

Analysis of the Temperature Distribution in Friction Stir Welding using the Finite Element Method

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Keywords: Friction Stir Welding, Modeling, Finite Element Method

Abstract. Welding is a fabrication process widely used in several industrial areas. The welding of metallic alloys presents some basic characteristics as the presence of a localized intensive heat input that promotes mechanical and metallurgical changes. Different from conventional welding processes, where macroscopic fusion is observed, friction welding is a solid state welding process where the joint is produced by the relative rotational and/or translational motion of two pieces under the action of compressive forces producing heat and plastic strain on the friction surfaces. Friction Stir Welding (FSW) process has received much attention for its special characteristics, like the high quality of the joints. Although there are several experimental works on the subject, numerical modeling is not well stated, as the process is very complex involving the coupling of several non-linear phenomena. In this contribution a tridimensional finite element model is presented to study the temperature distribution in plates welded by the FSW process. A weld heat source is proposed to represent the heat generated during the process. The heat source model considers several contributions present in the process as the friction between the tool and the piece and the plastic power associated to the plastic strain developed. Numerical results show that the model is in close agreement with experimental results, indicating that the model is capable of capturing the main characteristics of the process. The proposed model can be used to predict important process characteristics, like the TMAZ (Thermomechanically Affected Zone), as a function of the welding parameters.

Introduction

The welding of metallic alloys presents some basic characteristics as the presence of a localized intensive heat input that promotes mechanical and metallurgical changes. The temperature gradients developed through the piece promotes residual stresses fields when the piece reaches room temperature. Phenomenological aspects of welding involve basically three couplings: thermal, phase transformation and mechanical phenomena. Welding process can be classified by the type of the heat source used and can involve metal fusion or not. Conventional welding processes, like TIG and laser, involve the metal fusion promoted by a highly localized heat source. Near the welding joint a Heat Affected Zone (HAZ) develops, where microstructural alterations and residual stresses are present. Friction welding process is a solid state process where metal fusion does not occur. Friction Stir Welding (FSW) is a welding process that has received much attention for his special characteristics, like the high quality of the joints. In this process the heat is generated by an intense mechanical work due friction between the pieces to be welded and a welding tool with rotational and transverse movements. The welded material softens at a temperature lower than the melting point, generating a weld joint with lower levels of residual stress and distortion than conventional fusion welding processes [1]. Fig. 1 shows a schematic representation of the FSW process.

In FSW process three zones develop [2]: Heat Affected Zone (HAZ), Thermomechanically Affected Zone (TMAZ) and Weld Nugget Zone (WNZ). The WNZ experiments extensive plastic strain and softening, and usually results in a fine equiaxed grain recrystallized structure. The TMAZ

experiments a lower level of plastic strain and is a relative small region surrounding the WNZ with a distorted grain structure. Finally the HAZ is the weakest region in the FSW.

Although there are a considerable number of references in experimental works related to FSW process, relatively, a reduced number references on modeling and numerical simulation of the process are available. Modeling the FSW process results in a complex problem involving the coupling of mechanical and thermal non-linear phenomena. Several authors have addressed these aspects separately: from uncoupled hybrids approaches considering combined experimental data and numeric results, to models considering the coupling of the several phenomena [1,3-6]. Some authors present analytic models based on Rosenthal [7] classic solution for a moving point heat source with a constant speed.

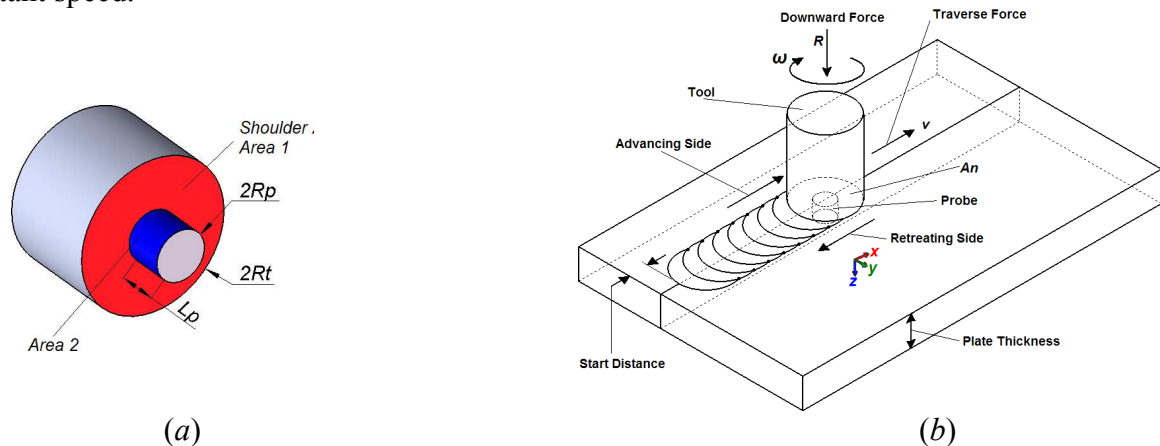


Figure 1. FSW process: (a) welding tool geometry and (b) FSW process parameters.

Russell and Shercliff [8] assess the heat generated by considering a friction force promoted by a constant stress at the interface tool-workpiece which value is equal to the material yield stress at high temperature. Russell [2] presents a detailed study of the several FSW heat generation mechanisms. Vilaça *et al.* [9] use an iterative process to adjust a point heat source parameters by minimizing the error obtained from experimental data and model results.

In this article, the heat source model proposed by Russel [2] is modified to incorporate a nonhomogeneous linear distribution for the heat generation contributions associated to tool-workpiece friction and workpiece plastic strain. The proposed heat source is used in a tridimensional finite element model and applied to study the welding of two aluminum plates. The model is general and can be used to predict the temperature distribution generated by the FSW process in welded plates. Important characteristics of the joint, like TAZ extension, can be predicted for different FSW process parameters, like tool geometry and speed, and for different workpieces geometries and materials.

Heat Source

Accurate prediction of residual stress, distortion, and strength of welded structures require an accurate analysis of the thermal cycle. The importance of an adequate model for the weld heat source in the analysis of the thermal cycle has been emphasized by several investigators [10-12].

Although there are several works that present experimental data for FSW process, the modeling of the FSW heat source is not well established [2,13]. The majority of the models consider a heat source distributed along the tool surface and that the heat generation occurs at the interface by friction and/or at a thin superficial layer by viscous dissipation. Hypotheses usually adopted are: a symmetric distribution and the effects of the metal flow in the heat generation are not considered.

The boundary conditions at the tool-workpiece are very complex and can be either slipping contact or sticking friction or a combination of both. In the first one the tool rotates at a higher speed than the material workpiece whereas in the second both the tool and the local material have the same speed.

There are three major mechanisms that contribute for the heat source: (1) friction at the shoulder-workpiece interface (q_s); (2) friction at the probe-workpiece interface (q_p); and (3) plastic strain at the piece (q_{ε_p}). Russell [2] presents a simple analytical model to represent these mechanisms.

In this work a proposed model based on Russell model [2] is adopted. The model considers some improvements like the dependence of the heat source contributions on the distance from the tool center [14]. Some hypotheses are adopted: the representation of the material behavior through a perfectly plastic material without hardening model and the integrally transformation of mechanical power in thermal power without any loss.

Heat generation contributions associated to the friction between the shoulder-workpiece interface are obtained from a material strip with a width dr located at a distance r from the tool center, considering translational and rotational relative movements between the tool and the workpiece. For the first one a constant translational relative speed, v_{trans} , is considered while for the second one a linear circumferential relative speed distribution, $v_{rot}(r)$, is considered, as shown in Fig. 2.

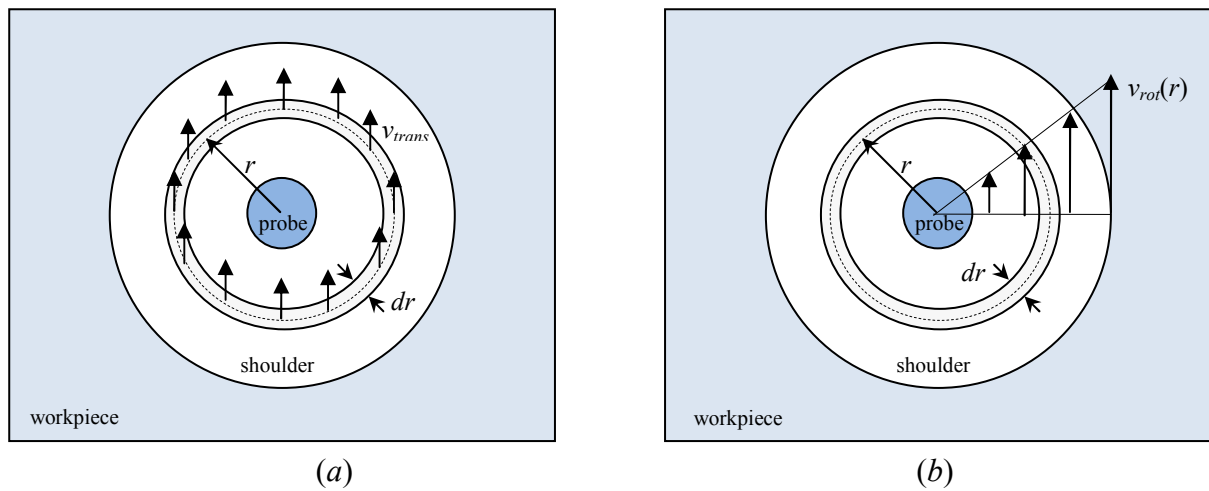


Figure 2. Material strip with a width dr at distance r from the tool center: (a) constant translational speed, v_{trans} , and (b) linear circumferential speed distribution.

Therefore, considering that a constant circumferential shear stress acting on the workpiece material with a magnitude equal to the shear yield stress at the process temperature (S_Y^{Shear}), the heat power associated to translational and rotational contributions, generated at the annular region of Fig. 2 with a width dr , can be represented by:

$$q_{Shoulder}^{Transl} = S_Y \pi r dr v_{transl} \quad ; \quad q_{Shoulder}^{Rot} = \pi S_Y \omega r^2 dr \quad (1)$$

where S_Y is the yielding stress ($S_Y^{Shear} = S_Y/2$, from *Tresca* criterion), v_{transl} the tool translational speed and ω the tool rotational speed.

The proposed model considers that the contributions associated to friction at the probe-workpiece interface and to the plastic strain developed in the workpiece are complementary and three conditions can be achieved: (1) a stick condition where there is no slip between the probe and the workpiece; (2) a slip condition, where a slip condition is observed between both surfaces; and (3) an intermediary condition where stick and slip are both present. A stick factor, δ , similar to the one used by Nadan *et al.* [5] is introduced to permit the inclusion of these three conditions in the model. This factor represents the relative amount of heat generated by plastic strain developed in the workpiece in comparison to the amount of heat generated by the friction at the probe-workpiece interface. Therefore, for these two heat generation contributions, when $\delta = 1$ a limit condition of integral stick is achieved and an integral amount of heat generated by the plastic strain developed in

the workpiece is considered, whereas when $\delta = 0$ a limit condition of integral slip is achieved and an integral amount of heat generated by the friction at the probe-workpiece interface is considered. Through this parameter it is possible to establish intermediary conditions between stick and slip conditions. The amount of stick can be assessed through fitted experimental data [15].

The contributions associated to the friction at the probe-workpiece interface, heat generation can be represented by:

$$q_p = (1 - \delta) \left[\pi S_Y \omega L_p (R_p)^2 \right] \quad (2)$$

where L_p and R_p are, respectively, the length and the radius of the probe. This equation considers that a constant circumferential shear stress acts on the material in contact with the probe surface, with a magnitude equal to the shear yield stress at the process temperature (S_Y^{Shear}).

For the contribution of the heat generated by the plastic power developed in the workpiece, the model considers that the mechanical power is integrally transformed in thermal power. The intensive plastic strain occurs inside a material region named *weld nugget*. Fig. 3 presents a schematic representation and a macrograph of the *weld nugget*. The use of these simple models requires the calibration of the model, and several parameters, like the weld nugget dimension, must be estimated from experimental data.

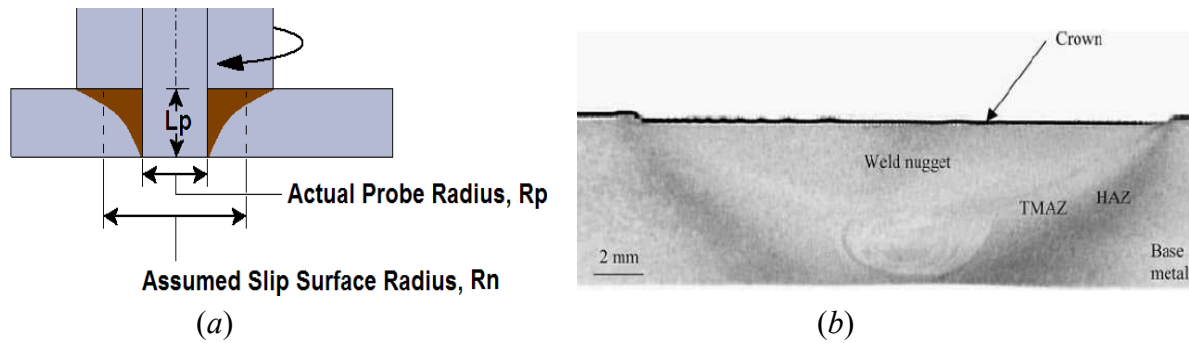


Figure 3. Weld nugget parameters (a) and *weld nugget* macrograph [1] (b).

The stress/strain state present in the workpiece is very complex and some hypotheses are adopted: (i) the process promote a circumferential linear displacement distribution (u) in the annular region between the probe interface ($r = R_p$) and the *weld nugget* limit ($r = R_n$), as shown in Fig. 4a; and (ii) the annular region is submitted to a constant circumferential stress state with a magnitude equal to the material yield stress limit (S_Y), as shown in Fig. 4b, which presents a straightened representation of a dr width material strip.

The circumferential linear displacement distribution, $u(r)$, and the strain rate, $\dot{\epsilon}(r)$, in the annular region between the probe interface ($r = R_p$) and the *weld nugget* limit ($r = R_n$), can be written as:

$$u(r) = \left[\frac{R_n - r}{R_n - R_p} \right] u_p \quad ; \quad \dot{\epsilon}(r) = \frac{\dot{u}(r)}{L_0} = \frac{v(r)}{2\pi r} = \left[\frac{R_n - r}{R_n - R_p} \right] \frac{v_p}{2\pi r} \quad \text{for } R_p \leq r \leq R_n \quad (3)$$

where u_p and v_p are, respectively, the circumferential displacement and speed at the probe-workpiece interface.

Considering that large strains are present in the *weld nugget* annular region, elastic strains can be disregarded. Therefore, $\epsilon = \epsilon_p + \epsilon_e \cong \epsilon_p$, where ϵ_p is the plastic strain part and ϵ_e is the elastic strain part. The proposed model considers a maximum value of plastic strain at the material in

contact with the probe and a null value outside the *weld nugget* region, as show in Fig. 4c. The plastic power generated by plastic strain developed at the workpiece is equal to $\sigma \dot{\varepsilon}_p(r)$, and the associated heat generated can be written as:

$$q_{\dot{\varepsilon}_p}(r) = \delta[\sigma \dot{\varepsilon}_p(r)] = \delta \frac{S_y R_p \omega}{2\pi r} \left[\frac{R_n - r}{R_n - R_p} \right] \quad \text{for } R_p \leq r \leq R_n \quad (4)$$

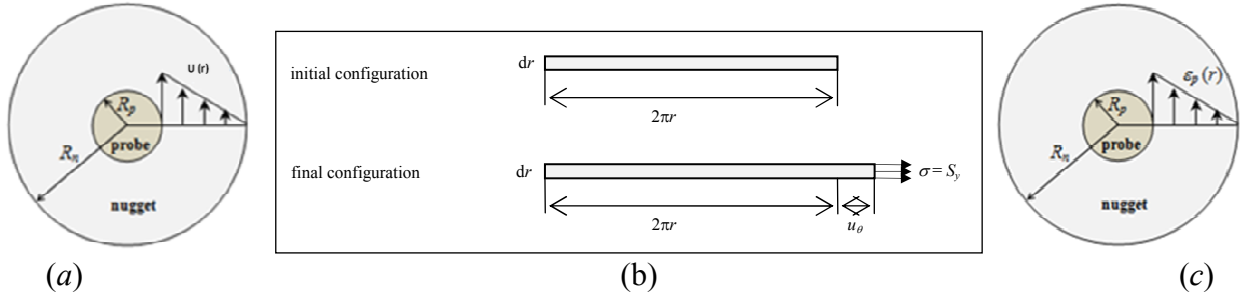


Figure 4. *Weld nugget* region: (a) linear displacement distribution, (b) strain in a strip material with *dr* width and (c) linear plastic strain distribution.

Numerical Model

A tridimensional numerical model based on the finite element method is presented to study the temperature distribution in plates welded by the FSW process. The proposed model is applied to the welding of two aluminum AA2014-T6 6.35 thickness plates by FSW process, reproducing the process studied by Russel [2] where 5 thermocouples are incorporated to the plates to measure temperature evolution during the process. The geometry, the thermocouples position, the material properties are presented in Fig. 5 and Table 1. The following welding parameters are used: welding speed, v , of 1.33 mm/s, a rotational speed, ω , of 500 rpm, a total power generated, q_{gen} , of 1300 W, a heat flux fraction of the working tool, f , of 0.85 and a effective power of the working tool, q_{net} , of 1105 W.

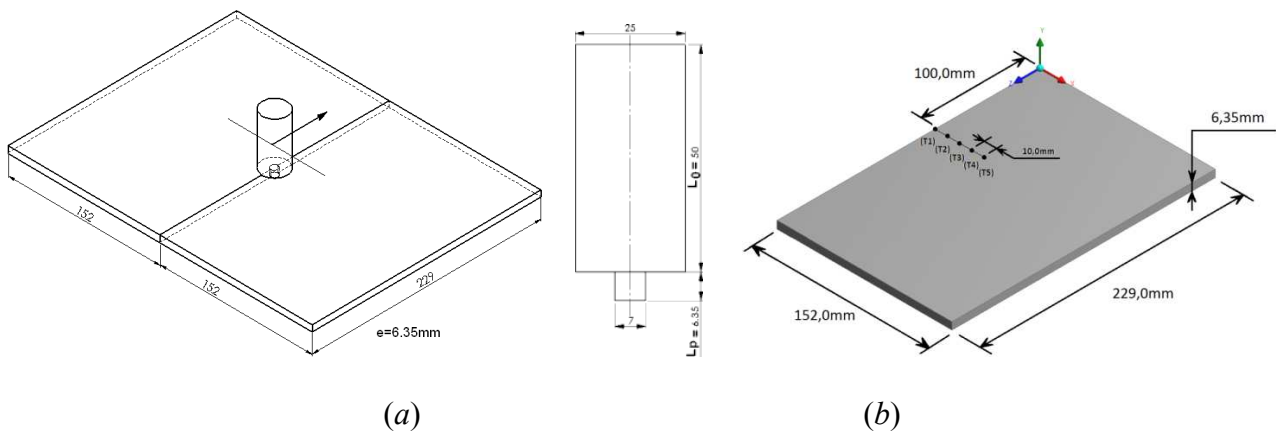


Figure 5. (a) Welded plates and tool geometry. (b) thermocouple positions [2].

The tridimensional model considers a symmetry condition at the welding path. The model considers thermal transient response and contemplate the effects of translational motion. Numerical simulations are performed with commercial finite element code ANSYS [16], employing thermal element SOLID70 (8 nodes with a single degree of freedom – temperature - per node) for spatial discretization. Fig. 6a presents the mesh used after a convergence analysis whereas Fig. 6b presents the convective boundary conditions.

Table 1. AA2014-T6 material properties [2].

Material Properties	AA2014 -T6	HS Steel Tool
Thermal conductivity, K (W/mK)	155	20
Yield stress at room temperature, $S_Y^{RoomTemp}$ (MPa)	400	-
Yield stress at FSW temperature, $S_Y^{FSWTemp}$ (MPa)	12	-
Onset melting temperature, T_m (°C)	507	-

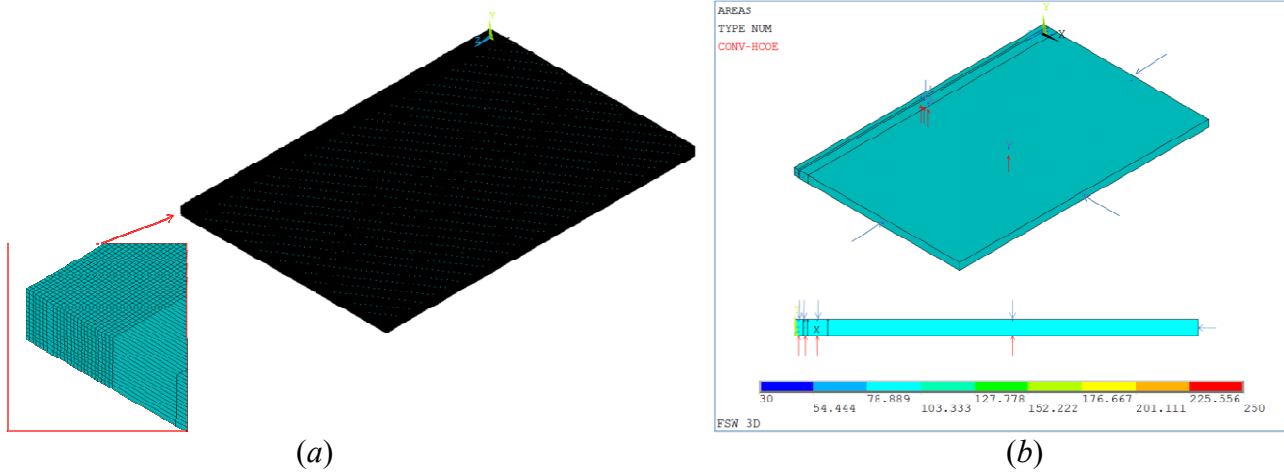


Figure 6. Finite element mesh (a) and convective boundary conditions (b).

Heat generation contributions are applied to selected elements as a heat generation rate through ANSYS command BFE (element body force load, using the label HGEN for heat generation rate body load type). The present analysis considers the 4 heat source mechanisms described in section 2 associated to equations (1-2) and (4). A numerical routine developed in APDL programming language [16] is used to apply the 4 heat generation contributions ($q_{Shoulder}^{Transl}$, $q_{Shoulder}^{Rot}$, q_{ε_p} , q_p) as the source moves through the plate.

The material is assumed to be at an initial temperature of 20°C, which is similar to the ambient temperature, and convective boundary conditions are applied to lines associated to the plate surface and tool surface. A convection coefficient, h , of 30 W/m² °C is adopted for the aluminum plate free surfaces. At the aluminum plate bottom an equivalent convection coefficient, h , of 250 W/m² °C is adopted to represent the heat transfer between the plate and the base (*backing plate*). Finally, for the top of the tool an equivalent convection coefficient, h , of 1500 W/m² °C is adopted to represent the heat transfer between the tool and the mandrel [17,18]. The model consider the yield stress at FSW temperature ($S_Y^{FSWTemp}$).

Numerical Simulations

Fig. 7a presents a comparison between experimental data obtain by Russell [2] and numerical results. Coordinate x measures the perpendicular distance from the welding path. Experimental data is collected at the time instant, $t = 76$ s, when the tool walk through the thermocouples line (at a distance of 100 mm from the plate end - Fig. 5). Fig. 7b shows the temperature evolution at thermocouples positions for experimental data and numerical results obtained from 3D model. E_i and N_i represents, respectively, thermocouple data and numerical data at point i ($i = 1,., 5$ - Fig. 5b). A good agreement can be observed. The interruption of thermocouple TP1 data is associated to its destruction during the passage of the tool. A good agreement can be observed between numerical and experimental data. The numerical data presented represents the temperature distribution at the thermocouples position. Figure 7b and 7c shows temperature distribution for 3D model at time instant $t = 76$ s.

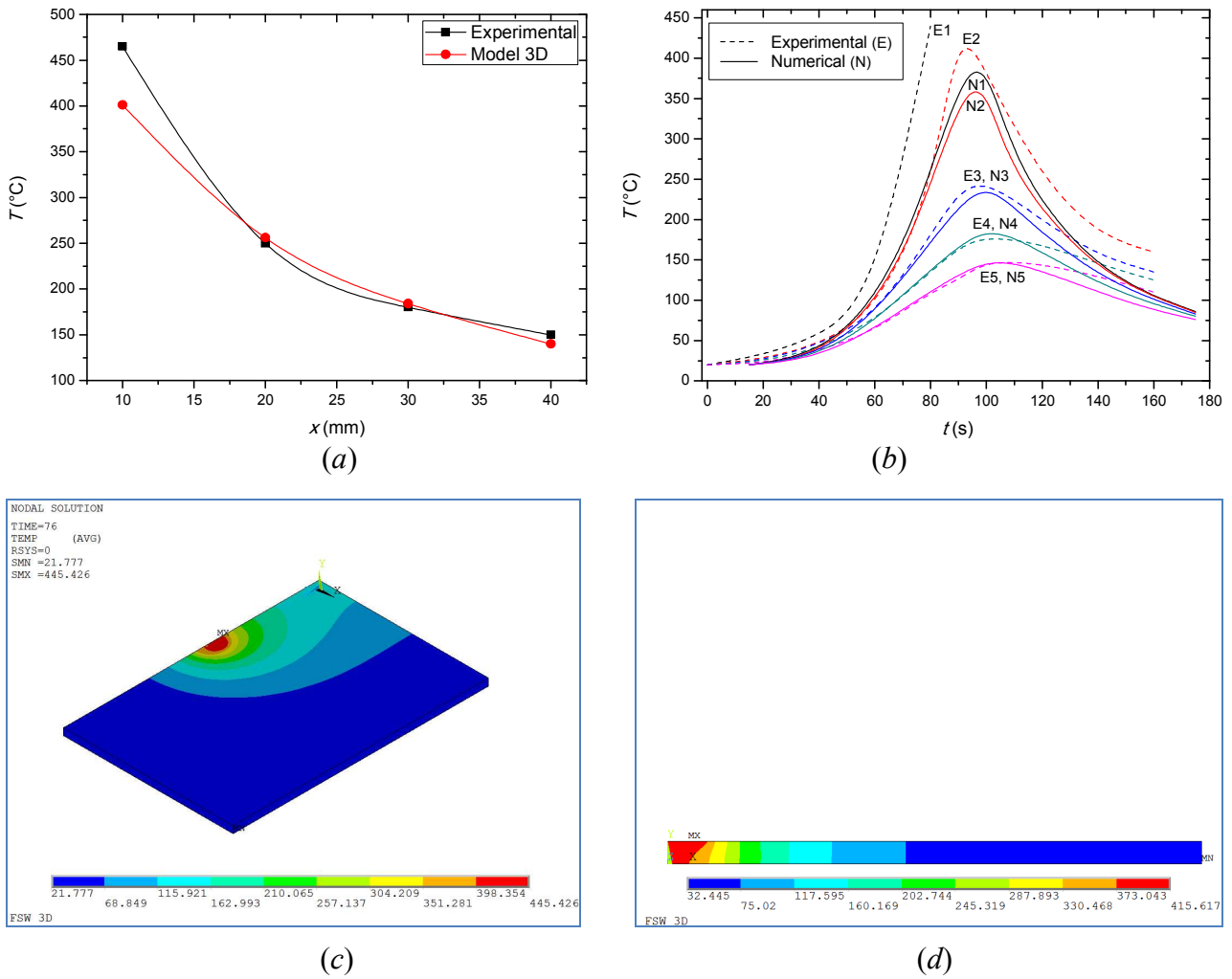


Figure 7. Temperature at the thermocouples position for experimental and numerical data (a). Temperature evolution at thermocouples positions for experimental and numerical results (b). Temperature distributions for 3D model (c) and at a cross section (d) at $t = 76$ s.

At this point the proposed models are used to study the parameters influence on the temperature distribution promoted by the FSW process.

Figures 8a-c shows, respectively, the effect of rotational speed, translational speed and stick factor on the temperature distribution using the 3D model. Comparing the rotational and translational speed effects, results shows that the first one presents a larger influence on temperature. As expected, higher temperature values are obtained for higher rotational speeds and for lower translational speeds. For the stick factor, higher temperature values are observed when $\delta = 0$, which is associated to a total slip condition where the q_p contribution is integral.

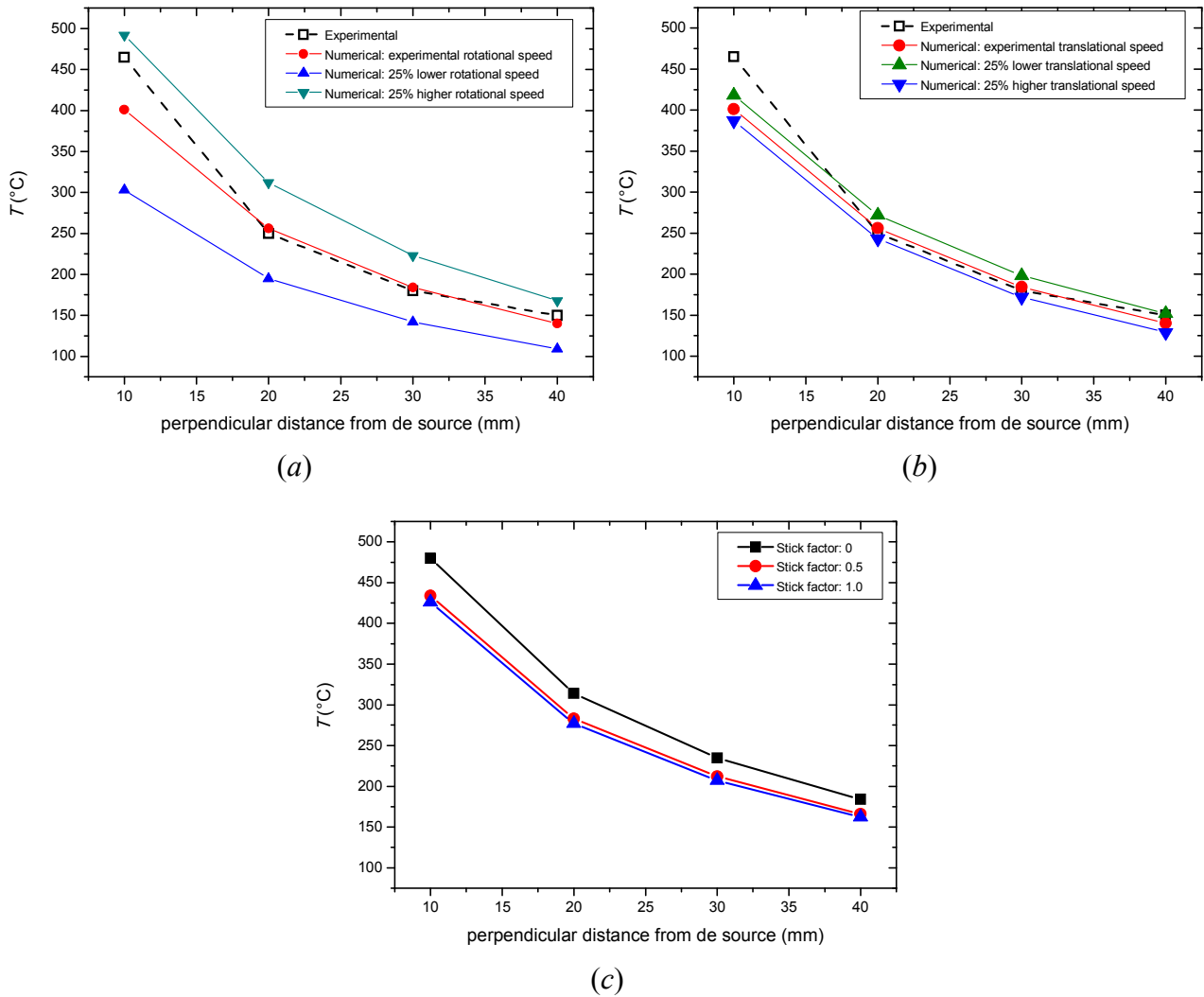


Figure 8. Effect of rotational speed (a), translational speed (b) and stick factor (c) on the temperature distribution.

Conclusions

Two finite element models are proposed to study the temperature distribution in FSW welded plates. The models consider the contribution of the several phenomena present in the process, as the heat generated by the tool-workpiece friction and the workpiece plastic strain. The proposed model for the heat source presents a linear distribution and is applied to study the temperature distribution for the welding of aluminum plates. For the studied conditions, rotational speed is the FSW process parameter that presents larger effects on the workpiece temperature evolution. Numerical results show that the model is in close agreement with experimental results, indicating that the model is capable of capturing the main characteristics of the process. The proposed model can be used to predict important process characteristics, like the TMAZ (Thermomechanically Affected Zone), as a function of the welding parameters.

Acknowledgments

Authors would like to acknowledge the support of the Brazilian Research Agency CNPq and ESSS.

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