MODELING TEMPERATURE DISTRIBUTION IN FRICTION STIR WELDING USING THE FINITE ELEMENT METHOD

Mauricio Rangel Pacheco, pacheco@esss.com.br
ESSS – Rua Lauro Muller, 116 - 14º andar – 1404 – 22290-160 – Rio de Janeiro – RJ – Brasil
CEFET/RJ - PPEMM - Av. Maracanã, 229, 20271-110 - Rio de Janeiro - RJ – Brasil

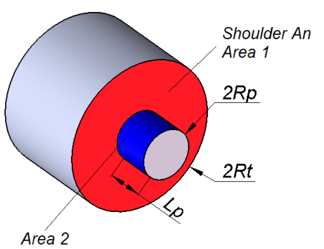
Pedro Manuel Calas Lopes Pacheco, calas@cefet-rj.br
CEFET/RJ - PPEMM - Av. Maracanã, 229, 20271-110 - Rio de Janeiro - RJ – Brasil

Abstract. *Welding is a complex process where localized intensive heat input is furnished to a piece promoting mechanical and metallurgical changes. Temperature gradients developed through the piece promote residual stress fields when the piece reaches room temperature. 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 his special characteristics, as 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 finite element model is presented to study the temperature distribution in plates welded by the FSW process. A weld heat source is used 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 as the TAZ (Thermal Affected Zone) as a function of the welding parameters.*

Keywords: *Welding,* Friction Stir Welding, *FSW, Modeling, Numerical Simulation, Finite Element Method.*

1. INTRODUCTION

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. 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 as 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 microstrutural alterations and residual stress 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, as 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 less than the melting point generating a weld joint with less residual stress and distortion than conventional fusion welding processes (Chen and Kovacevic, 2003). Figure 1 shows a schematic representation of the FSW process.



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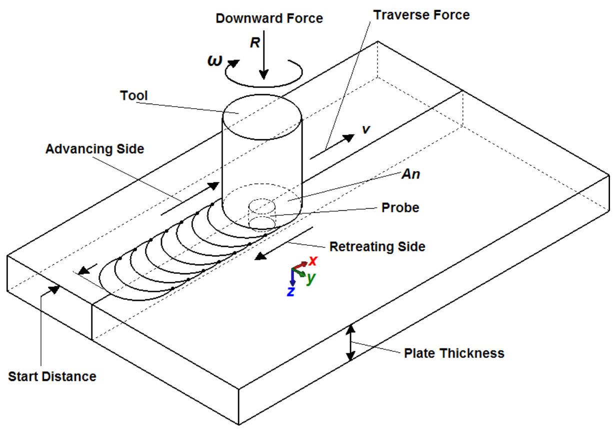


(*b*)

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

In FSW process three zones develop (Russell, 2000): Heat Affected Zone (HAZ), Thermomechanically Affected Zone (TMAZ) and a Weld Nugget Zone (WNZ). The WNZ experiments extensive plastic and softening, and usually results in a fine equiaxed grain recristallized 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. Figure 2 presents a schematic view of the three regions.

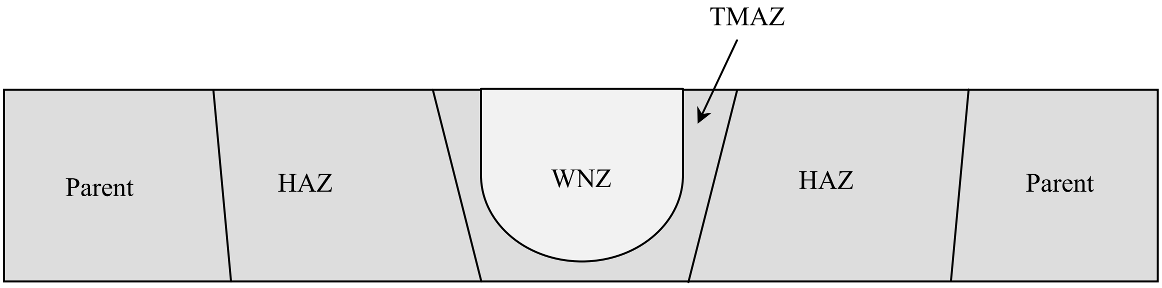


Figure 2. FSW process zones: Heat Affected Zone (HAZ), Thermomechanically Affected Zone (TMAZ) and a Weld Nugget Zone (WNZ).

Although there are a considerable number of references in experimental works related to FSW process there is, relatively, a reduced number references on modeling and numerical simulation of the process. Modeling the FSW process is 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 (Colegrove, 2000; Den and Xu, 2001; Chen and Kovacevic, 2003; Nadan *et al.*, 2006). Some authors present analytic models based on Rosenthal (1946) classic solution for a moving point heat source with a constant speed.

Russell and Shercliff (1999) assess the heat generated by assume a friction force promoted by a constant stress at the interface tool-workpiece equal to the material yield stress at high temperature. Russell (2000) presents a detailed study of the several FSW heat generation mechanisms. Vilaça *et al.* (2005) use an iterative process to adjust a point heat source by minimizing the error obtained from experimental data and model results.

Xu e Deng (2002) presents a tridimensional numerical model based on the finite element method to study the mechanical behavior of the welded material. Non-linearities as large displacements and temperature dependent properties are considered. Therefore it is an uncoupled model as the thermal phenomenon is not considered and temperature data obtained from experimental analysis is used as a prescribed loading.

Zhu e Chao (2003) proposes a heat source model where the heat flux presents a linear distribution through the radial direction. The heat source amplitude is adjusted by comparing results obtained from a thermal finite element model with experimental data obtained from thermocouples. Temperature data is then used as a prescribed loading in a finite element thermoelastoplastic model to obtain the stress field. As the previous model this is an uncoupled model.

Buffa *et al.* (2006*a*, 2006*b*) present a coupled model for a rigid-viscoplastic material where the heat generation is dependent on the tool-workpiece friction and the plastic strain promoted by the process. This coupled model calculates the plastic strain associated to the developed stress and plastic strain fields.

In this article, the heat source model proposed by Russel (2000) is modified to incorporate a linear distribution for the heat generation contributions associated to tool-workpice friction and workpiece plastic strain. The proposed heat source model is incorporated to a bidimensional finite element code and applied to study the welding of two aluminum plates. The model can be used to predict the temperature distribution generated by the FSW process in welded plates. Important characteristics of the joint as the TAZ can be predicted for different FSW process parameters as tool geometry and speed and for different workpieces geometries and materials.

2. 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 (Pavelik *et al.*, 1969; Goldak *et al.*, 1984; Ronda and Oliver, 2000). For traditional welding process some authors represent the heat source as a geometric distribution of heat flux. Pavelic *et al.* (1969) suggested a Gaussian surface flux distribution disc. Friedman (1975) presents an alternative form for the Pavelic model expressed in a moving coordinate system, with an origin located at the center of the heat source. Goldak *et al.* (1984) presents a more accurate model comprising a non-axisymmetric three-dimensional "double ellipsoidal power density distribution" for moving weld heat sources based on a Gaussian distribution of power density in space.

Although there are several works that present experimental data for FSW process the modeling of the FSW heat source is not well established (Russel, 2000; Mishra and Mahoney, 2007). 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 thin superficial layer by viscous dissipation. Hypothesis usually adopted are a symmetric distribution and to ignore the effects of the metal flow in the heat generation.

The boundary conditions at the tool-workpiece are very complex and can be either slipping contact or sticking friction or a combination of the two. In the first one the tool rotates at a higher speed than the material workpice 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-piece interface (q_S), (2) friction at the probe-piece interface (q_P) and (3) plastic strain at the piece ($q_{\varepsilon p}$). Simple analytical models can be developed to represent these mechanisms.

For the first mechanism there are contributions associated from translational (q_S^{Transl}) and rotational (q_S^{Rot}) motion of the tool. Therefore, for slip and stick conditions:

$$q_S = q_S^{Transl} + q_S^{Rot} \qquad \text{slip:} \begin{cases} q_S^{Transl} = \mu\, p\, \pi\, R^2 v \\ q_S^{Rot} = (2/3)\mu\, p\, \pi\, \omega\, R^3 \end{cases} \qquad \text{stick:} \begin{cases} q_S^{Transl} = S_Y^{Shear}\, \pi\, R^2 v \\ q_S^{Rot} = (2/3)\, S_Y^{Shear}\, \pi\, \omega\, R^3 \end{cases} \tag{1}$$

where, μ is friction coefficient, p the normal pressure, the S_Y^{Shear} is the yielding shear stress, v the tool translational speed and ω the tool rotational speed. Usually the tool translational motion contribution is very small (Russel, 2000; Mishra and Mahoney, 2007).

For the second mechanism (q_P) heat develops due friction between probe and piece therefore:

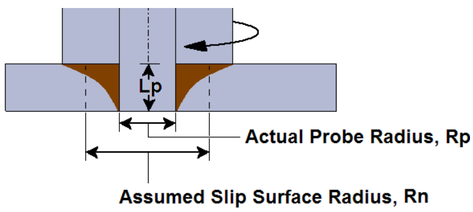
$$q_P = 2\pi\, S_Y^{Shear}\, \omega\, L_p (R_p)^2 \tag{2}$$

where L_p and R_p are, respectively, the length and the radius of the probe.

Finally the third mechanism ($q_{\varepsilon p}$) associated to the plastic strain developed can be represented by:

$$q_{\varepsilon p} = 2\pi\, S_Y^{Shear}\, \omega\, L_p (R_n)^2 \tag{3}$$

where R_n is the slip radius associated to the *weld nugget*. The weld nugget represents a region where intensive plastic strain occurs. Figure 3 presents a schematic representation and a macrograph of the *weld nugget*.



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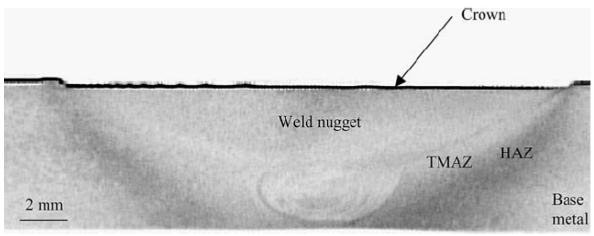


(*b*)

Figure 3. Weld nugget parameters (*a*) and *weld nugget* macrograph (Chen and Kovacevic, 2003) (*b*).

The use of these simple models requires the calibration of the model and several parameters, as p and R_n, must be estimated from experimental data.

Russel (2000) applied equations (1-3) to the study of a 2000 series aluminum alloy. In the analysis considers that the pressure between the tool and the piece is equal to the yielding shear stress, whose value is temperature dependent. Results obtained by Russel (2000), using analytic models, shows that the major contribution to the heat generation is due to friction at the shoulder-piece interface (q_S) mainly associated to the rotational term. Translational friction at the shoulder presents a very small contributions and the probe contribution is also small for thin plates. Table 1 presents some results for three different sheet thicknesses.

Table 1. Contribution of the three mechanisms for the heat source 2000 Al alloy (Russell, 2000).

Sheet Thickness	**HEAT GENERATED** (W)			
	q_S^{Transl}	q_S^{Rot}	q_P	$q_{\varepsilon p}$
2 mm	4	1300	48	98
4 mm	4	1300	96	196
6 mm	4	1300	144	294

This work considers the dependence of the heat source contributions q_S^{Rot} and $q_{\varepsilon p}$ on the distance from the tool center. Both contributions are obtained for a strip of material with a width *dr* at distance *r* from the tool center (Fig. 4*a*).

For q_S^{Rot} it is considered that the material near the tool experiment slower speeds than material far for the tool and the heat generation contribution depends on the distance from the tool (Chen and Kovacevic, 2003):

$$dq_S^{Rot} = \begin{cases} 2\pi\, \mu\, p\, \omega\, r^2 dr & \text{(slip)} \\ 2\pi\, S_Y^{Shear}\, \omega\, r^2 dr & \text{(stick)} \end{cases} \tag{4}$$

$q_{\varepsilon p}$ is associated to the heat generated by the plastic power, $\sigma\,\dot{\varepsilon}^p$, developed by the material inside the welding nugget region. The model considers only the circumferential stress and strain components and a linear distribution for the plastic strain with 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. 4*b*. Therefore the contributions due material plastic strain can be rewritten for a strip of material with a width *dr* at distance *r* from the tool center as:

$$\dot{\varepsilon}^p_{r=R_p} = \frac{\dot{u}^p_{r=R_p}}{2\pi\, R_p} \approx \frac{v_{r=R_p}}{2\pi\, R_p} = \frac{\omega}{2\pi} \quad ; \quad \dot{\varepsilon}^p(r) = \frac{\omega}{2\pi}\left(\frac{R_n - r}{R_n - R_p}\right) \qquad \text{for } R_p \le r \le R_n \tag{5}$$

$$dq_{\varepsilon p} = 2\pi\, \sigma \dot{\varepsilon}^p L_p\, r\, dr = \frac{S_Y \omega L_p\, r}{R_n - R_p}(R_n - r)\, dr \qquad \text{for } R_p \le r \le R_n \tag{6}$$

where S_Y is the material yielding stress, $\dot{\varepsilon}^p_{r=R_p}$ is the plastic strain rate at the probe interface and σ the stress. A constant stress field with a magnitude of the yielding stress is considered inside the welding nugget region.

In the presented analysis the heat generated by the tool translational motion is not considered and only the stick condition is assessed.

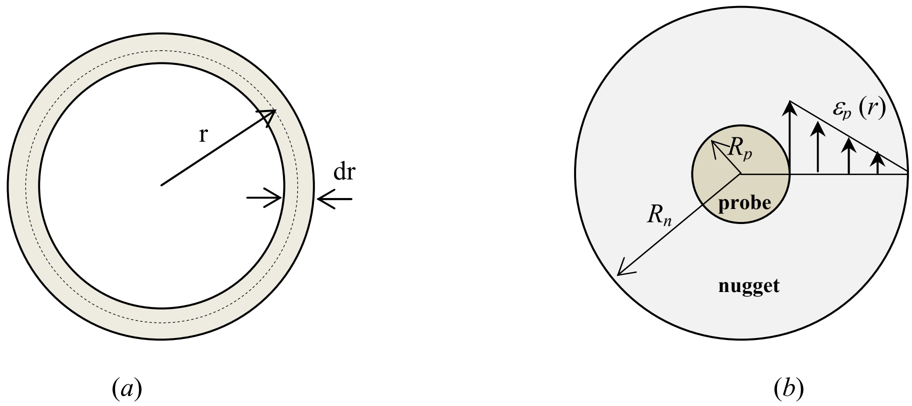


Figure 4. Material strip with a width *dr* at distance *r* from the tool center (*a*) and linear plastic strain distribution at the welding nugget region (*b*).

3. NUMERICAL MODEL

A finite element model is presented to study the temperature distribution in plates welded by the FSW process. An axissymmetric model is chosen as a first approach in order to minimize the computational cost. This hypothesis of axissymmetry can be justified by the fact that the tool rotational motion introduces a small perturbation on the temperature radial distribution. The model considers the thermal steady-state response and do not contemplate the effects of translational motion. Numerical simulations are performed with commercial finite element code ANSYS (Ansys, 2008), employing thermal element PLANE 55 (4 nodes with a single degree of freedom – temperature - per node) for spatial discretization.

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 (2000). The geometry and the material properties and process parameters are presented in Fig. 5 and Tables 2-3, respectively.

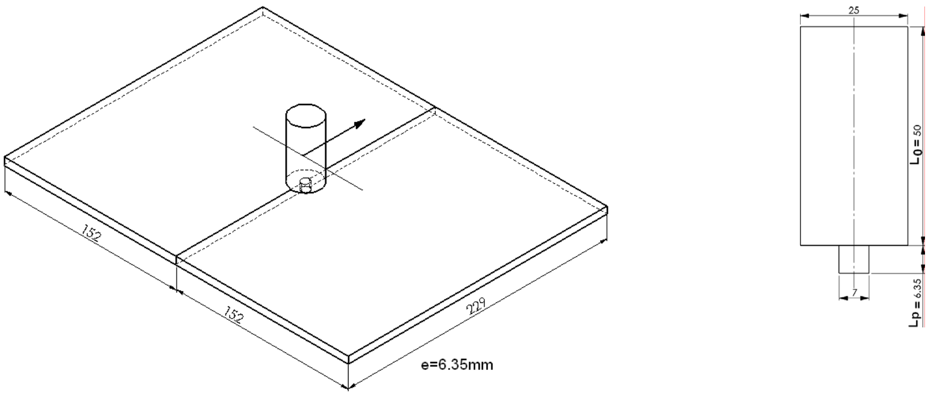


Figure 5. Geometry of the welded plates (Russell ,2000).

Table 2. AA2014-T6 material properties (Russell, 2000).

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

Table 3. FSW parameters – AA2014-T6 (Russell, 2000).

FSW Parameters	Value
Tool radius, R_t (mm)	12.5
Welding speed, v (mm/s)	1.33
Rotational speed, ω (rpm)	500
Total power generated, q_{gen} (W) ≈	1300
Heat flux fraction of the working tool, f	0.85
Effective power of the working tool, q_{net} (W)	1105

Figure 6 presents the geometry of the model composed by 5 areas. Area 1 represents the tool and areas 2 to 5 the plate. Areas 3 to 5 are used to control the mesh discretization. Figure 7 presents the mesh used after a convergence analysis. Convection boundary conditions are applied to the surface.

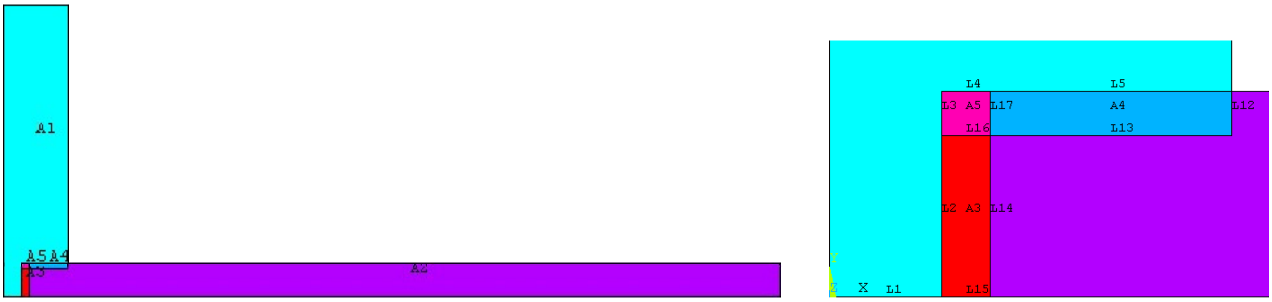
The present analysis considers the three heat source mechanisms described in section 2. In order to analyze the heat source model in the welding process, two models are considered:

Model 1: heat source model is based on Russel (2000) proposed equations (1-3);
Model 2: heat source model is based on modified equations proposed in this work (4-6).

For *Model 1* q_S^{Rot} is applied through surface loads command SFL on lines L4 and L5 of Fig.6*b*. q_S^{Rot}, q_p and $q_{\varepsilon p}$ are applied through surface loads command SFL on lines L2 and L3 of Fig.6*b*

For *Model 2* q_S^{Rot} and $q_{\varepsilon p}$ contributions heat generation is applied through element body force load command BFE on areas A5 and 4 for q_S^{Rot}, A5 and A3 for $q_{\varepsilon p}$ of Fig.6. For q_p contribution heat generation is applied through surface loads command SFL on lines L2 and L3 of Fig.6*b*.

The material is assumed to be at an initial temperature of 20ºC 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 15 W/m^2 ºC is adopted for the aluminum plate free surfaces. At the aluminum plate bottom an equivalent convection coefficient, *h*, of 1500 W/m^2 ºC is adopted to represent the heat transfer between the plate and the base. Finally, for the top of the tool an equivalent convection coefficient, *h*, of 1500 W/m^2 ºC is adopted to represent the heat transfer between the tool and the mandrel (Khandkar *et al.*, 2003; Hamilton *et al.*, 2008). Both models considers the yield stress at FSW temperature ($S_Y^{FSW\ Temp}$).



(*a*) (*b*)

Figure 6. Model geometry (*a*) and detail (*b*).

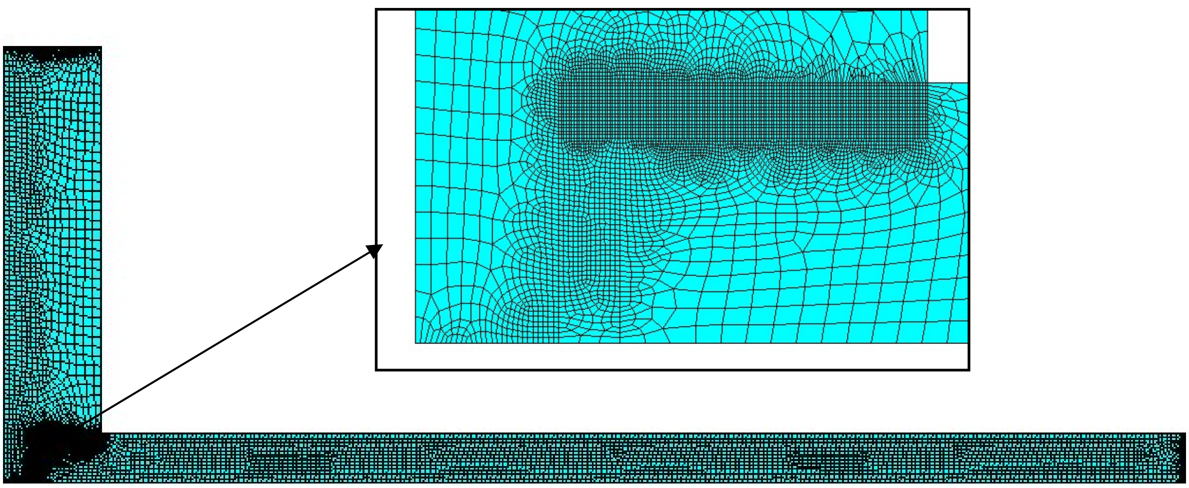


Figure 7. Finite element mesh.

4. NUMERICAL SIMULATIONS

Figure 8 presents the temperature distribution for *Model 1* whereas Figs. 9-10 present the temperature distribution for *Model 2* considering. R_n is a model parameter that must be obtained from experimental data. Russel (2000) uses R_n = 5 mm. To study the influence of R_n *Model 2* considers two nugget radius: R_n = 5 and 7.5 mm.

For the situations considered the thermal phenomena is localized on the region near the welding tool. For a distance higher than three tool diameters temperatures near the ambient temperature are observed. Maximum temperatures of approximately 763, 502 and 686 ºC are observed for, respectively, *Model* 1*, Model 2* with R_n = 5 mm and *Model 2* with R_n = 7.5 mm. In spite of the maximum temperatures observed for the first and third cases are higher that the material melting temperature (507 ºC), during the FSW process on the melting onset the heat generation is reduced as the friction and plastic strain heat generation mechanisms cannot be sustained.

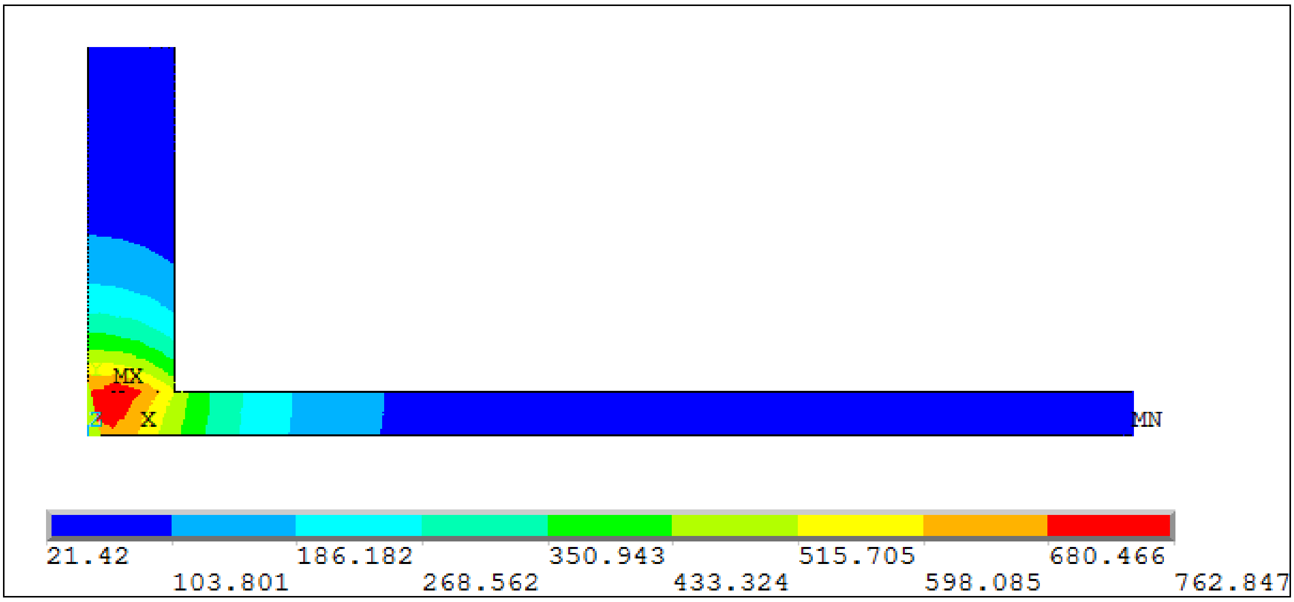


Figure 8. Temperature distribution. *Model 1* - R_n = 5 mm.

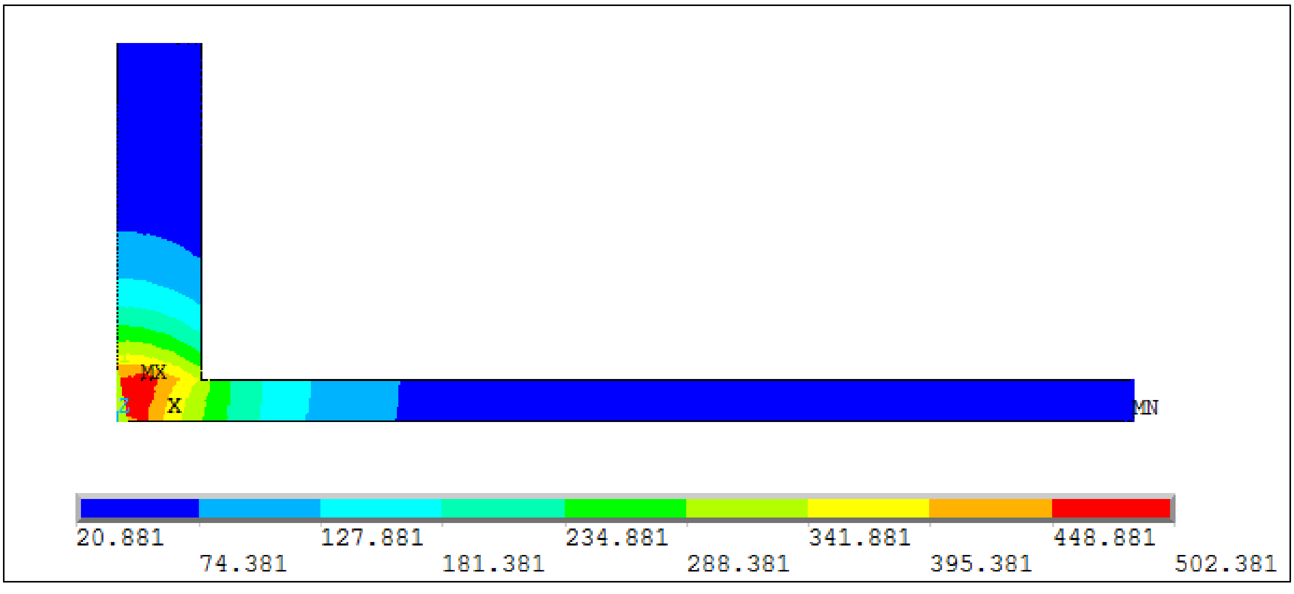


Figure 9. Temperature distribution. *Model 2* - R_n = 5 mm.

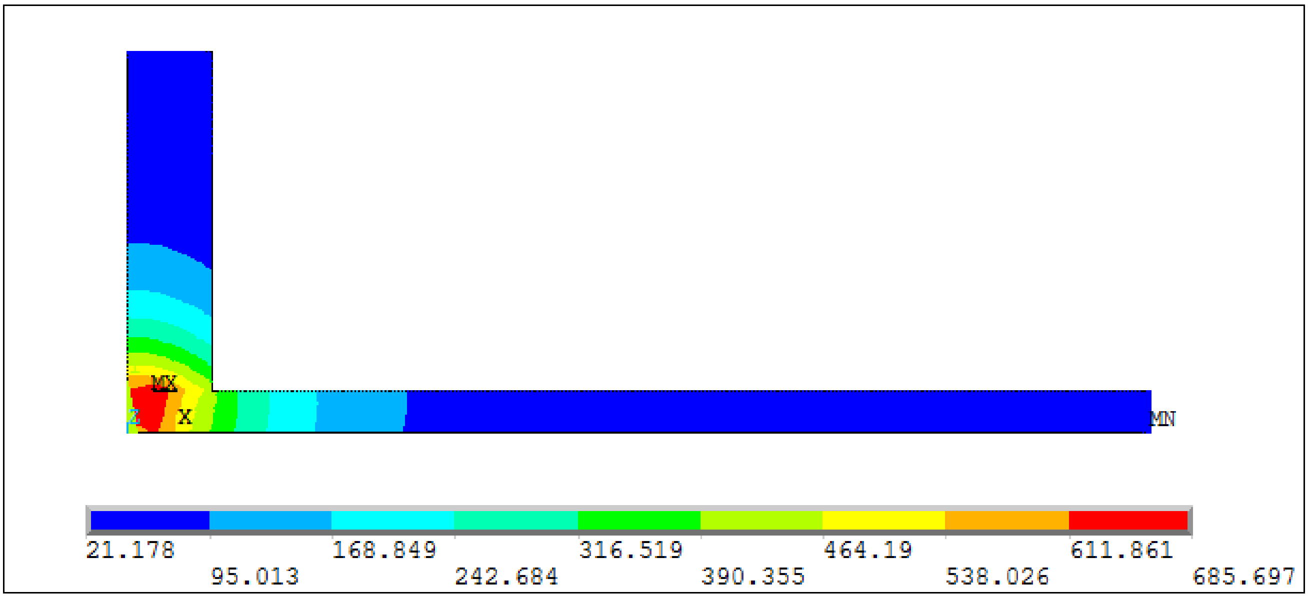


Figure 10. Temperature distribution. *Model 2* - R_n = 7.5 mm.

Figure 11 presents a comparison between experimental data obtained by Russel (2000) and numerical results obtained from *Model 1* and *Model 2*. Russell (2000) analytic model is also presented. Results shows that the proposed models capture qualitatively the thermal behavior observed in the process. *Model 2* for R_n = 7.5 mm presents a close agreement with experimental results.

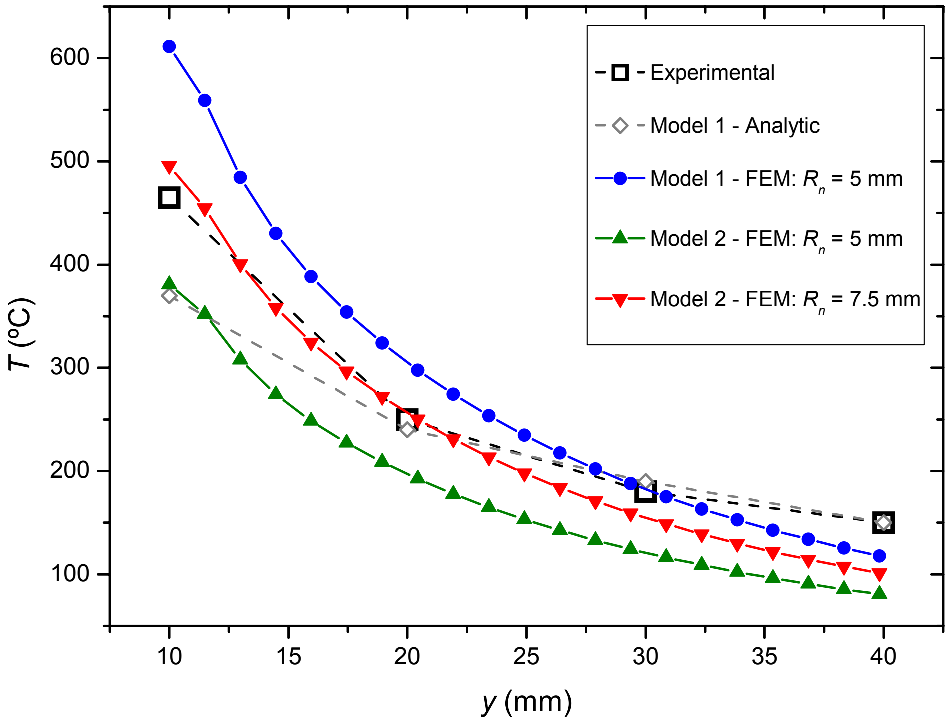


Figure 11. Temperature distribution through *y* direction (normal to the welding direction).

5. CONCLUSION

A bidimensional finite element model is proposed to study the temperature distribution in FSW welded plates. The model considers the contribution of the several phenomena presents in the process as the heat generated by the tool-workpiece friction and the workpice 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. 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 as the TAZ (Thermal Affected Zone) as a function of the welding parameters.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

ANSYS Inc., *Structural Analysis Guide*, Release 11, 2006.

Buffa G., Hua J., Shivpuri R., Fratini L., 2006*a*, "Design of the stir welding tool using the continuum based FEM Model", *Materials Science and Engineering*, 10.

Buffa G., Hua J., Shivpuri R., Fratini L., 2006*b*, "A continuum based model for friction stir welding – model development", *Materials Science and Engineering*, 10.

Chen, C.M.; Kovacevic, R., 2003; "Finite element Modeling of Friction Stir Welding – termal and thermomechanical Analysis", *International Journal of Machine Tools & Manufacture*, pp.1319-1326.

Colegrove, P; Painter, M; Graham, D.; Miller, T., 2000; "Three-dimensional flow and thermal modelling of the friction stir welding process", *Proceedings of the Second International Symposium on Friction Stir Welding*, Gothenburg, Sweden.

Deng, X. e Xu, S., 2001; "Solid Mechanics Simulation of Friction Stir Welding Process", *Trans. NAMRI/SME SME*, 29, 631–638.

Friedman, E., 1975; *Jounal of Pressure Vessel Technology*, Trans ASME, Vol. 97, pp.206-213.

Goldak, J., Chakravarti, A. and Bibby, M., 1984, "A New Finite Element Model for Welding Heat Sources", *Metallurgical Transactions B*, Volume 15B, June 1984, pp. 299–305.

Hamilton, C., Dymek, S. and Sommers, A., 2008; "A thermal model of friction stir welding in aluminum alloys", *International Journal of Machine Tools & Manufacture*, 48, 1120–1130.

Khandkar, M.Z.H., Khan, J.A. and Reynolds, A.P., 2003; "Prediction of temperature distribution and thermal history during friction stir welding: input torque based model", *Science and Technology of Welding and Joining*, Vol. 8, No. 3, pp.165-174.

Mishra, R.S. and Mahoney, M.W., 2007, *"Friction Stir Welding and Processing"*, ASM.

Nandan, R.; Roy, G.G.; Debroy, T., 2006; "Numerical Simulation of Three-Dimensional Heat Transfer and Plastic Flow During Friction Stir Welding", *Metallurgical and Materials Transactions A*, v.37A, pp.1247-1259.

Pavelic, Z., Tanbakuchi, R., Uyehara, O.A. and Meyers, P.S., 1969**,** *Welding Journal Research Supplement*, Vol. 48, pp. 295s–305s.

Ronda, J. and Oliver, G.J., 2000, "Consistent Thermo-Mechano-Metallurgical Model of Welded Steel with Unified Approach to Derivation of Phase Evolution Laws and Transformation-Induced Plasticity", *Comput. Methods Appl. Mech. Engrg.* Vol. 189, pp. 361-417.

Rosenthal, D., 1946, "The theory of moving sources of heat and its. applications to metal treatments", *Transactions of the ASME*, p.849- 866.

Russelll, J. M., 2000; "*Development and Modelling of Friction Stir Welding"*, Thesis, University of Cambridge.

Russelll, M.J.; Sheercliff, H.R., 1999; "Analytic modeling of microstructure development in friction stir welding", *Proceedings of the First International Symposium on Friction Stir Welding*, Thousand Oaks, CA, USA.

Vilaça, P., Quintino, L. e dos Santos, J.F., 2005; "iSTIR—Analytical Thermal Model for Friction Stir Welding", *Journal of Materials Processing Technology,* 169, 452–465.

Xu, S. e Deng, X. 2002; "A three-dimensional model for the friction-stir welding process", *Proceeding of the 21st Southeastern Conference on Theoretical and Applied Mechanics (SECTAM XXI)*, pp. 699–704.

Zhu, X. K.; Chao, Y.J., 2003; "Numerical simulation of transient temperature and residual stresses in friction stir welding of 304L stainless steel", *Journal of Materials Processing Technology*,V. 146, 2,pp. 263-272

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