as a bi-dimensional optimization problem. The modelling phase fixed the friction coefficient *m* and the convection coefficient *h* as the optimization variables while T_{distr} and T_{max} are the objective functions to minimize. Once the numerical simulations were run and the objective error functions values were calculated, a polynomial regression strategy was applied in order to approximate the two error functions all over the interest domain.

The best performing response functions were obtained by a "heuristic" regression procedure (developed within Minitab environment) by subsequent exclusions of factors, which are statistically less significant. Such procedure led to third order polynomial equations for both the objective functions taken into account, providing very satisfying correlation indexes. Figure 4 shows the obtained response surfaces over the normalized variables space: a conflicting trend of the objective functions is evident.

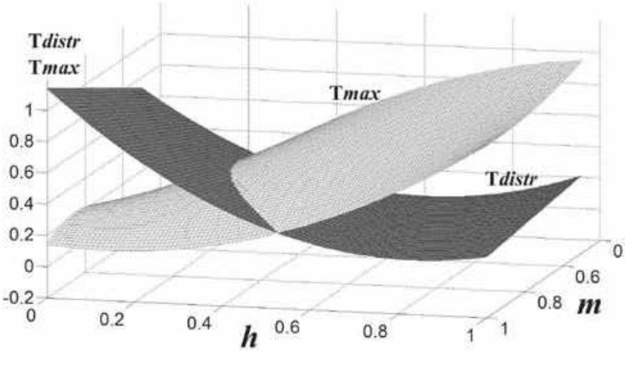

Figure 4. Response surface for T_{max} and T_{distr}.

The conflicting trends of the error functions approximations led to the conclusion that it is not possible to obtain a unique optimum able to minimize the two objectives at the same time. As a consequence, the optimization problem was modeled as constrained minimization one. In particular, the T_{distr} was selected as objective function to minimize while the function error T_{max} was chosen as constraint to be respected. To sum up the optimization problem can be modeled as follows (m and h normalized values):

$$Min: T_{distr}(m,h) \quad (1)$$

Subjected to:

$$T_{max}(m,h) < C; \quad (2)$$

C=20 °C; $0<m<1$; $0<h<1$

The C value was fixed equal to 20 °C because it was assumed that a prediction error within this range does not significantly affect the microstructural evolution occurring in the welded joints during the process.

The procedure led to an optimum which was in proximity of one of the DOE points and it was stopped as far as no further improvement of the objective function were possible. In particular the optimum is characterized by a friction factor value *m* of 0.8 and a convection heat transfer *h* of 1.1. The optimum found out is very close to a point belonging to the D.O.E., nevertheless an improvement of the temperature prediction was obtained as well, the results are detailed in the following section.

4. DISCUSSION OF THE RESULTS AND CONCLUSIONS

The results coming from the optimization procedure, i.e. friction factor m equal to 0.8 and convection coefficient h equal to 1.1, were utilized for a further simulation. Figure 5 shows the comparison between the experimental and numerical temperature histories for the two thermocouples T1 and T2.

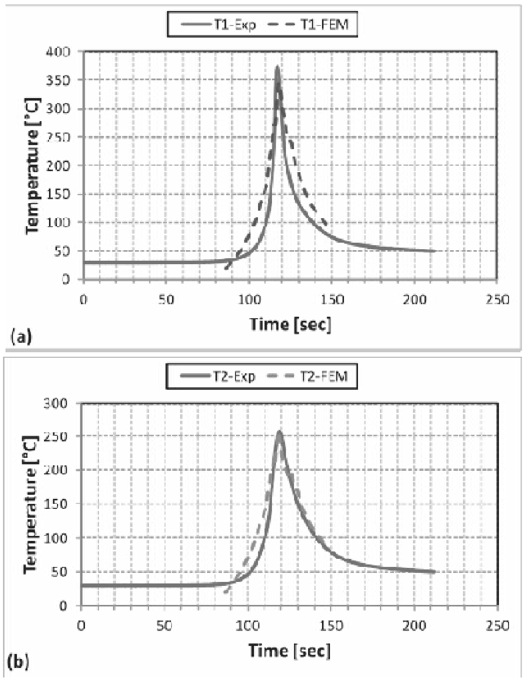

Figure 5. Experimental vs. Numerical temperature histories for the two thermocouples – optimized parameters.

As it can be seen a good agreement is found, especially as far as the T2 thermocouple is regarded. The difference between experimental and calculated maximum temperature predicted for the T1 thermocouple is equal to about 20°C, namely the value of the constraint superimposed, as expected. Additionally, a distribution error larger then the one found for T2 is observed. On the contrary, both the maximum value and the thermal history predicted for the thermocouple T2 are very close to those experimentally measured.

Summing up, in the paper an inverse approach has been managed as an optimization problem in order to identify the proper friction factor m and the convection coefficient h in the Fem simulation of FSW processes of corner fillet joints. In particular, the integration between numerical simulation, response surface approach and constrained minimization techniques was applied. The proposed procedure led to satisfactory results with a minimum computational effort. As a matter of fact only 10 numerical simulations were necessary to reach the numerical parameters calibration. According to the obtained results, the proposed procedure is suitable to properly tune the existing numerical model for FSW of corner fillet joints making it a useful design tool for the process.

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