FINITE ELEMENT ANALYSIS OF MULTIPASS WELDED STEEL PLATES

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Abstract. *Welding process promotes mechanical and metallurgical changes that can affect significantly the structural integrity of a mechanical component. One important aspect associated with structural integrity of welded mechanical components is the presence of residual stresses. Residual stresses result directly from the thermal cycle associated with the welding process. Basically, three couplings are essentials: thermal, phase transformation and mechanical phenomena. As the welding problem involves different knowledge areas, several authors have addressed these three aspects separately. The present contribution regards on modeling and simulation of single pass and multipass welded steel plates using a coupled bi-dimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties. A parametric model is used to study multipass welded steel plates that can be applied to more complex geometries. Numerical results indicate that high values of temperature and stress can be obtained. The proposed methodology can be used as a powerful tool to study the effects of welding parameters, like heat input or welding speed, in the Heat Affected Zone or in the residual stresses of welded mechanical components.*

Keywords*: Welding, Thermomechanical Coupling, Modeling, Numerical Simulation, Finite Element Method.*

1. INTRODUCTION

The welding process has always played a major role in industrial production, especially in the automotive, maritime and aerospace industries. Despite many advantages, welding has some process-specific disadvantages: microstructural transformations, residual stresses and component distortions. All, of which, need to be controlled.

Welding is a very complex process where an intensive localized heat input is furnished to a piece promoting mechanical and metallurgical changes. In the welding mechanical and metallurgical processes occur and phenomenological aspects of welding involve couplings among different physical processes and their description is unusually complex. Basically, three couplings are essential: thermal, phase transformation and mechanical phenomena, although several authors have addressed these three aspects separately.

The problems of distortion, residual stresses, and reduced strength of a structure in and around a welded joint are a major concern of the welding industry. These problems result directly from the thermal cycle promoted by the localized intensive heat input, causing significant mechanical and metallurgical changes around the weld area of structural steels. 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).

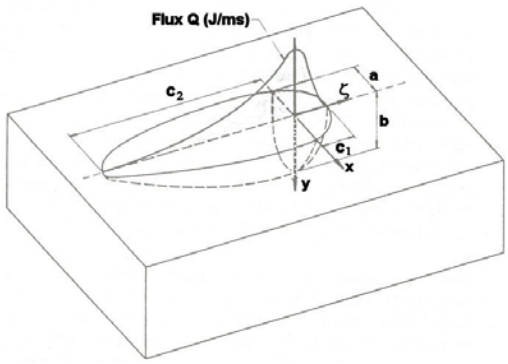
One important aspect associated with structural integrity of mechanical components is the presence of residual stresses (Almer *et al*., 2000; Pacheco *et al.*, 2001, 2002, 2003; Fernandes *et al.*, 2003; Silva *et al.*, 2004; Oliveira, 2004; Oliveira *et al.*, 2006; Silva, 2007). Residual stresses result directly from the thermal cycle caused by the localized intensive heat input that promotes temperature gradients. High temperatures developed by the heat source promote phase transformation and plasticity. Mechanical properties present lower values at higher temperatures allowing the development considerable plastic strain. Moreover, phase transformation can promote phase transformation induced strain (Pacheco *et al.*, 2001; Silva *et al.*, 2004). The temperature gradients developed through the piece results in a nonhomogeneous plastic strain distribution, which promotes residual stresses fields when the piece reaches room temperature. Due to the importance of estimate residual stresses in welding, several investigators had addressed this subject (Zacharia *et al.*, 1995; Taljat *et al.*, 1998; Ronda and Oliver, 2000; Frickle *et al.*, 2001; Bang *et al.*, 2002; Sarkani *et al.*, 2002; Fernandes *et al.*, 2003; Silva *et al.*, 2005a, 2005b; Bezerra *et al.*, 2006).

The present contribution regards on modeling and simulation of single-pass and multipass welded steel plates using a coupled bi-dimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties. A parametric model is used to study multipass welded steel plates that can be applied to more complex geometries.

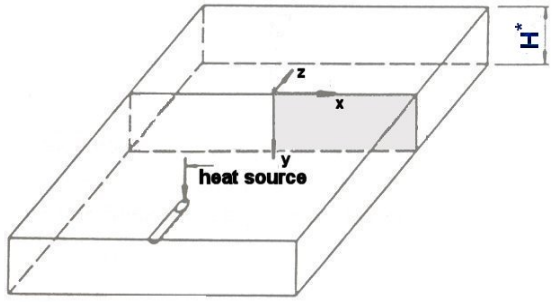
2. MODEL DESCRIPTION

An accurate model for a moving weld heat source is essential in the analysis of the thermal cycle promoted by the welding process. Pavelic *et al.* (1969) first suggested a Gaussian surface flux distribution. Goldak *et al.* (1984) presents a more accurate model comprising a nonaxisymmetric three-dimensional “double ellipsoidal power density distribution” for moving weld heat sources based on a Gaussian distribution of power density in space. Goldak *et al.*

(1984) studies reveal that the temperature in front of the heat source was not as steep as expected and the gentler gradient at the trailing edge of molten pool was steeper than experimental experience. Therefore, the Goldak model considers two ellipsoidal sources combined as show in Fig. 1*a*. The front half of the source in the quadrant of one ellipsoidal source, and the rear half is the quadrant of another ellipsoid.



(*a*)



(*b*)

Figure 1. (*a*) Double ellipsoid power distribution heat source (*b*) Arrangement for the section bead on plate welds (Goldak, 1984).

The power density distribution of the source inside the ellipsoid becomes in according to:

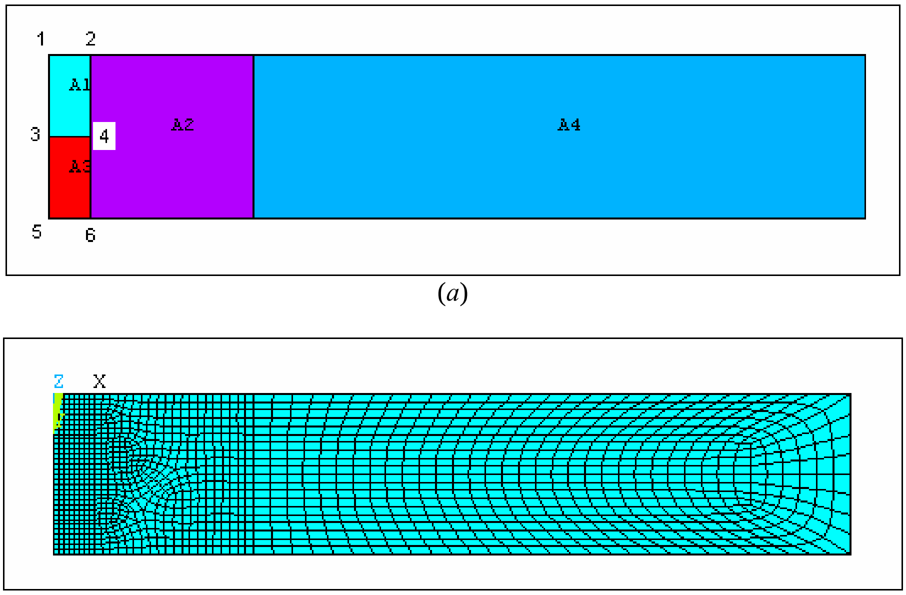
$$q\left(x,y,\zeta,t\right)=\frac{6\sqrt{3}f\,Q}{abc\,\pi\sqrt{\pi}}\,\mathrm{e}^{-3(x/a)^2}\,\mathrm{e}^{-3(y/b)^2}\,\mathrm{e}^{-(\zeta/c)^2} \tag{1}$$

where a, b, c ($c = c_1$ inside the front quadrant and $c = c_2$ inside the rear quadrant) are the semi-axis of the power density Gaussian distribution in an ellipsoid with center at (0,0,0) and parallel to coordinate axes, x, y, ζ. The coordinate $\zeta = v(\tau - t)$, where v is the velocity of the heat source, t is the time and τ is a lag factor needed to define the position of the source at time $t = 0$. f is the fraction of heat ($f = f_f$ inside the front quadrant and $f = f_r$ inside the rear quadrant) and $Q = \eta V I$ is a power heat input source welding, where η is the heat source efficiency, V the voltage and I the current.

A bi-dimensional finite element thermo-elastoplastic model with temperature-dependent properties is developed to study the thermomechanical behavior of long welded plates. A bi-dimensional model is chosen in order to minimize the computational cost. For long plates, at a distance far from the edges, heat flow in the welding direction can be neglected (Goldak *et al.*, 1984). Considering these hypotheses, the model for a moving weld heat source of Eq. (1) and a symmetry condition at the plane *yz* (adiabatic condition), it is possible to reduce the analysis to the gray area region of Fig. 1*b*. This model can be applied to different geometries and welding conditions. Numerical simulations are performed with commercial finite element code ANSYS (Ansys, 2006), employing coupled thermal and mechanical fields element PLANE 13 for spatial discretization.

Two cases were analyzed in this work: single-pass welding process and multipass welding process with two pass. To simulate two passes welding, the geometry of the welding region is divided in two areas (A1 and A3) as shown in Fig. 2*a*. Area A1 represents the region where the first pass is deployed and area A3 represents the region where the second pass is deployed. When the first pass is applied, elements associated to area A3 are deactivated by the command EKILL (Ansys, 2006), modeling the absence of material in this region. For the second pass, elements associated to this region are reactivated by the command EALIVE (Ansys, 2006).

The finite element analysis is carried out in two stages: welding process and cooling process. In the welding process stage, the volumetric weld heat source flux distribution described by Eq. (1) is applied to the plate. In the cooling process stage, the weld heat source is removed and convection with the surrounding medium develops until a thermal equilibrium is reached. The final mesh and the time step are defined after a convergence analysis (Fig. 2*b*). A non-linear transient thermo-elastoplastic analysis is conducted to obtain the time evolution of thermal and mechanical variables during the two stages of the welding process.



(*a*)

(*b*)

Figure 2. Finite element model. Geometry (*a*) and mesh (*b*).

3. NUMERICAL SIMULATIONS

The proposed model is applied to the welding of a API 5L X-65 (API, 2000) steel plate by Submerged Arc Welding (SAW) process. This process requires a continuously fed consumable solid or tubular (metal cored) electrode. The molten weld and the arc zone are protected from atmospheric contamination by being "submerged" under a blanket of granular fusible flux. When molten, the flux becomes conductive, and provides a current path between the electrode and the work. A butt-joint is considered for a plate with a thickness, t, of 4.76 mm (3/16 in), a length, L, of 47.6 mm (30/16 in) and a root opening, g, of 2.38 mm (3/32 in). The numerical simulations developed considers thermal and mechanical temperature-dependent properties for API 5L X65 presented by Bang *et al.* (2002) and the following parameters: $a = g/2$, $c_1 = g$, $c_2 = 4g$, $f_f = 0.6$, $f_r = 1.4$, v = 16.9 mm/s (40 in/min), a density, ρ, of 7800 kg/m^3, a convection coefficient, h, of 10 W/m^2, an air temperature, T_∞, of 25°C, an initial temperature, T_{ini} of 25°C, an austenitization and solidification temperatures of 730°C and 1530°C, respectively. Also for single pass welding process Q = 6750 W and $b = t$ and for multipass welding process Q = 4275 W and $b = 2t$. Natural convection boundary conditions were used at plate free surfaces but at the symmetry plane yz. For the two cases studied, plane position welding is considered. To permit plane position welding in the second pass of the multipass welding process, the plate is turned upside down before welding.

Temperature time evolution is assessed at 6 points positioned at the boundary of the weld region shown in Fig. 2*a*.

4. RESULTS AND DISCUSSION

At first results for single pass welding is presented. Figure 3 shows temperature evolution for the 6 points shown in Fig. 2*a*. A peak temperature of approximately 2500°C is observed on the top surface at time instant t = 0.4 s. Figure 4*a* shows the temperature distribution for the time instant where the peak temperature occurs and Figs. 4*b*-4*d* shows the Heat Affected Zone (HAZ) evolution for three time instants. Results show that the HAZ presents a regular distribution (square like) from top surface to bottom surface, reaching a distance from the symmetry plane of the plate thickness magnitude.

Figure 5 shows the residual stresses distribution for the final time instant, where a thermal equilibrium is achieved. The smallest stress values (in magnitude) are observed for y direction and the larger ones are observed for z direction (of room temperature yield strength magnitude). Figure 6 shows the residual stress distribution along top and bottom surfaces. Stress in z direction presents the characteristic stress distribution reported in literature, with tensile stress near the welding region and compressive stress far from this region. Similar stress distributions are observed for both top and bottom surfaces.

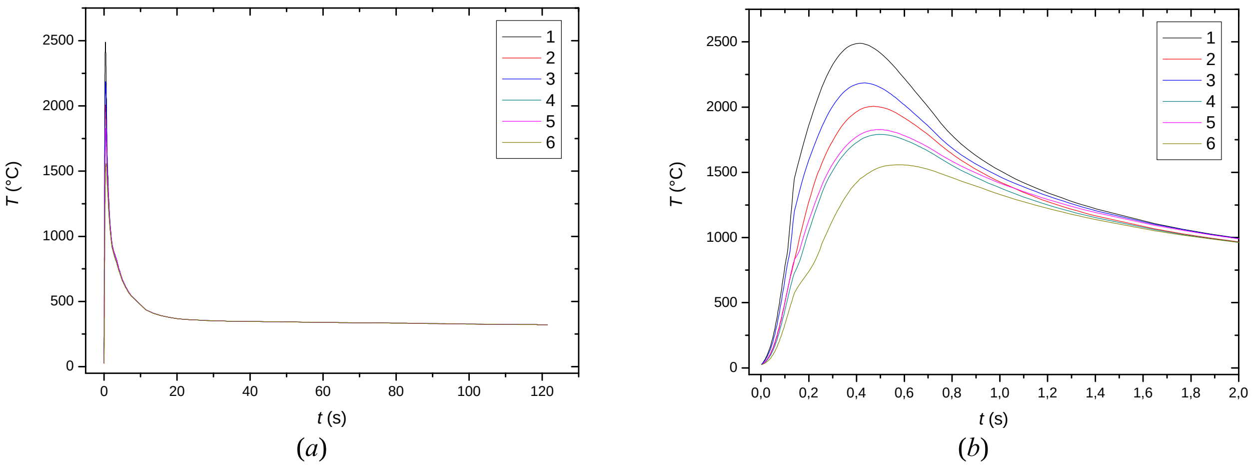


Figure 3. Temperature evolution (*a*) and temperature evolution detail (*b*). Single pass.

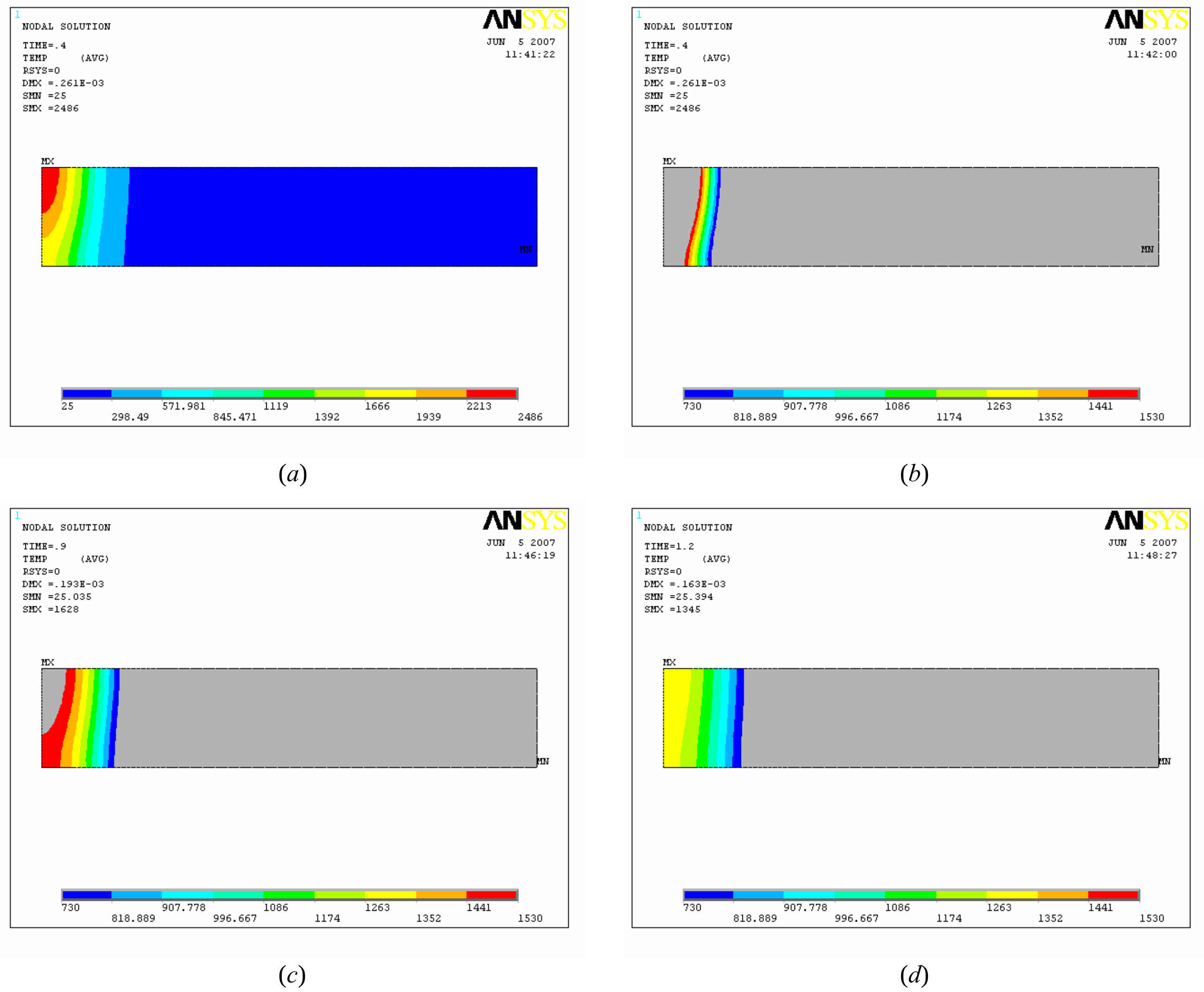


Figure 4. Temperature distribution at the peak temperature for t = 0.4 s (*a*) and HAZ evolution for t = 0.4 s (*b*), t = 0.9 s (*c*) and t = 1.2 s (*d*). Single pass.

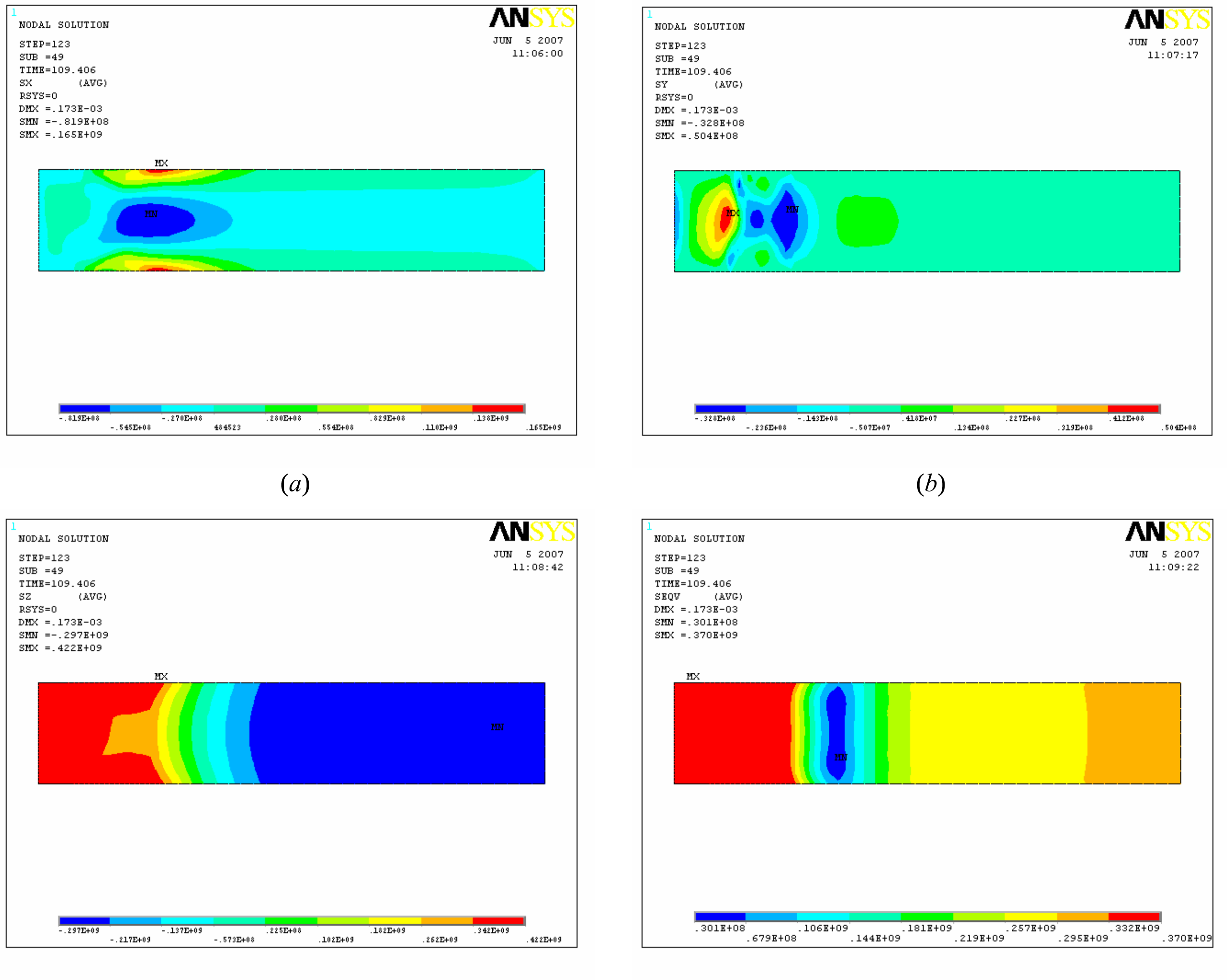


Figure 5. Residual stresses distribution: (*a*) σ_x, (*b*) σ_y, (*c*) σ_z and (*d*) σ_{eq}. Single pass.

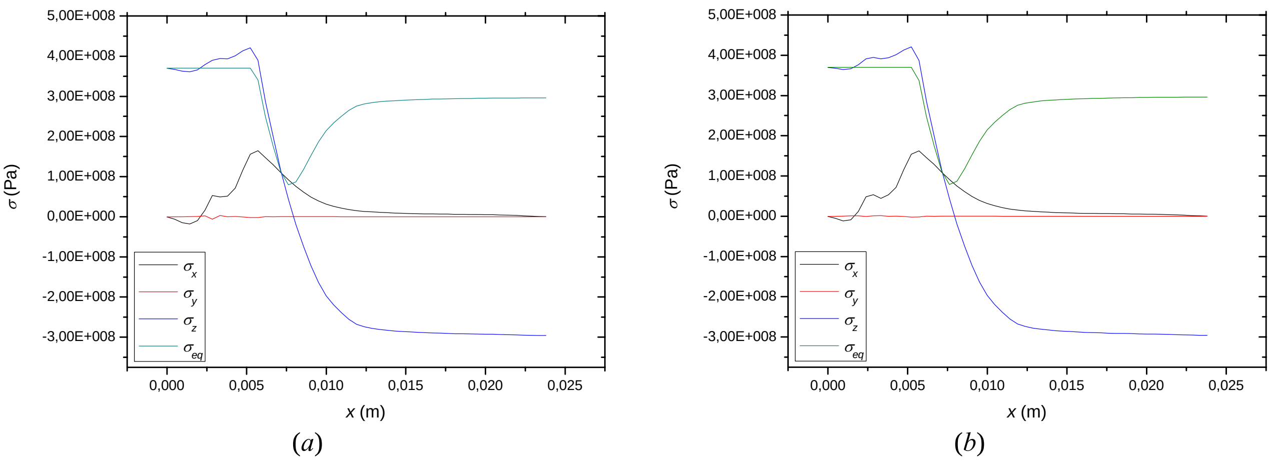


Figure 6. Residual stresses: (*a*) top surface and (*b*) bottom surface. Single pass.

At this point multipass welding is considered. Figure 7 shows temperature evolution for the 6 points shown in Fig. 2*a*. A time interval of 120 s is prescribed between the two passes. The convection process removes heat from the plate and after this period the plate reaches a homogeneous temperature distribution near 200ºC. Two peak temperatures of approximately 2750°C are observed. For the first pass the peak occurs at time instant t = 0.4 s and for the second pass at time instant t = 121.75 s.

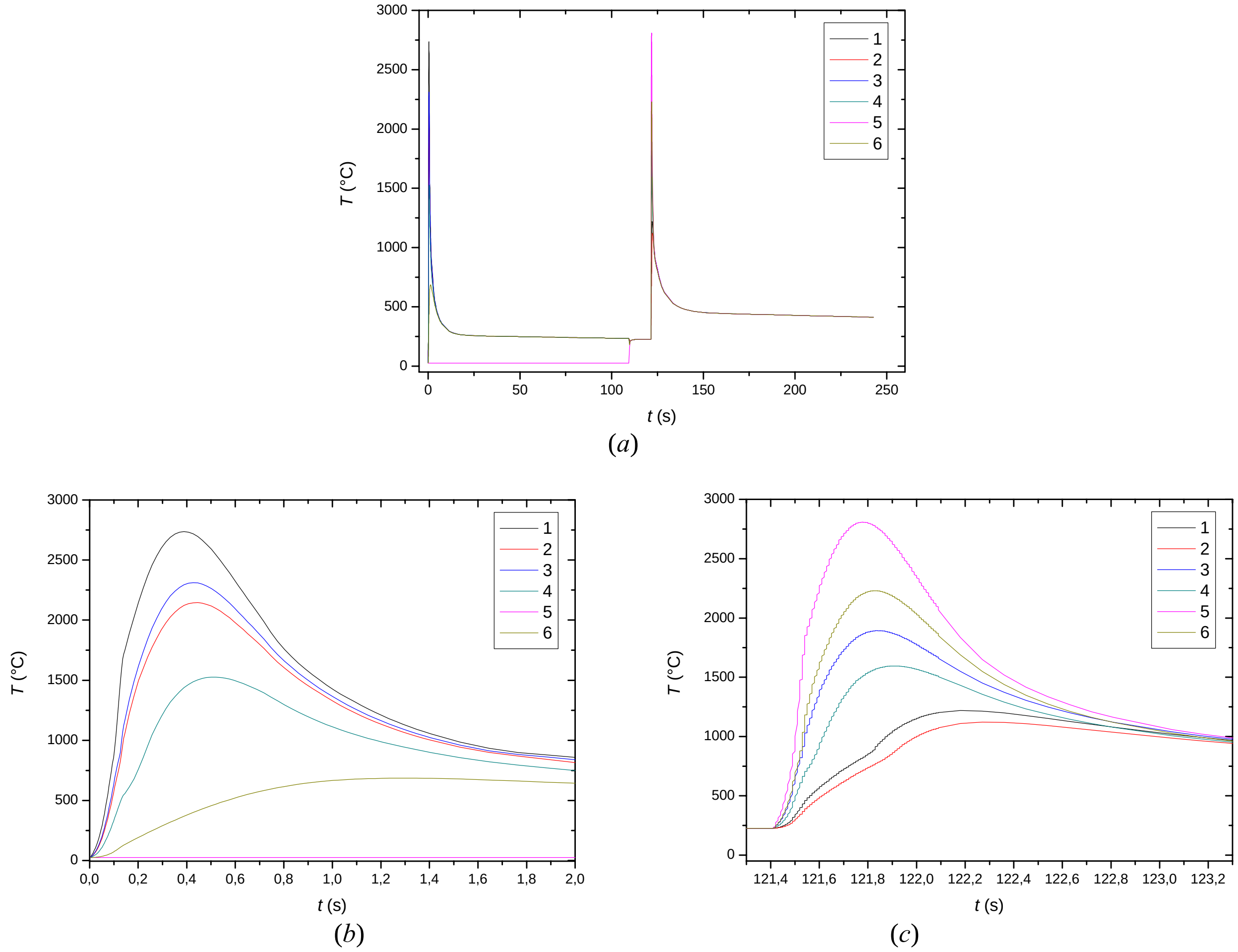
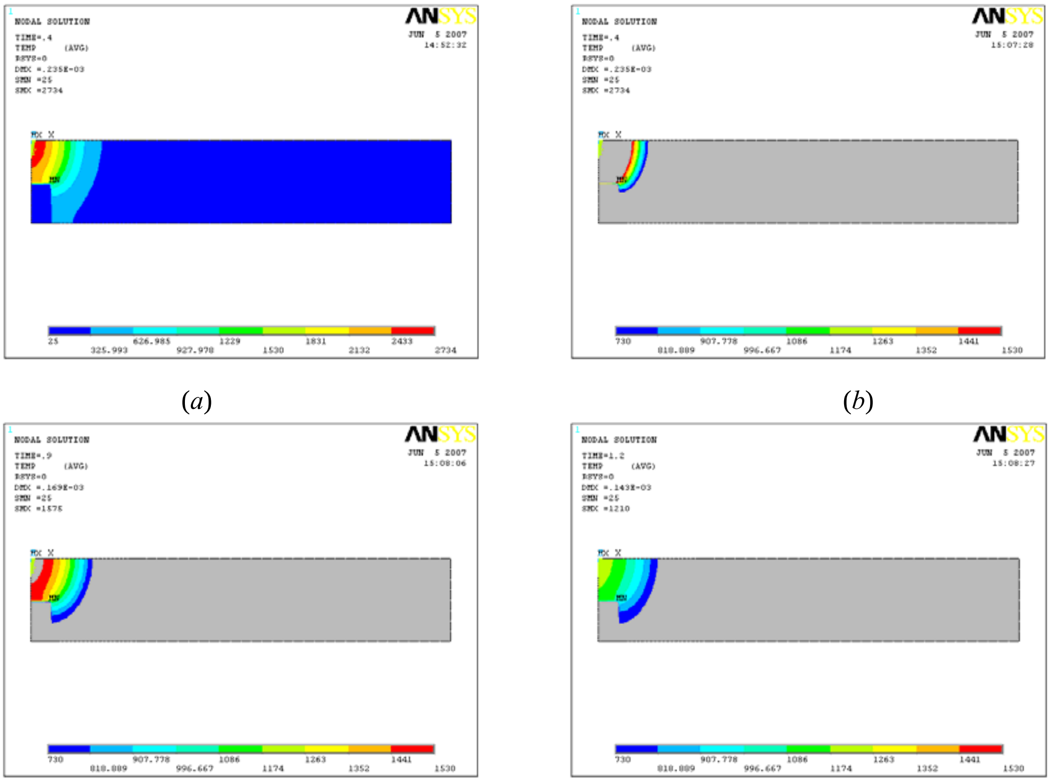


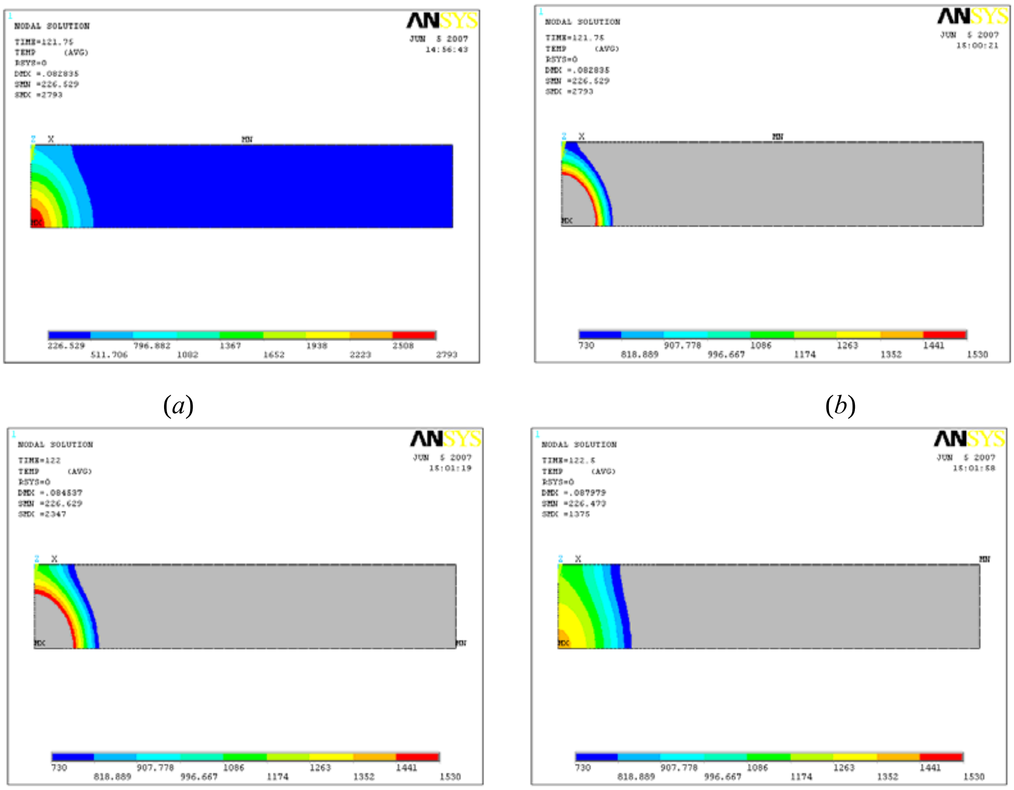
Figure 7. Temperature evolution (*a*) and temperature evolution detail for pass 1 (*b*) and pass 2 (*c*). Multipass.

Figure 8*a* shows the temperature distribution for the time instant where the peak temperature of the first pass occurs and Figs. 8*b*-8*d* shows the HAZ (Heat Affected Zone) evolution for three time instants. Figure 9 presents the same data for the second pass. A comparison between Figs. 4, 8 and 9 shows that both cases predict similar dimensions for the HAZ. However different final microstructure distributions can result from different temperature evolution in the two welding processes (Figs. 3*b*, 7*b* and 7*c*).



(c) (d)

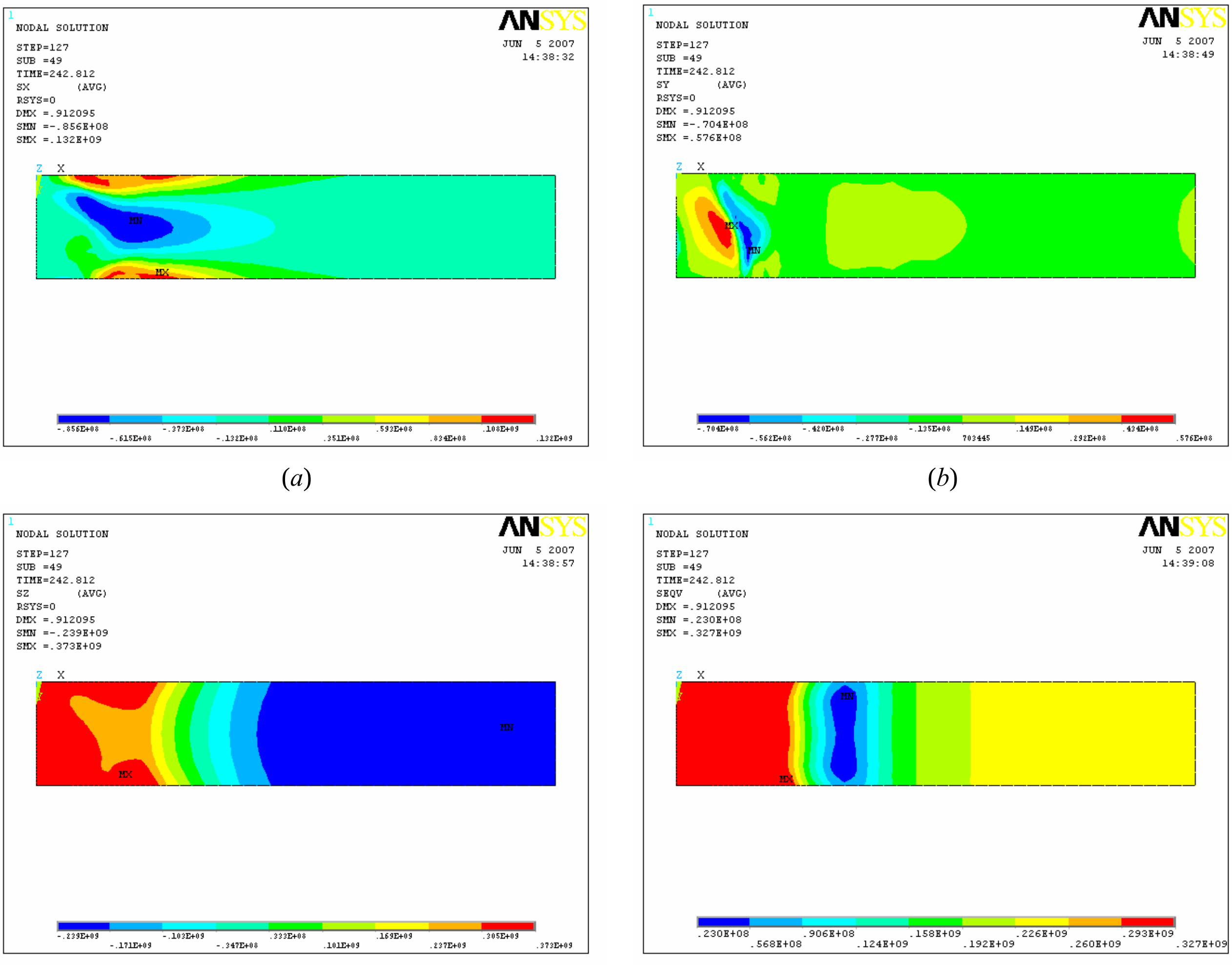
Figure 8. Temperature distribution at the peak temperature for pass 1 at t = 0.4 s and HAZ evolution for t = 0.4 s (b), t = 0.9 s (c) and t = 1.2 s (d). Multipass.



(c) (d)

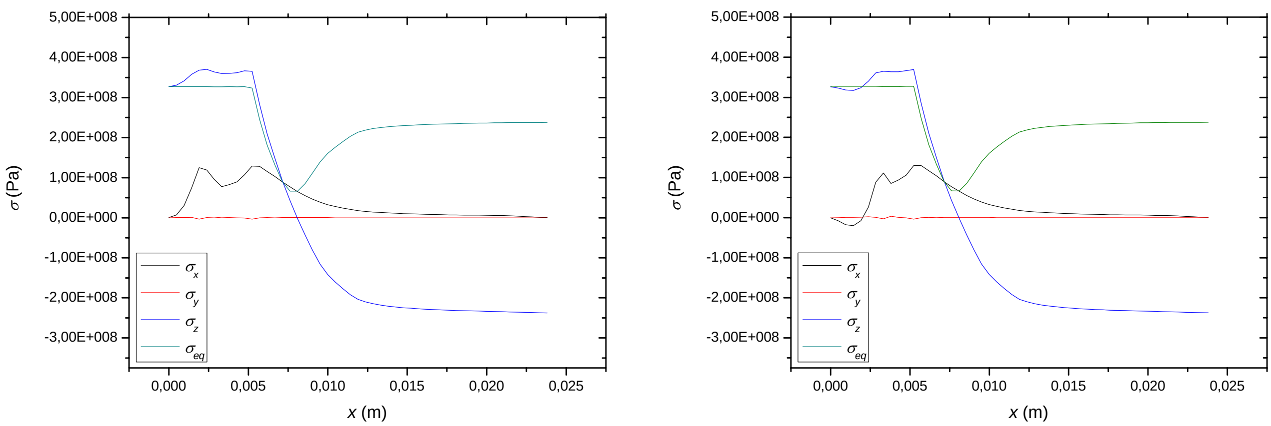
Figure 9. Temperature distribution at the peak temperature for pass 2 at t = 121.75 s and HAZ evolution for t = 0.4 s (b), t = 0.9 s (c) and t = 1.2 s (d). Multipass.

In the following analysis residual stress are of concern. Figure 10 presents residual stresses distribution for the final time instant, where a thermal equilibrium is achieved. Figure 11 shows the residual stress distribution along the top and bottom surfaces. As for single pass higher residual stress values (in magnitude) are observed in z direction and similar residual stress distributions are observed for both top and bottom surfaces.



(*a*) (*b*) (*c*) (*d*)

Figure 10. Residual stresses distribution: (*a*) σ_x, (*b*) σ_y, (*c*) σ_z and (*d*) σ_{eq}. Multipass.



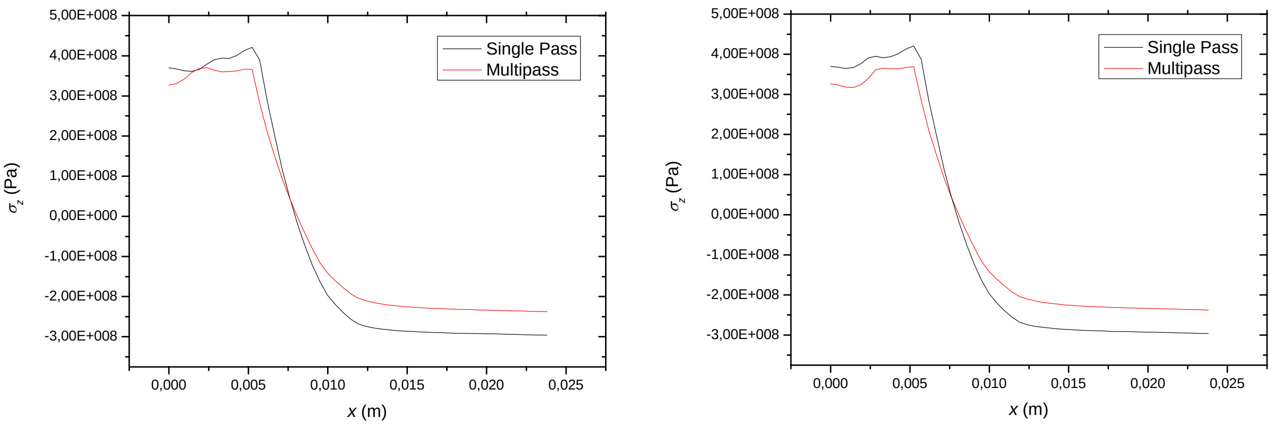
(*a*) (*b*)

Figure 11. Residual stresses: (*a*) top surface and (*b*) bottom surface. Multipass.

Figure 12 shows a comparison between σ_z residual stress component predicted by single and multipass welding processes at the plate surface. This stress component presents the larger values of stress magnitude. Table 1 presents maximum (σ_z^{max}) and minimum (σ_z^{min}) residual stresses values observed. Numerical results show that the two pass welding process presents a reduction of 12% and 20% in the values of tensile and compressive residual stresses, respectively, in comparison with the ones predicted for the single pass welding process.

Table 1. Maximum and minimum residual stresses values observed.

	Single Pass	Multipass	Δ (%)
σ_z^{max} (MPa)	422	373	-12
σ_z^{min} (MPa)	-297	-239	-20



(*a*) (*b*)

Figure 12. Residual stresses: (*a*) top surface and (*b*) bottom surface.

The results obtained with the proposed model show that the behavior is very complex as it involves several coupled phenomena. Moreover, the proposed methodology can be used as a powerful tool to study the influence of welding parameters, like the heat input or the welding velocity, in the development of residual stresses in welded mechanical components. The finite element approach permits the direct application of the model to more complex geometries.

It is important to note that the proposed model presents some approximations that can influence the response and must be taken into account when analyzing the results. First, contrary to a real piece, the proposed model considers the presence of material in the region of weld deposition at all time instants (thus, before the weld deposition). Therefore, this region experiments first a temperature rise followed by a cooling. In a real welding process an empty region is first filled by weld material that is at a high temperature.

Moreover, phase transformation can promote phase transformation induced strain (Silva *et al.*, 2005a, 2005b; Ronda and Oliver, 2000) that can affect considerable residual stresses in welded pieces.

5. CONCLUSION

A coupled bi-dimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties is developed to study single-pass and multipass welding of long plates. The proposed model is applied to the welding of API 5L X-65 steel plates by submerged arc welding process. Two processes are considered: single pass and two pass welding. Numerical results indicate that large values of temperature and residual stresses (of room temperature yield strength magnitude) can be obtained. A comparison between results obtained from single pass and two pass welding numerical simulations indicate that multipass processes can be used to reduce the residual stresses present at the end of the process. For the cases studied, the two pass welding process presents a reduction of 12% and 20% in the values of tensile and compressive residual stresses, respectively, in comparison with the ones predicted for the single pass welding process.

The proposed methodology can be used as a powerful tool to study the effects of welding parameters, like heat input or welding speed, in the Heat Affected Zone or in the residual stresses of welded mechanical components. Moreover, an experimental program must be established to validate the proposed model.

6. ACKNOWLEDGEMENTS

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