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MODELING POST WELD HEAT TREATMENT FOR RESIDUAL STRESSES RELIEVING IN WELDED STEEL PLATES USING THE FINITE ELEMENT METHOD

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Abstract: *Welding is a complex process where localized intensive heat input is furnished to a piece promoting mechanical and metallurgical changes. Phenomenological aspects of welding process involve couplings among different physical processes and its description is unusually complex. Basically, three couplings are essential: thermal, phase transformation and mechanical phenomena. High temperatures developed by the heat source promote phase transformations and plasticity. Mechanical properties present lower values at higher temperatures allowing the development considerable plastic strain. Moreover, phase transformation can promote phase transformation induced plastic strain. Temperature gradients developed through the piece results in a nonhomogeneous plastic strain distribution, which promotes residual stresses fields when the piece reaches room temperature. It is well know that residual stress plays a preponderant part in the structural integrity of a mechanical component. Nevertheless, the presence of residual stress is not fully considered in traditional design of mechanical components. The presence of tensile residual stresses can be especially dangerous to mechanical components submitted to fatigue loadings. In the presence of tensile stresses promoted by the operational loading conditions, both stresses are added resulting in much higher tensile stress levels than the ones predicted. The present contribution regards on modeling and simulation of post weld heat treatments (PWHT) for residual stress relieving in welded steel plates using a coupled bidimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties. A parametric model is used to study the effect of the PWHT on the residual stresses of welded steel plates. The results indicate that the temperature levels of the PWHT affects the values of residual stresses. The proposed methodology can be used in complex geometries as a powerful tool to study and adjust the PWHT to minimize the residual stresses on welded mechanical components.*

Keywords: *Welding, Residual Stresses, Stress-Relieving, Heat Treatment, Modeling, Numerical Simulation*

1. INTRODUCTION

Welding is the most common method among the fabrication processes available for joining mechanical elements. The great variety of welding processes offers versatility whose application can vary from small electronic components to shipbuilding industry. Each welding process has its proper characteristics including advantages and disadvantages which must be carefully balanced for the specific application or project.

Phenomenological aspects of welding involve basically, three couplings: thermal, phase transformation and mechanical phenomena. Due to the complexity of these couplings interaction, several authors have addressed these three aspects separately: some authors consider only the thermomechanical coupling (Bang *et al.*, 2002; Teng and Chang, 2004; Costa *et al.*, 2007) but it is important to note that in many situations the phase transformation must be also considered (Zacharia *et al.*, 1995; Taljat *et al.*, 1998; Ronda and Oliver, 2000; Silva and Pacheco, 2005, 2007; Silva, 2007).

Among the disadvantages related to the welding processes based on the electric arc is the generation of the residual stress due to the thermal gradient imposed to the workpiece in association to geometric restrictions. It is well know that residual stress plays a preponderant part in the structural integrity of a mechanical component. Nevertheless, the presence of residual stress is not fully considered in traditional design of mechanical components. Some traditional design methodologies assume that the component is submitted to a null stress state before the application of the operational loading and the use of precise analytic and/or computational methods is not sufficient for a reliable structural integrity life prediction. The presence of tensile residual stresses can be especially dangerous to mechanical components submitted to fatigue loadings. In the presence of tensile stresses promoted by the operational loading conditions, both stresses are added resulting in much higher tensile stress levels than the ones predicted, and may be responsible for nucleation and propagation of cracks.

In order to minimize the residual stress effects in a welded joint some precautions may be carried out as the application of preheating or the post welding heat treatments (*PWHT*). There are many options of heat treatments which can be applied to the welded joint aiming to reduce the residual stress levels being the most common the annealing for stress relieving. The annealing for stress relieving consists on heating the workpiece uniformly in a range of temperature for specific period of time followed by air cooling to room temperature. The parameters selection (temperature and time) depends particularly on the base and weld metal chemical compositions. It is due to the possibility of occurring undesirable phase transformations, microstructural changes and carbides precipitation mechanisms for instance which can impair the mechanical properties, particularly the notch toughness. Such phenomena can arise more complex when base metal and weld metal are not similar, so it is necessary to establish *PWHT* parameters to attend both alloys. Depending on the *PWHT* temperature and the applied technique a complete remove of residual stress can be obtained. Beyond the removal of residual stress the tensile strength and the yield strength also can be affected particularly on the heat affected zone (*HAZ*) of high strength low alloy carbon steels due to the tempering action of the *PWHT*. In other situations depending on the alloy composition local brittle zones can arise also on the *HAZ*. Form the exposed it is expected as an ideal condition the selection of the temperature for the *PWHT* that leads to the maximum reduction of the residual stress levels without impairing the mechanical properties of the welded joint by the occurrence of phase transformations or microstructural changes.

Some authors have addressed the effect of *PWHT* temperature. Cao *et al.* (2009) studied the effects of *PWHT* on metallurgical and tensile properties of Inconel 718 alloy butt joints welded by laser process. Kanga *et al.* (2007) investigated the effects of residual stress and heat treatment on fatigue strength of weldments. Paradowska *et al.* (2010) used hole drilling techniques to assess how local *PWHT* contributes for residual stress reduction and improvement in fatigue life of welded tubular joints.

Figure 1 shows residual stress reduction for different *PWHT* temperatures as a function of time for a steel containing 0.21% carbon and 1.44% manganese (Linnert, 1967). Several mechanisms contribute to residual stress relieve and the larger release occurs during the first hour. Recovery phenomenon and material yielding are the major mechanisms involved. At low temperatures recovery is the first effect to be found. Despite there is no observable changes in grain structure some decrease in residual stress can be attained, being it attributed to the reduction of the dislocations density. Similar to a creep phenomena, effective relaxation can be obtained at higher temperatures where the yield strength of the metal is lower than the residual stress imposed to metal that will flow plastically until the stress is reduced to the yield strength of the metal at the treatment temperature. The plastic deformation resulting from the flow can cause a progressive strengthening as cold working during stress relief. As a resulting effect, the higher the initial residual stress the higher the residual stress after stress relief at a given temperature. In association with the plastic deformation developed during relief other effects as recristalization which corresponds to the formation of new strain free grains followed by grain growth can contribute for the relaxation effect. It is important to observe that the occurrence of recristalization depends on strain hardening level in such way that a competitive mechanism between strain hardening and recristalization can occur.

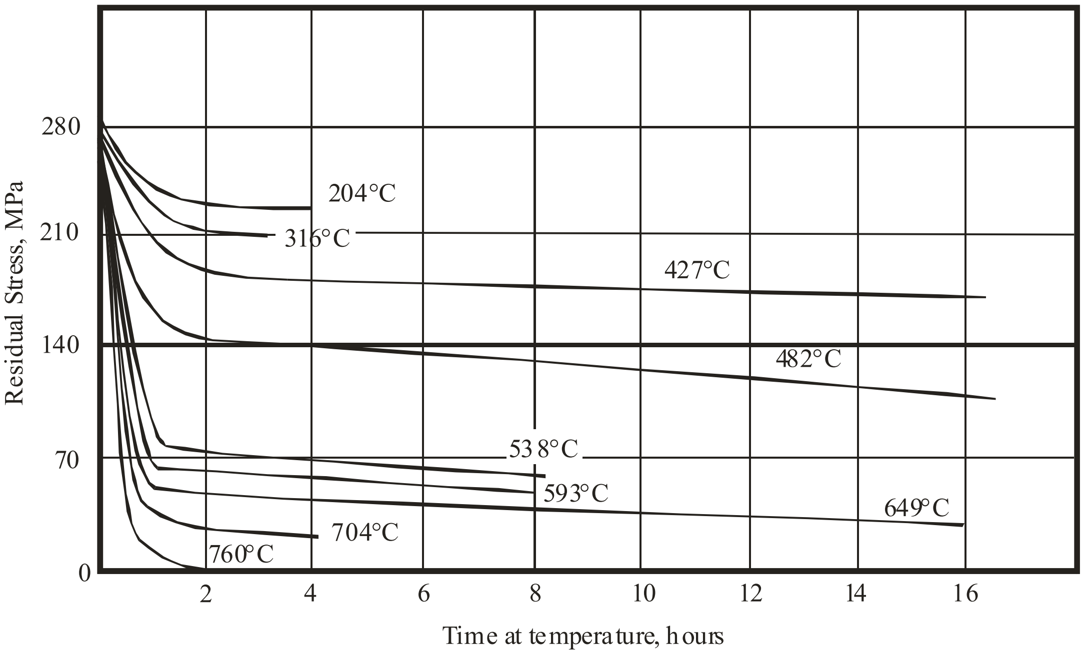
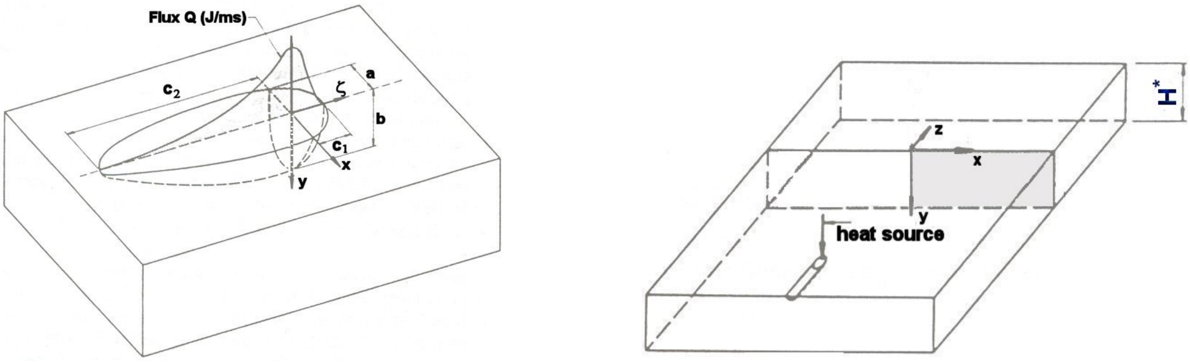


Figure 1. Residual stress relieving as a function of *PWHT* temperature (Linnert, 1967).

The present contribution regards on the study of the influence of the *PWHT* temperature on residual stresses relieve using a coupled bidimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties. The finite element analysis is carried out in three stages: 1) *welding process*; 2) *cooling process* and 3) *post weld heat treatment (PWHT)*. Its worthy of note that the model developed presents some simplifications as it does not take into consideration other mechanisms which can contribute to the stress relieving as the recristalization and grain growth phenomenon.

2. HEAT SOURCE MODEL

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. 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. 2*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 2. (*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:

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

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 the welding energy input rate, where η is the heat source efficiency, V the voltage and I the current.

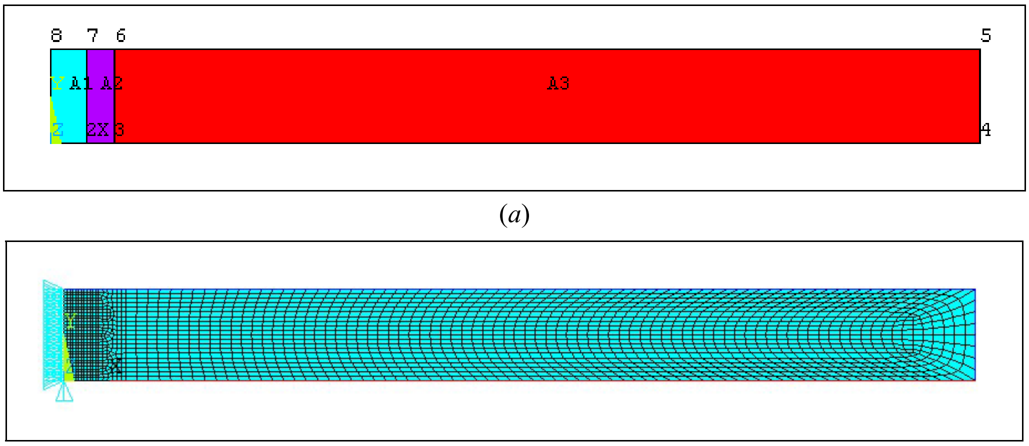
3. NUMERICAL MODEL

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. 2*b*. This model can be applied to different geometries and welding conditions. Numerical simulations are performed with commercial finite element code ANSYS (Ansys, 2010), employing coupled thermal and mechanical fields element PLANE 13 for spatial discretization.

Figure 3*a* shows the plate section analyzed by the proposed model that represents the gray area region of Fig. 2*b*. To permit a better control on mesh discretization the plate section is divided in three areas (A1, A2 and A3) as shown in Fig. 3*a*. The mesh and the boundary conditions are shown in Figure 3*b*. Blue triangles represents displacement symmetry conditions whereas red arrows represents convection boundary conditions.

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. Thus, this region is only submitted to a cooling stage. The second important approximation consists in the plane strain state adopted, which limits deformations in the z direction. In a real piece the surrounding material offers some degree of restriction in this direction, but not completely. Finally, the model does not compute the influence of phase transformations in residual stress. Some authors present models that consider this effect (Zacharia *et al.*, 1995; Taljat *et al.*, 1998; Ronda and Oliver, 2000; Silva *et al.* 2004, 2005; Oliveira, 2004; Silva *et al.*, 2007; Silva, 2007; Oliveira *et al.*, 2010).

The finite element analysis is carried out in three stages: 1) *welding process*; 2) *cooling process* and 3) *post weld heat treatment (PWHT)*. 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. In the *PWHT stage*, a convection boundary condition considering a medium temperature equal to the furnace temperature is prescribed. For the two first stages a plane strain condition is adopted to simulate the restriction at z direction promoted by the material at lower temperature. In the *PWHT stage* a plane stress condition is adopted to simulate the stress relief at z direction and a null stress is obtained in this direction. The final mesh and the time step are defined after a convergence analysis (Fig. 3*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*)

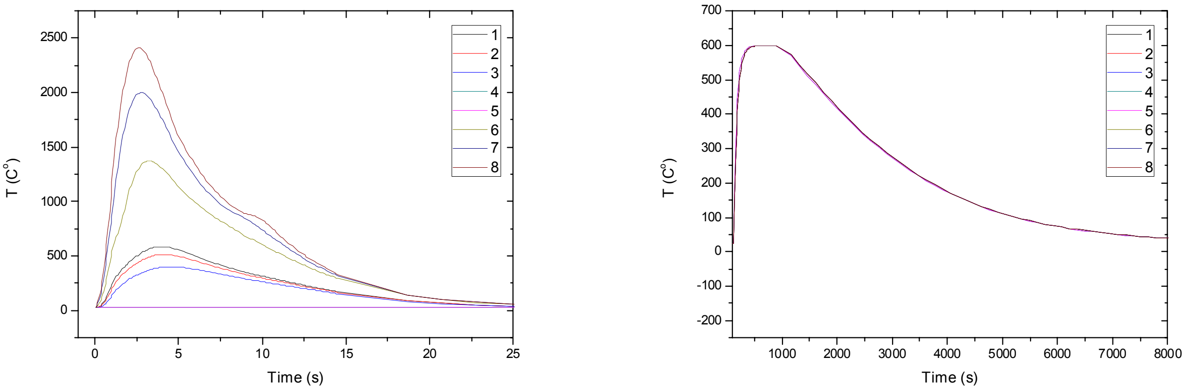
Figure 3. Finite element model. Geometry (*a*), mesh and boundary conditions (*b*).

4. NUMERICAL SIMULATIONS

The proposed model is applied to the welding of a API 5L X65 (API, 2007) steel plate by Metal Inert Gas (MIG) process. A bead on plate type welding is considered for a plate with a thickness, t, of 10 mm, a length, L, of 50 mm and a root opening, g, of 1 mm. The numerical simulations developed considers thermal and mechanical temperature-dependent properties for API 5L X65 steel (Bang *et al.*, 2002) and the following parameters: Q = 5938 W, a = 11.25 mm, b = 10 mm, c_1 = 3.75 mm, c_2 = 11.25 mm, f_f = 0.6, f_r = 1.4, v = 3.3 mm/s, 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. At the bottom of the plate a convection coefficient, h, of 10 kW/m^2 is used to represent the heat transfer with the base where the plate is supported. Natural convection boundary conditions were used at plate free surfaces but at the symmetry plane yz. Temperature time evolution is assessed at 8 points positioned at the boundary of the weld region shown in Fig. 2. Different *PWHT* temperatures are analyzed to study the effect on residual stress relieve.

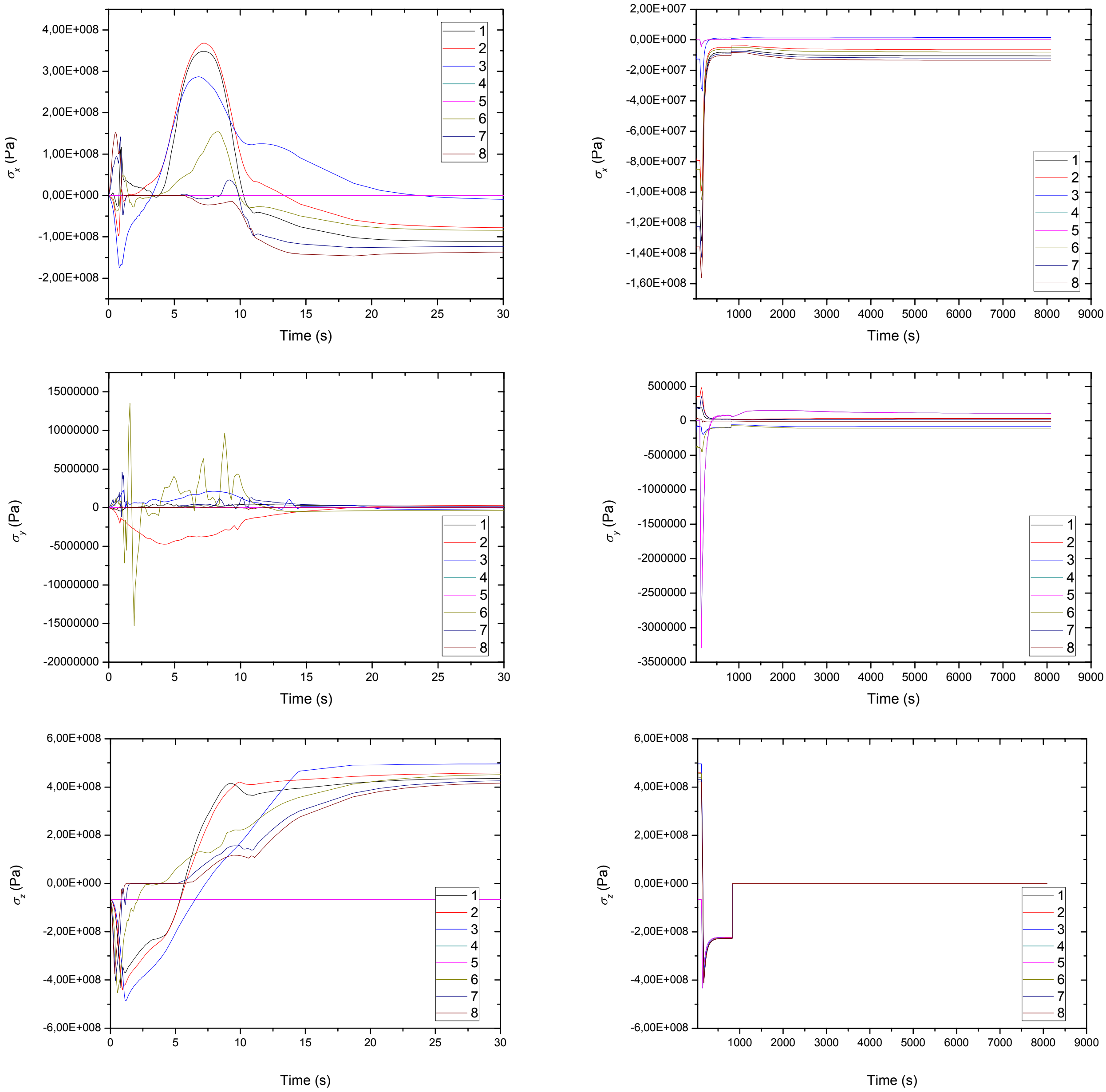
First the model is applied to the welding process described in the last section considering a 600°C *PWHT* temperature. This value is usually adopted in literature.

Figures 4 and 5 show, respectively, temperature and stress time evolution for the 8 points shown in Fig. 3*a*. A peak temperature of approximately 2400°C is observed on the top surface at time instant t = 2.652 s. Stress time evolution present a complex behavior during *welding* and *cooling* stages due to the strong temperature dependence of mechanical properties and the coupling between thermal and mechanical phenomena.



(*a*) (*b*)

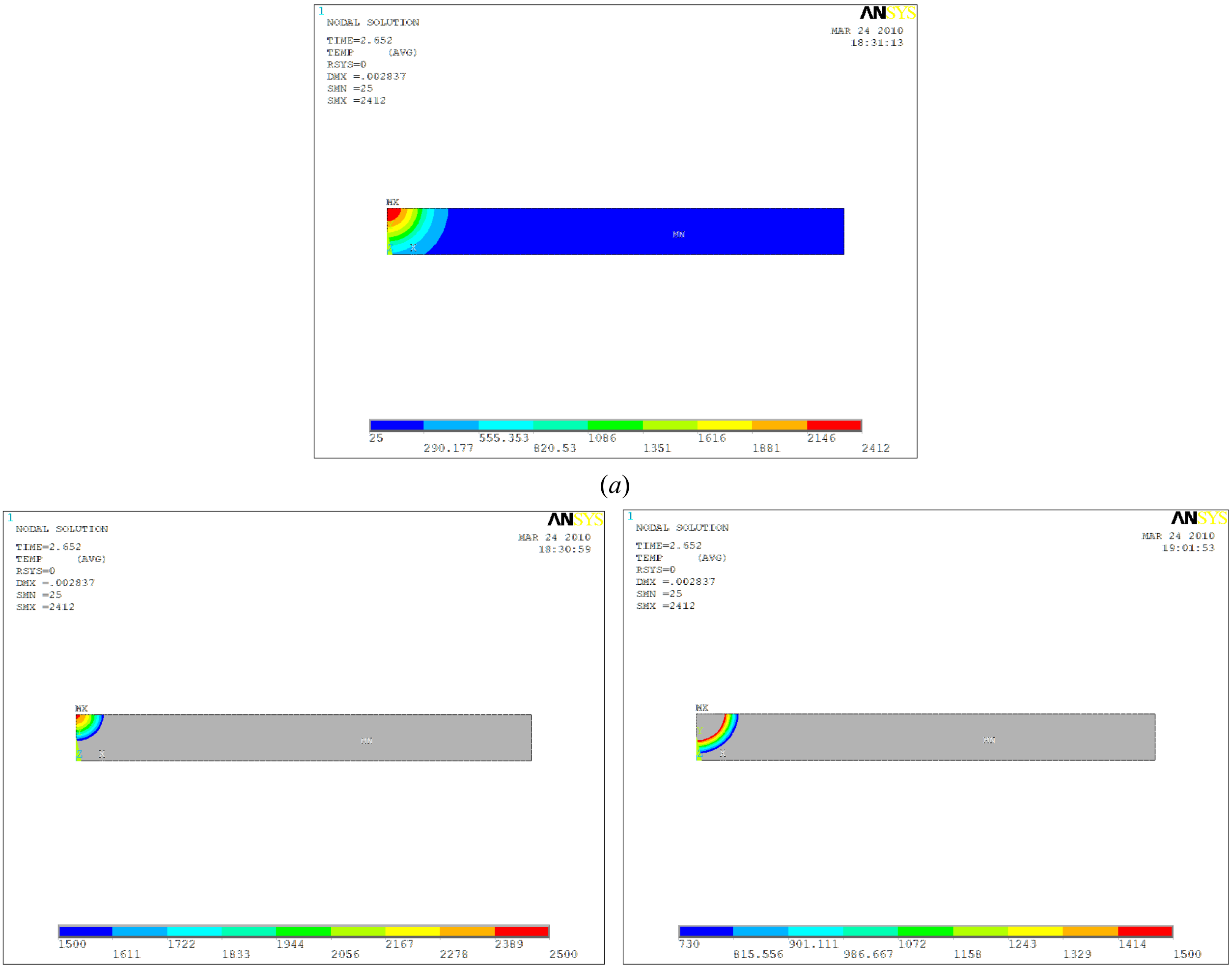
Figure 4. Temperature time evolution: (*a*) *welding* and *cooling* stages and (*b*) *PWHT* stage. 600°C *PWHT* temperature.



(*a*) (*b*)

Figure 5. Stress time evolution: (*a*) *welding* and *cooling* stages and (*b*) *PWHT* stage.

Figure 6*a* shows the temperature distribution for the time instant where the peak temperature occurs (t = 2.652 s) whereas Figs. 6*b* and 6*c* show the weld pool and the Heat Affected Zone (*HAZ*) fort this time instant. Results show that the *HAZ* presents a thickness of 3 mm and the fusion pool presents a semicircle geometry with a 6 mm radius.



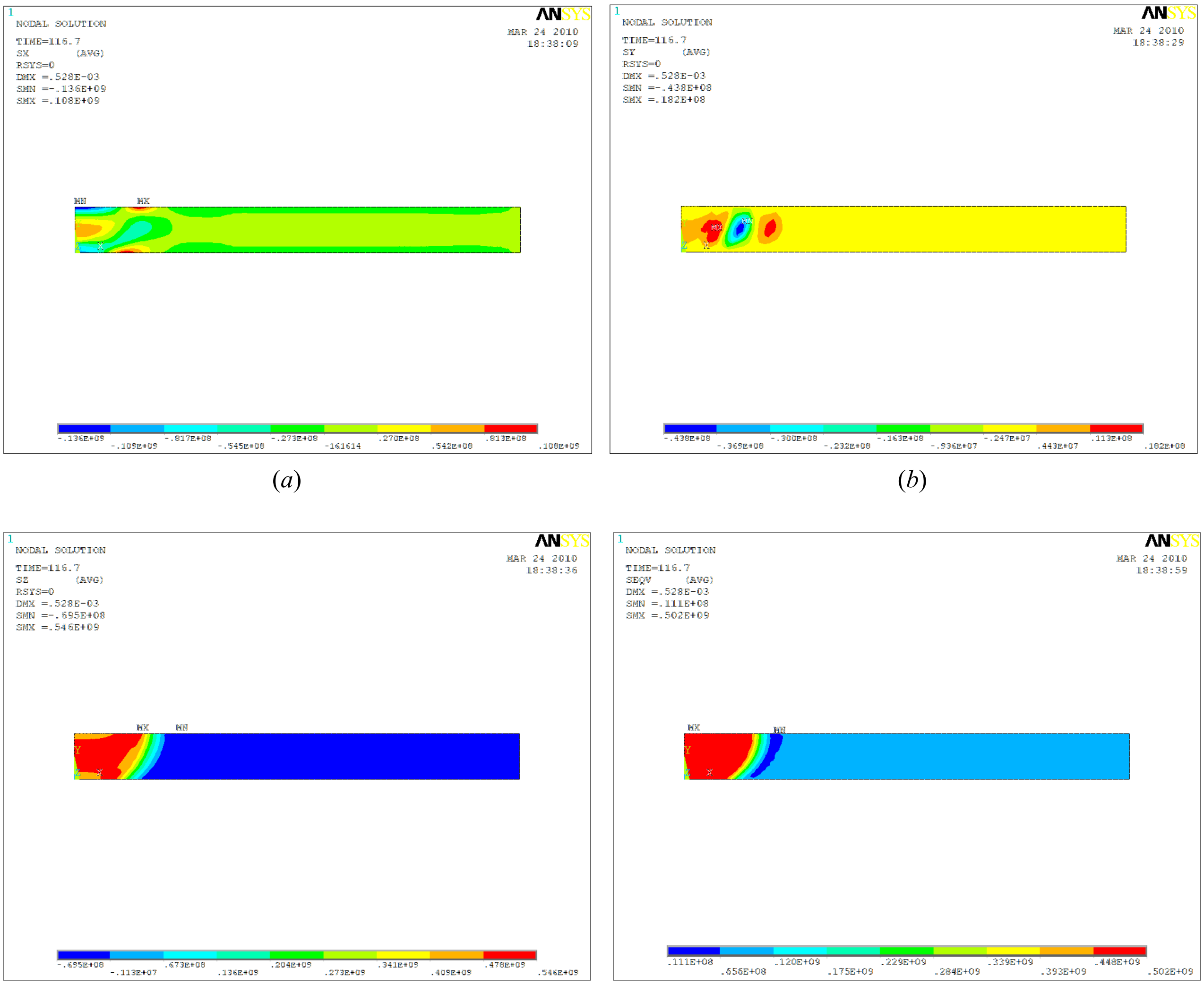
(*a*)

(*b*) (*c*)

Figure 6. Temperature distribution at the peak temperature for *t* = 2.652 s (*a*), weld pool (*b*) and HAZ (*c*). 600°C *PWHT* temperature.

Figure 7 shows the residual stresses distribution at the final of the *welding stage*, 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 8 shows the residual stresses distribution at the final of the *PWHT stage*, where a thermal equilibrium is achieved. 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.

Figure 9 shows the σ_x residual stress distribution along top and bottom surfaces after de *PWHT*. Similar stress distributions are observed for both top and bottom surfaces. A maximum tensile value of 13.5 MPa is observed on the upper surface at a distance of 11 to 15 mm from the symmetry plane, whereas a maximum compressive value of 13.5 MPa is observed on the lower surface at the symmetry plane.



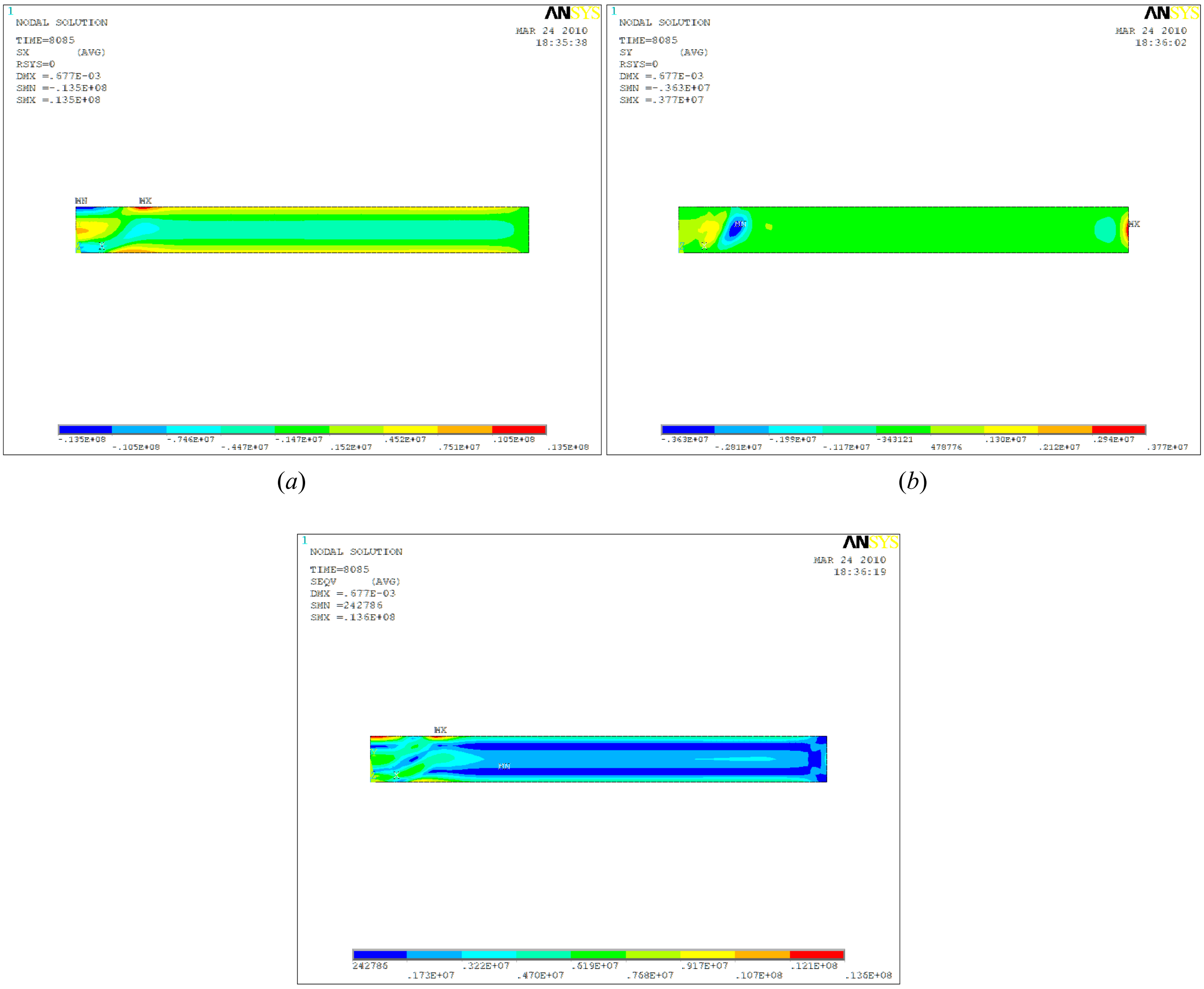
(*a*) (*b*)

(*c*) (*d*)

Figure 7. Residual stresses distribution after the *welding stage*: (*a*) σ_x, (*b*) σ_y, (*c*) σ_z and (*d*) σ_{eq}. 600°C *PWHT* temperature.

At this point the effect of *PWHT* temperature on residual stresses is considered. Figure 10 shows σ_x, σ_y and *von Mises* residual stresses after *PWHT* process. It can be observed that stress relieving occurs for *PWHT* temperatures higher than 300 °C. The amount of stress relieving rises up with *PWHT* temperature until a value of 600 °C, where stabilization is observed. This temperature is usually recommended in literature for *PWHT* processes.

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 the *PWHT* temperature and the 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.



(*a*) (*b*)

(*c*)

Figure 8. Residual stresses distribution after the *PWHT* stage: (*a*) σ_x, (*b*) σ_y, and (*c*) σ_{eq}. 600°C *PWHT* temperature.

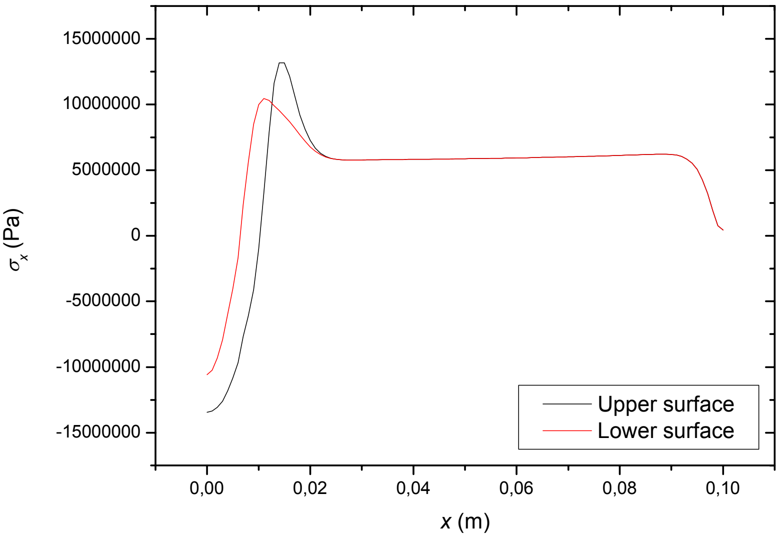
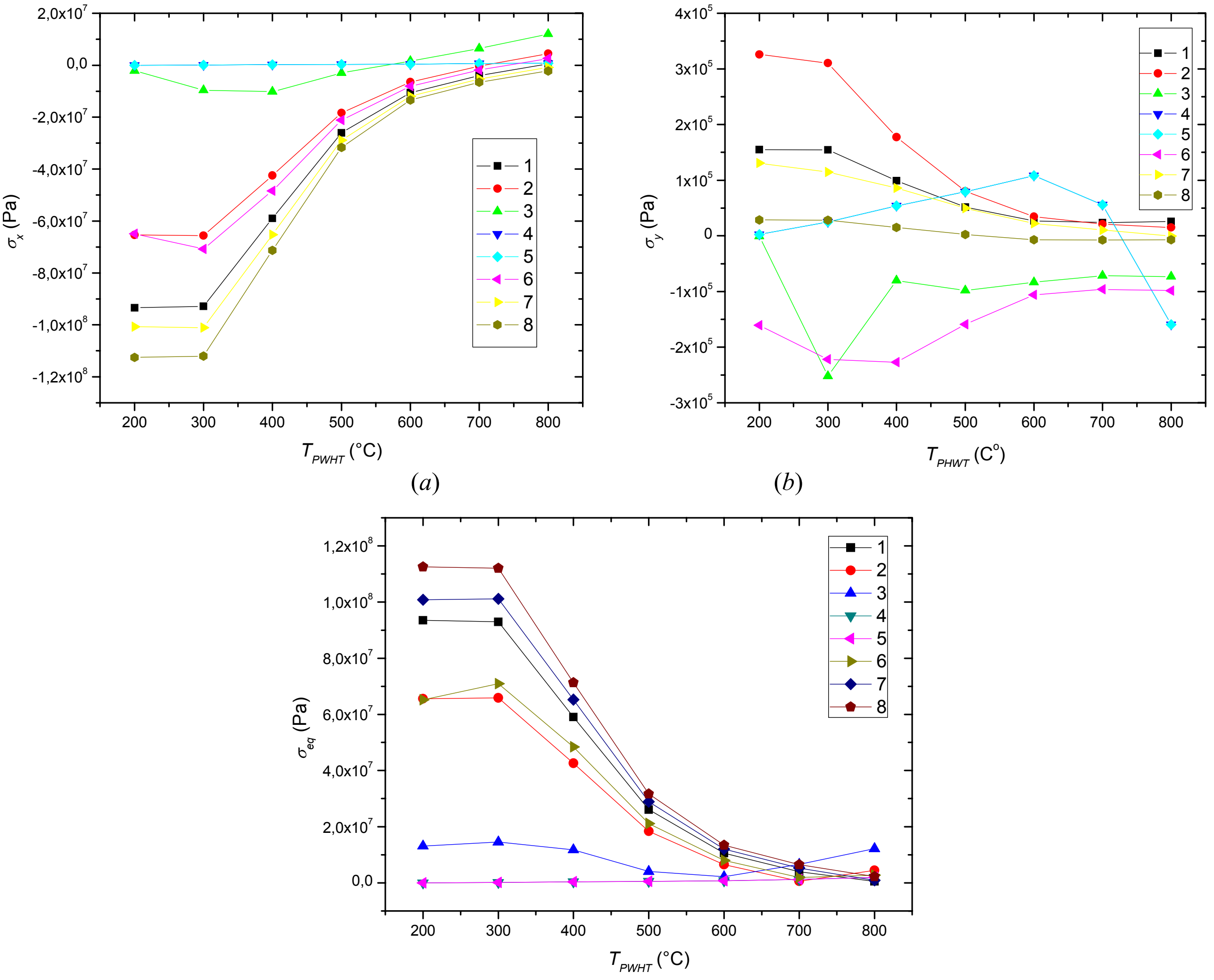


Figure 9. Residual stresses σ_x at top and bottom surfaces. 600°C *PWHT* temperature.



(*a*) (*b*)

(*c*)

Figure 10. Residual stresses for different *PWHT* temperatures: (*a*) σ_x, (*b*) σ_y. and (*c*) *von Mises* equivalent stress.

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. Also the bi-dimensional model uses plane strain and plain stress hypothesis conditions and it is not capable to capture adequately the stress behavior in the *z* direction. To deal with this a three-dimensional approach is necessary. Moreover, phase transformation can promote phase transformation induced strain (Silva *et al.*, 2005a, 2005b; Ronda and Oliver, 2000; Silva and Pacheco, 2005,2007; Silva, 2007) that can affect residual stresses in welded pieces.

5. CONCLUSION

The present contribution regards on modeling and simulation of post weld heat treatments (*PWHT*) for residual stress relieving in welded steel plates. A coupled bi-dimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties is developed to study *PWHT* of welded plates. The proposed model is applied to the bead on plate type welding of API 5L X65 steel plates.

Numerical results indicate that the temperature levels of the *PWHT* affects the values of residual stresses. Stress relieving occurs for *PWHT* temperatures higher than 300 °C and the amount of stress relieving rises up with *PWHT* temperature until a value of 600 °C, where stabilization is observed. These results are in accordance with the literature for *PWHT* processes.

The proposed methodology can be extended to complex geometries and used as a powerful tool to study and adjust the *PWHT* process to minimize the residual stresses on welded mechanical components. Moreover, an experimental program must be established to validate the proposed model.

6. ACKNOWLEDGEMENTS

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