Effects of Boundary Conditions and Operating Parameters on Temperature Distribution during the Friction Stir Welding Process

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Abstract. This work deals with a numerical simulation of the friction stir welding FSW process of alloy material AA2195-T8. A 3D transient thermal model for simulating the heat transfer phenomena in the welding phase is applied. In this model, the FSW tool is considered as a circular heat source moving in a rectangular plate having a cooling surface and subjected to non-uniform and non-homogeneous boundary conditions. The thermal problem is solved using the finite element method as part of a Lagrangian formulation. The obtained results allow us to determine the maximum value of the temperature in the Nugget zone of the welded joint. During this process, the thermal cycle and the temperature distribution were determined for different values of the welding process parameters. The obtained numerical results are in good agreement with the one available in the literature.

Keywords: Friction Stir Welding, heat transfer, finite element method, AA2195-T8.

1. Introduction

In aeronautics and aerospace domains, the use of structurally hardened aluminium alloys represents a major advantage. However, the difficulty of assembling them through fusion welding techniques (TIG, MIG-MAG...) remains a crucial problem. In 1991, a new solid-state welding technique [1] was introduced by the welding institute. This technique is called the Friction Stir Welding process (FSW). Its uses a specific rotational tool (formed by a shoulder and a shaped probe) to provide required weld properties [2]. The heat energy requires to join the two sides of the plates (retreating side RS and advancing side AS respectively) [3] is generated by the friction between the rotating tool and the mentioned surface as described in Figure 1. In the last decade, many researchers have investigated numerically and experimentally how to optimize the FSW technique. In particular, the heat transfer phenomena and materials flow [4], [5]. Underlined in different references, the perpendicular distribution of temperature is nearly isothermal under the shoulder tool. Besides, increasing the pressure and the rotation speed enhances the maximum value of welding temperature.
Figure 1. Presentation of the different steps of the FSW process: (a) start, (b) penetrations, (c) welding and (d) finishing [3].

It is important to mention that an inadequate heat generation in this welding process could lead to failure of the tool-probe or the workpiece shape. Thus, understanding heat flow behaviour is important to achieve good welding [1–3, 6]. Simar et al. [7] determined the thermal history experimentally at positions near the weld line during the FSW process. Also, they have developed a numerical model based on the finite element method (FEM), considering the effect of the welding parameters such as the welding speed, rotational speed of the tool, axial force and tool geometry. Moraitis et al. [8] have calculated using semi-analytical methods, the total energy and the heat produced by stirring the material during the FSW process. They also proposed a 3D numerical simulation to analyze the thermal histories during the welding process. The obtained results were introduced into a thermo-mechanical model to determine residual stress. Results were validated experimentally. A recent study [9], the authors analyzed experimentally and numerically the thermo-mechanical behaviour for FSW of PMMA plate. Their objective was to look for suitable conditions to attain optimal thermomechanical properties. The developed model was used to determine the thermal profile in the longitudinal and transversal directions of the welded plates, while the temperature of the surface plate was measured experimentally and compared to the simulation. The authors underlined that at higher heat input, with an increase of the axial force within the plastic material led to material sticking around the probe and to the formation of defects.

In this work, a numerical simulation of the FSW process is carried out, making it possible to study the thermal phenomena and heat transfer. A 3D thermal model is applied in order to consider the thermal transient in the welding tool, regarded as a mobile heat source. The effect of boundary conditions and the operating parameters (Welding speed, rotational speed, axial force and probe radius) on the heat transfer during the welding process were investigated.

2. Physical model and numerical simulation
The workpiece is composed of two plates to be welded by the FSW process. Its dimensions are \( L \times W \times H = 610 \times 102 \times 8.1 \text{ mm}^3 \). The intersection of the workpiece with a tool is represented by a circular red section that moves throughout the weld joint line. Boundary conditions are also specified to update the mathematical model presented in the next session. Since the plates were made from the same material (aluminium alloy) and had similar dimensions, the symmetric condition is applied along the joint, so the calculation was performed on one side (Figure 2).
Mathematical model

The modelling of the FSW heat phenomena is based on the resolution of the heat conduction equation in the workpiece with an appropriate model of the heat source. In this work, a modified heat source $Q_{\text{source}}$ is used for the friction effects of the welding tool on the workpiece, taking into account the appropriate boundary and initial conditions [10].

Hypothesis

Some hypotheses were necessary to solve the obtained system:

- The heat transfer process was considered 3D and transient in the entire workpiece,
- The peak temperature in the workpiece during the welding always remains below the melting temperature of the studied material ($T_m$ below 773 K),
- The heat exchange between the workpiece and the environment occurs only through a natural convection process with a heating coefficient $h_\infty$ and radiation effect during the process is neglected,
- The heat due to the plastic deformation of the material by the FSW tool is neglected compared to the heat generated by the rotational friction,
- The force applied vertically by the welding tool generates a uniform pressure at the workpiece/shoulder interface.

Heat transfer equation

The tool moves at constant speed $u_w$ along the joint line according to the above assumptions. The thermal energy equation in the workpiece can be written in the Lagrangian coordinates as:

$$\rho(T)c_p(T) \frac{dT}{dt} = \nabla(K\nabla T) + S \tag{1}$$

Where

- $\rho(T)$, $c_p(T)$ and $K(k_x, k_y, k_z)$ are the material density, the thermal capacity and the thermal conductivity, which depend on temperature.
- $S$ is the volumetric heat source due to the plastic deformation of the material, it is often neglected compared to the main source of the heat created by the friction of the shoulder $q_s$ and the probe $q_p$ on the workpiece.

In the FSW process, the heat is directly linked to the contact conditions of the workpiece/tool interfaces and the process parameters. Therefore, there are two main sources of energy produced by friction at the two interfaces: the heat $Q_p$ created at the workpiece/probe interface and the heat $Q_s$ created at the workpiece/shoulder interface. These frictional contacts depend on the surface state, which is defined by the friction coefficient $\mu$. Our model is based on Chao at al. model [11] (Figure 3) as follow:
\( q(r) = \frac{3Q_{\text{source}}}{2\pi R_S^3} r \) for \( r \leq R_S \)

Where

\( Q_{\text{source}} = \frac{\pi^2 \omega P}{45} \mu (R_S^3 + 3R_p^2 h_p) \)

\( q(r) \) is the heat flux source, \( R_s \) and \( R_p \) are the shoulder and probe radii, \( P \) is the pressure, \( \mu \) is the friction coefficient, \( \omega \) rotation speed and \( h_p \) is the height of the tool probe [10]

3. Numerical procedure and validation

The numerical calculation of the temperature fields during the FSW process was performed by ANSYS, which requires the resolution of the governing equations by combining the appropriate boundary conditions and a moving heat source. To perform the numerical resolution of the problem and validate the thermal model, it is important to provide experimental data (operating parameters table 1 and observed thermal cycles observed in the following reference [11]).

Table 1. Operating parameters for welding the AA 2195-T8 alloy

| Probe radius | Shoulder radius | Rotational speed | Welding speed | Axial force |
|--------------|-----------------|------------------|---------------|-------------|
| 5mm          | 12.7mm          | 240 tr/min       | 2.36 mm/sec   | 25 kN       |

The material tool is M2 steel which is widely used in industries. It has a small and distributed carbides which give the tool high wear resistance. The evolution of the temperature at \( P1 (L/2, 12.7, H/4) \) and \( P2 (L/2, 25.4, H/4) \) are described in Figure 3. It can be observed that the temperature pick decreases with the increase of distance regarding the mid plan for both experimental and numerical analysis. Based on the good agreement between the simulation and the experiment, the proposed model can be used to predict the temperature profiles and cooling rates.

![Figure 3. Comparison of the numerical thermal histories obtained by Chao et al. and the experimental results at two positions of the workpiece (a) \( P (L/2, 12.7, H/4) \) and (b) \( P (L/2, 25.4, H/4) \).](image-url)

The results above in Figure 3 confirm the fast temperature increase in welded plates followed by slow cooling down. They also show a small difference in the cooling phase between numerical and experimental data due to the fact that the model does not take into account the coupling with other phenomena such as the material flow, mechanical deformations and radiation of the heat with the ambient environment. It is also related to uncertainties measures (Uncertainty of sensors) and also to the gap between the real position of the sensors and its location in the FE meshing.

4. Results and discussions

The results based on the predictive numerical model fit well the available experimental measurements. Influence of the welding parameters such as the speed of advance, rotation speed and the diameter of the welding tool on thermal cycling and temperature distribution in the workpiece were investigated.
In Figure 4 the contours of the temperatures in the plane perpendicular to the welding line during the FSW process are shown. These contours were obtained at longitudinal positions X=0.305m of the workpiece, for the welding speed values (1.5mm/s, 3mm/s and 4.5mm/s) and rotation speed values (300tr/min, 400tr/min and 500tr/min). We can notice that the temperature at a section increases rapidly when the tool passes through this point for the three cases studied. Meanwhile, the temperature decreases as the welding speed of the tool increases. Moreover, it is clearly observed that the lines of the isotherms are retracted towards of rotation axis of the welding tool when increasing the welding speed. The heat-affected zone near the welding tool is larger when the welding speed decreases because it has more time to conduct heat to the surrounding.

Increasing the rotation speed from 300 to 500 tr/min leads to an increases of the welding heat input, the maximum value of the temperature and the overall level of the temperature. The distance between the peak temperatures of the contour 523 K (250°C) and the shoulder/workpiece interface increases also.

4.2. Effect of the heat transfer coefficient $h_{inf}$ and $h_{lat}$

Figure 5 shows the temperature distribution in the perpendicular plane to the welding direction, for the following parameters of the welding process ($u_w=3\text{mm/s}$, $w=400\text{tr/min}$, $F=15\text{kN}$ and $R_S=12.7\text{mm}$).
When \( h_{\text{lat}} \) increases, the hottest zone of the workpiece is located more and more around the welding tool. The calculations with different \( h_{\text{inf}} \) values were made at the workpiece/backing interface and with the same operating parameters previously used for \( h_{\text{lat}} \). We observe, the same effect for \( h_{\text{lat}} \), when \( h_{\text{inf}} \) increased, the maximum value of the temperature at the tool/workpiece interface to be welded is slightly reduced as well as the hottest zone around the tool.

4.3. Thermal cycles

Figure 6a, 6b and 6c show the thermal cycles at point P1 (\( x = 305 \text{ mm}, y = 12.7 \text{ mm}, z = 2 \text{ mm} \)) for three welding speed (1.5, 3.0 and 4.5 mm/s), for three rotational speed (300, 400 and 500 tr/min) and for three tool shoulder diameters (10, 12.7 and 15 mm), respectively. For the three values of the welding speed (Figure 6a), very rapid variations of the temperature are observed during the passage of the tool. These variations are represented by a rapid increase in temperature (heating phase) up to a maximum value at the time of passage of the welding tool by position P1; as further than this, the temperature decreases to a uniform value of 320K (cooling phase). When the welding speed is doubled or tripled, the maximum temperature value decreases to 68.5 °C and 122.6 °C, respectively. This difference in terms of temperature is due to the rate of the amount of heat dissipated in the workpiece.
The rotational speed is a significant variable that influences the thermal cycle through the FSW process. When the rotational speed increases, the temperature gradient increases to the maximum value, with a heating time almost identical \( (t = 96\text{s}) \). Also, the thermal cycle obtained for the rotational speed 300 tr/min has a higher cooling speed compared to other cases (Figure 6b). Also, a larger shoulder increases the quantity of heat created by the friction, but also results in a greater quantity of entrained material. This implies an increase in the amount of heat generated as shown in Figure 6c for three values of shoulder diameter tools 10, 12.7 and 15mm.

5. Conclusions
In this article, transient thermal model for FSW process was used with a good prediction of temperature distribution, temperature profiles, cooling rates compared to the experimental data available in the literature. The three-dimensional model can be coupled with optimization [12] method to improve the welding process and reduce the manufacturing cost. Further investigation would be performed on other aeronautical or automotive materials.

6. References
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