MODELING RESIDUAL STRESSES IN REPAIRED WELDED STEEL PLATES USING THE FINITE ELEMENT METHOD

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Abstract. *Residual stresses in welded components are difficult to measure and predict. Mechanical and metallurgical phenomena occur and phenomenological aspects of welding process involve couplings among different physical processes and its description is unusually complex. 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 problems of residual stresses in a structure result directly from the thermal cycle caused by localized intensive heat input. High temperatures developed by the heat source induce phase transformation and plasticity that could promote significant mechanical and metallurgical changes near the welded area. The present contribution regards on modeling and simulation of residual stress distributions in repaired welded plates using a coupled bidimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties. A parametric model is used to study simple repaired welded steel plate geometries. The results indicate that the presence of residual stresses modifies significantly the stress distribution due plastic strains promoted by thermal gradients present during the welding process.*

Keywords: *Residual Stresses, Welding, Thermo-mechanical Coupling, Finite Element.*

1. INTRODUCTION

Welding is a very complex process where localized intensive heat input is furnished to a piece promoting mechanical and metallurgical changes. Nowadays there are several welding processes used in industry, each one with several different characteristics, advantages and disadvantages. Mechanical and metallurgical process occurs and phenomenological aspects of welding involve couplings among different physical processes and its description is unusually complex. Basically, three couplings are essential: thermal, phase transformation and mechanical phenomena meanwhile several authors have addressed these three aspects separately.

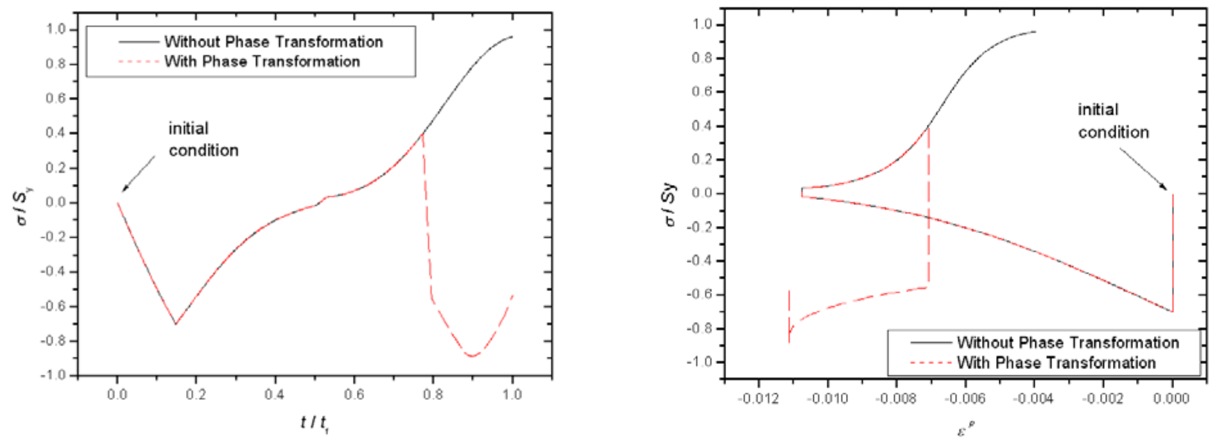
One important aspect associated with structural integrity of welded mechanical components is the presence of residual stresses (Almer *et al.*, 2000; Pacheco *et al.*, 2001, 2002, 2003; Fernandes 2002; Fernandes *et al.*, 2003). Residual stresses result directly from the thermal cycle caused by the localized 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). 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 (Antunes, 1995; Zacharia *et al.*, 1995; Taljat *et al.*, 1998; Ronda and Oliver, 2000; Bang *et al.*, 2002; Fernandes *et al.*, 2003).

Residual stresses can be very detrimental to the performance of a material or in the life of a mechanical component. Alternatively, beneficial residual stresses can be introduced deliberately as, for example, using the shoot penning technique. Residual stresses are more difficult to predict than the in-service stresses on which they superimpose. For this reason, it is important to have reliable methods for the prediction of residual stresses.

A very simple model comprising a one-dimensional bar clamped at both ends can be used to give an insight about the mechanical behavior of the material submitted to a thermal cycle similar to the one that occurs during welding. The heated material experiments a thermal strain but it is restricted by the surrounding material that is at a lower temperature. The bar can be seen as the heated material surrounded by the rest of the piece. Therefore, in this simple model the bar axial total strain, ε, is zero:

$$\varepsilon = \frac{\sigma}{E} + \varepsilon^{p} + \varepsilon^{PT} + \alpha \Delta T = 0 \qquad \text{or} \qquad \sigma = -E\left(\varepsilon^{p} + \varepsilon^{PT} + \alpha \Delta T\right) \tag{1}$$

where E is the Young modulus, α is the thermal dilatation coefficient, σ is the axial stress and ε^{p} is the plastic axial strain; ε^{PT} represents the axial strain due phase transformation, T is the temperature and $\alpha\Delta T$ is the axial thermal dilatation. In this simple analysis, phase transformation is not considered and therefore $\varepsilon^{PT} = 0$. First, the bar experiments a temperature rise ($\Delta T > 0$) that causes material softening (mechanical properties, as the yield stress, S_Y, and the Young modulus, E, fall considerable). During this stage, compressive stress promotes first compressive elastic strain followed by compressive plastic strain when the stress levels reach the yield stress. At high temperature, the low mechanical material properties permit the development of extensive plastic strain. In the cooling stage ($\Delta T < 0$), thermal contraction occurs and mechanical material properties rises reducing the development of further plastic strain. At room temperature, a tensile stress state is obtained as result of the compressive plastic strain developed at high temperature. It is important to note that in many situations the phase transformation must be considered (Zacharia *et al.*, 1995; Taljat *et al.*, 1998; Ronda and Oliver, 2000; Pacheco *et al.*, 2001; Silva *et al.*,2003, 2004). Figure (1) presents some previous results for the simple axial bar model subjected to a heating/cooling cycle (Pacheco *et al.*, 1997). Two situations are addressed: with and without phase transformation. It can be observed that, for this case, the phase transformation that occurs during the cooling stage promotes volume dilatation reducing considerable the final stress levels (residual stresses).



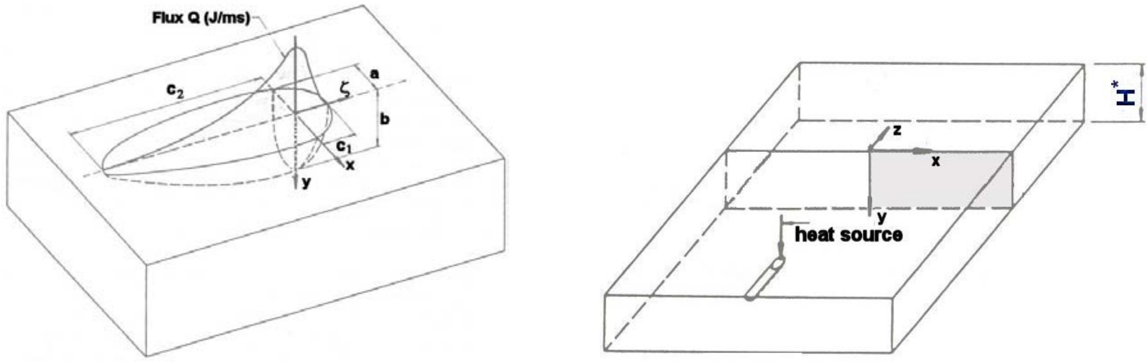
(*a*) (*b*)

Figure 1. (*a*) Stress evolution and (*b*) stress-plastic strain curves. Axial bar clamped at both ends.

The present contribution regards on modeling and simulation of residual stress distributions in repaired welded steel plates using a coupled bidimensional thermo-elastoplastic finite element model with temperature-dependent thermomechanical properties. A parametric model is used to study simple welded plate 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 Figure (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:

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

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 bidimensional finite element thermo-elastoplastic model with temperature-dependent properties is developed to study the residual stresses in a welded plate. A bidimensional model is chosen in order to minimize the computational cost. The analysis is developed considering the bidimensional finite element model in a plane normal to the welding direction as show by the rectangular gray area in Figure (2*b*). Thus, heat flow in the welding direction is neglected.

The above simplification is accurate in situations where comparatively little heat flow from the arc in the welding direction. This is reasonable when the arc speed is high. One plane of symmetry, plane *yz*, is considered. Numerical simulations are performed with commercial finite element code ANSYS (Ansys, 2001), employing coupled thermal and mechanical fields element PLANE13 (4 nodes bidimensional element with displacement and temperature degrees of freedom) for spatial discretization. A plane strain state is adopted. The final meshes are defined after a convergence analysis. The analysis considers two stages: *welding process* and *cooling*.

In the *welding process* stage, the distribution of the power density represented by Eq. (2) is applied to the model until the heat source passes through the plane of the model. The condition prior to operation, where a residual stress field develops, is achieved in the *cooling* stage where the workpiece changes heat by convection until it reaches thermal equilibrium with the surroundings.

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 considers this effect (Zacharia *et al.*, 1995; Taljat *et al.*, 1998; Ronda and Oliver, 2000; Pacheco *et al.*, 2001; Silva *et al.* 2004).

3. NUMERICAL SIMULATIONS

Numerical simulations are developed to estimate the residual stress distribution due to a repair welding operation in a plate with a groove, before it enters in operation. The case analyzed in this work comprises the modeling of a single-pass welding repair of a 1/2" thickness ($H^* = 12.7$ mm) plate with a submerged arc welding process (SAW) in a plate of API 5L X65 steel (API, 2000). The welding conditions are the following: velocity of welding of 1/60 m/s, voltage of 60 V and electric current varying from 100 A to 400 A (heat input from 360 kJ to 1440 kJ). Bang *et al.* (2002), presents thermal and mechanical temperature-dependent properties for API 5L X65. A convection coefficient (*h*) of 10 W/m^2 is used during the both stages. Figure (3) shows the mesh with six lines representing three vertical sections (*V1*, *V2*, *V3*) and three horizontal sections (*Hsup*, *Hmed*, *Hinf*). Table (1) presents the dimensions of the Heat Affected Zone (*HAZ*) for the four heat input conditions.

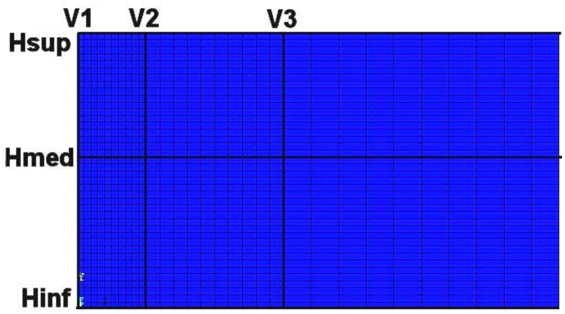


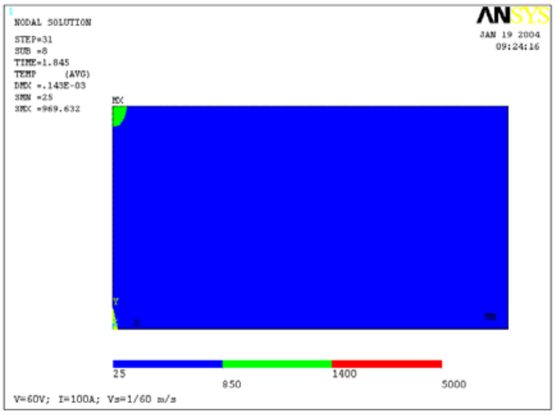
Figure 3. Bidimensional finite element mesh.

Table 1. *HAZ* for the four Heat Input Conditions.

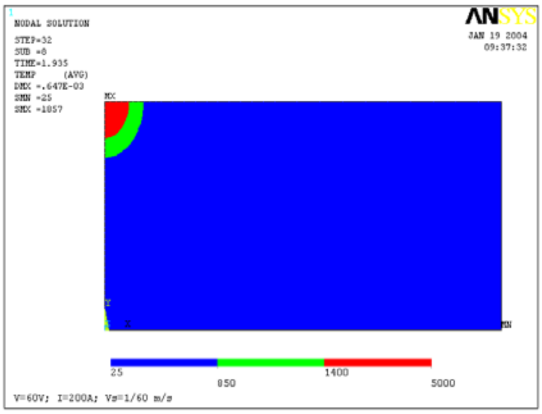
Current (A)	Heat Input (kJ)	Time (s)	x_{HAZ} / H^*	y_{HAZ} / H^*
100	360	1.845	0.059	0.094
200	720	1.935	0.170	0.247
300	1080	2.025	0.220	0.305
400	1440	2.205	0.257	0.350

Figure (4) shows the developed *HAZ* for electric currents of 100, 200, 300 and 400 A. Three regions are depicted: blue ($T < 850$°C), green (850°C $\leq T \leq$ 1400°C) and red ($T >$ 1400°C). Here the *HAZ* is considered the region composed by the green and red regions which represents the larger region developed during the process that experiments a temperature higher than 850°C. The time listed in Table (1) represents the instant when this condition is reached.

Figure (5) shows the temperature evolution during the *welding process* stage for three points at the symmetry section (*V1*): (0,0,0) - T_{sup}, (0, $H^*/2$,0) - T_{med} and (0, H^*,0) - T_{inf}, considering electric currents of 100 and 400 A. It can be observed that a high temperature gradient is developed between these three points.



(*a*)



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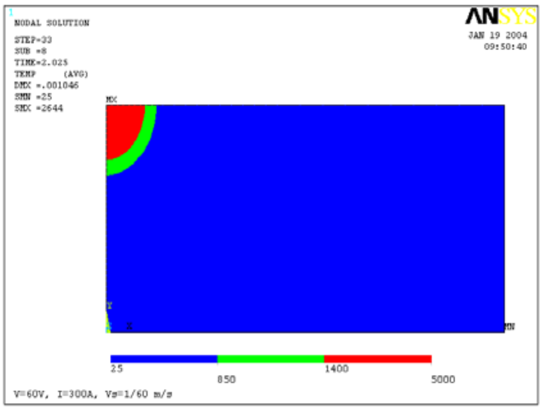
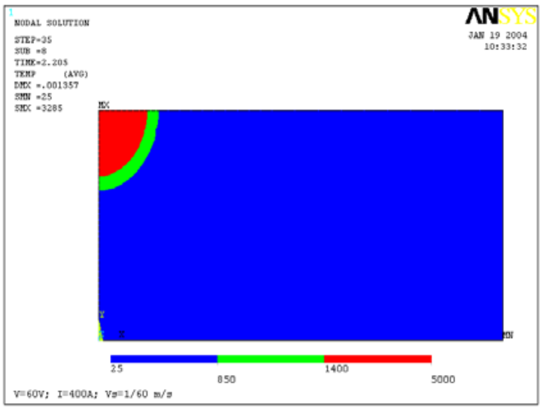
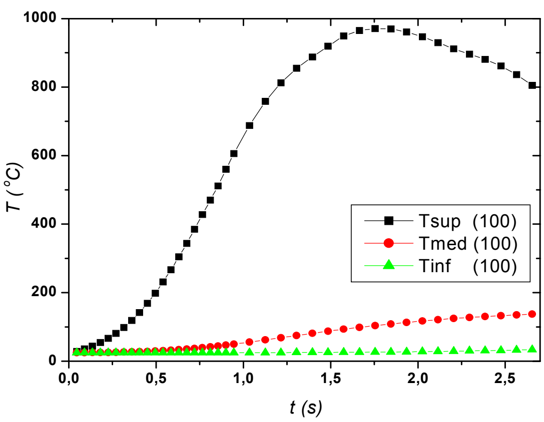


(*c*)

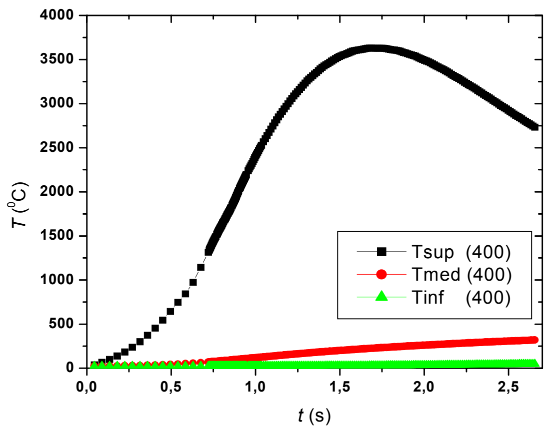


(*d*)

Figure 4. *HAZ* for (*a*) 100, (*b*) 200, (*c*) 300 and (*d*) 400 A.



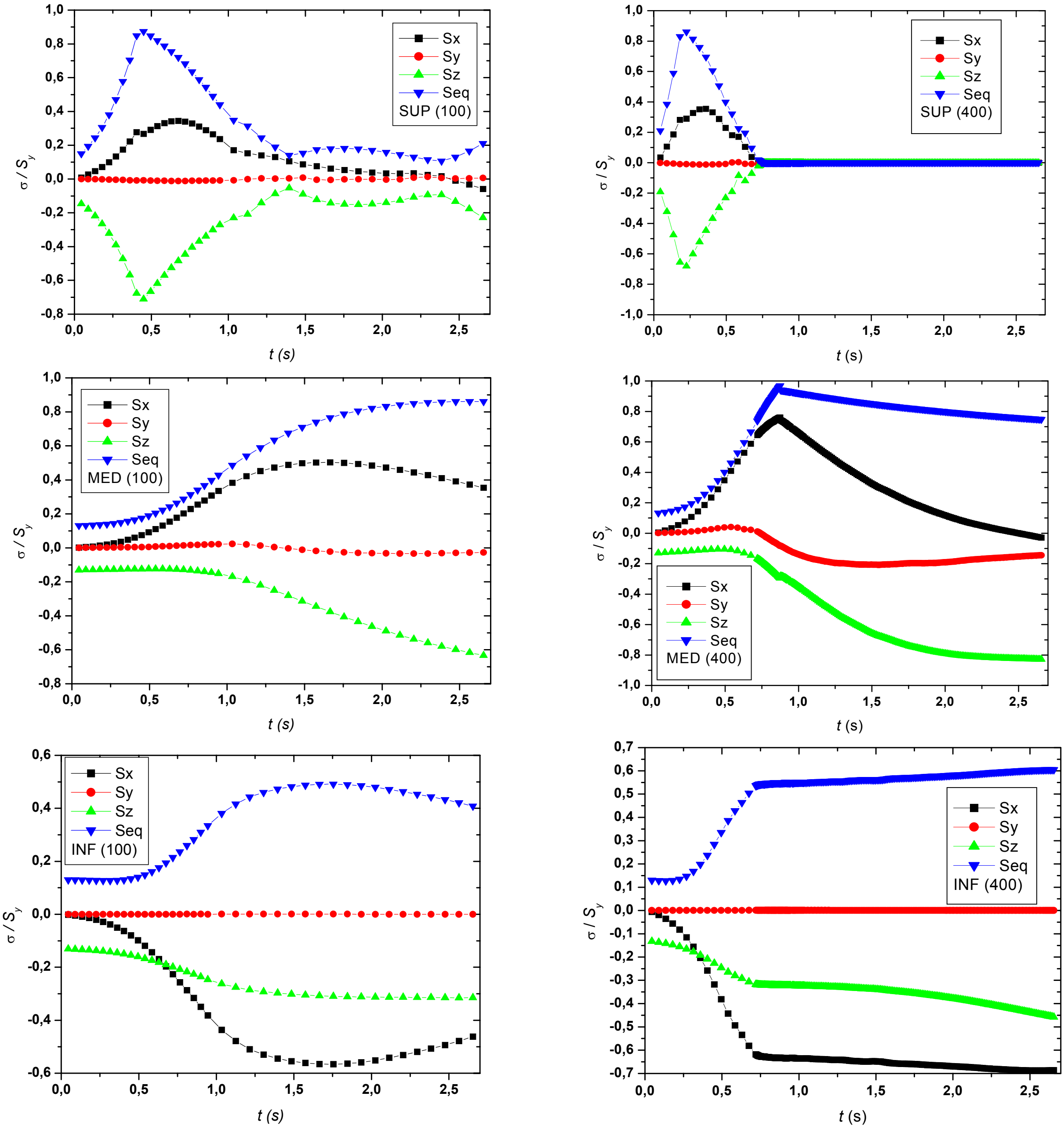
(*a*)



(*b*)

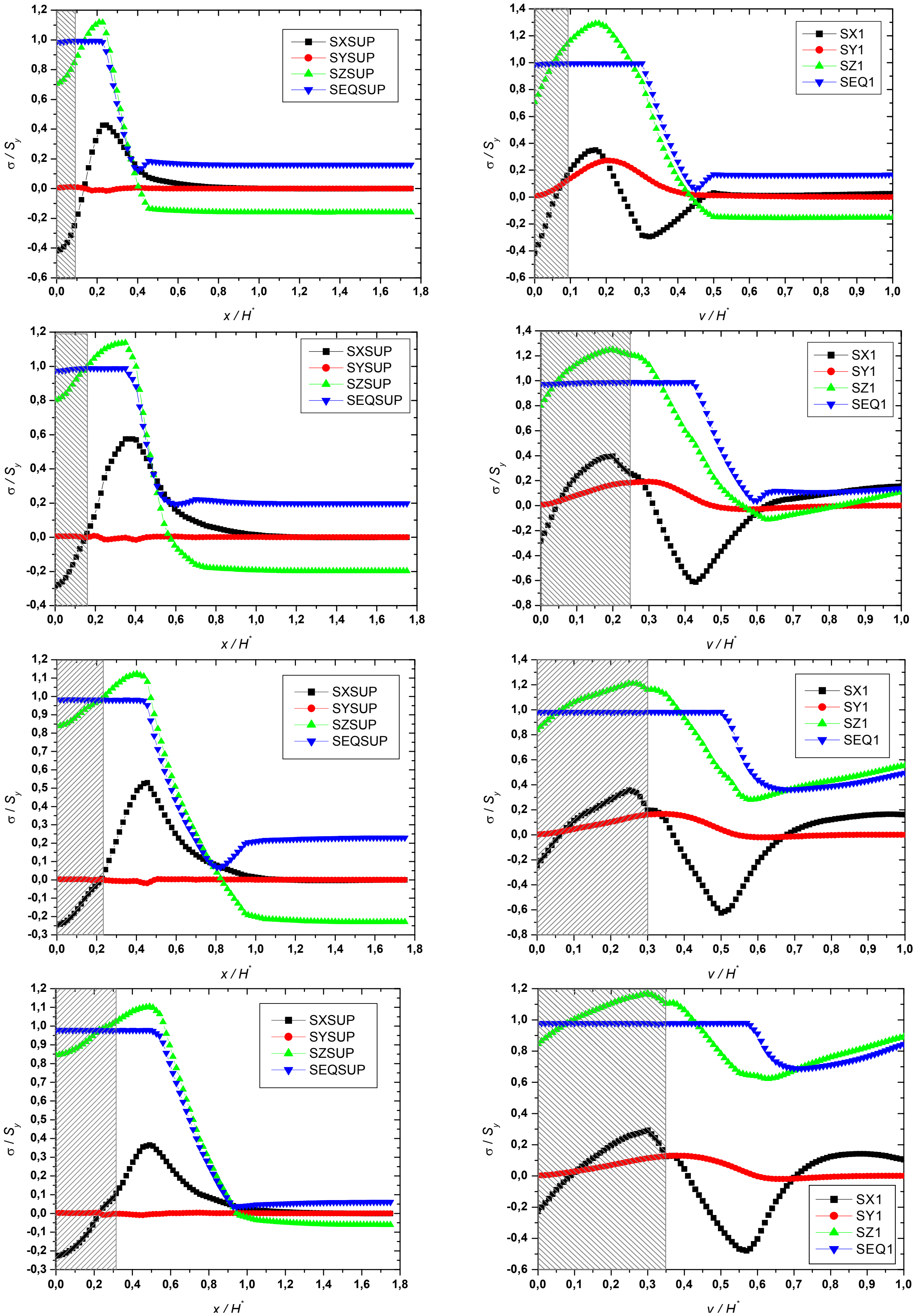
Figure 5. Temperature evolution in time for three points in the symmetry section (*V1*): (0,0,0) - T_{sup}, (0, $H^*/2$,0) - T_{med} and (0, H^*,0) - T_{inf}, considering electric currents of (*a*) 100 A and (*b*) 400 A.

Figure (6) shows the stresses evolution in the three directions plus *von Mises* equivalent stress (σ_x, σ_y, σ_z, σ_{eq}) during the *welding process* stage for three points at the symmetry section (*V1*): (0,0,0) - *SUP*, (0, H^*/2,0) - *MED* and (0, H^*,0) - *INF*, considering electric currents of 100 and 400 A. The first two graphics (*SUP*) in the figure show a stress rising stage that develops until a peak is reached, followed by a stress falling stage (stress in magnitude). In the first stage, the material temperature is low and material properties high, allowing the stress rise promoted by the combined effects of thermal dilatation and deformation restriction by the lower temperature surrounding material. The second stage occurs as material temperature is high enough to promote material softening and, as consequence, the stress falling. The presented curves are normalized with respect to the room temperature yield stress.



(*a*) (*b*)

Figure 6. Stresses evolution (**σ_x, σ_y**, σ_z, **σ_{eq}**) for electric currents of (*a*) 100 A and (*b*) 400 A at points (0,0,0) - *SUP*, (0,H^*/2,0) - *MED* and (0, H^*,0) - *INF*.



(*a*) (*b*)

Figure 7. Residual stresses distribution (σ_x, σ_y, σ_z, σ_{eq}) at sections (*a*) *V1* and (*b*) *Hsup* for 100, 200, 300 and 400 A. The gray area represents the *HAZ* region.

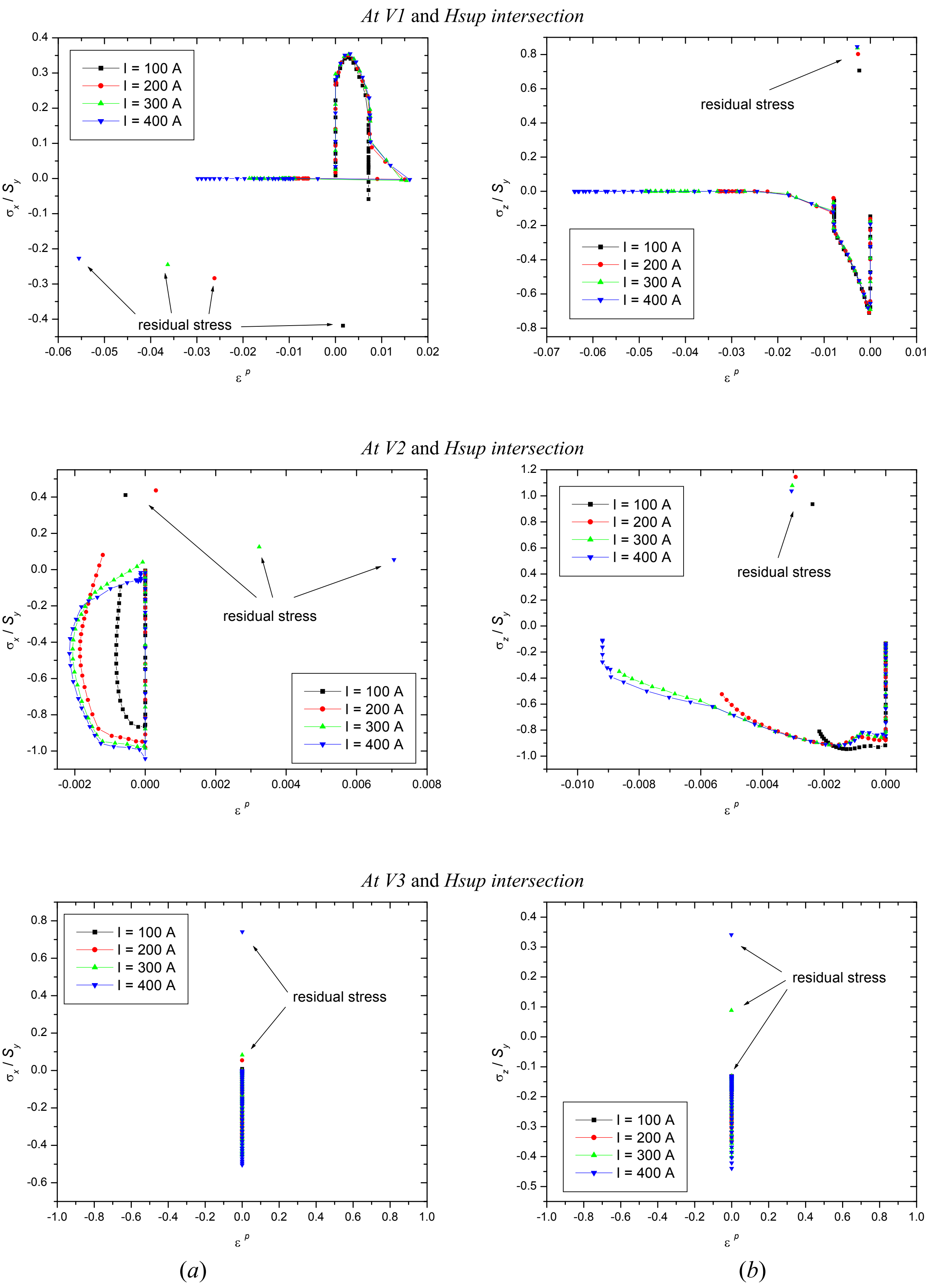


Figure 8. Stresses-plastic strain curves for three points at the superior surface that are at the intersection of sections *V1*, *V2* and *V3* with section *Hsup*. (*a*) *x* and (*b*) *z* directions.

Figure (7) shows the residual stresses distribution (σ_x, σ_y, σ_z, σ_{eq}) at vertical section *V1* and horizontal section *Hsup* for 100, 200, 300 and 400 A. The gray area represents the *HAZ* region. It can be seen that a complex stress distribution is obtained in all situations. From the structural integrity standpoint, the region near the *HAZ* boundary (outside the *HAZ*) is a critical one as presents the higher levels of tensile stress in *z* direction. This region can be favorable to the propagation of defects.

Figure (8) shows the stresses-plastic strain curves for three points at the superior surface that are at the intersection of sections *V1*, *V2* and *V3* with section *Hsup*, during the whole process. For section *V3* an elastic behavior is observed and the residual stresses are caused by plastic strains developed in other regions. The behavior described for Fig. (6) is also observed in Fig. (8). Here, tensile residual stress in the *x* direction is observed for all the situations except for the first figure (σ_x in the intersection of sections *V1* and *Hsup*). For the *z* direction, tensile residual stress is observed for all the situations except for the last figure for the two lower currents (100 and 200 A - σ_z in the intersection of sections *V3* and *Hsup*). Also, it is worth to note that σ_z at sections *V1* and *V2* presents a behavior similar to the observed in Fig. (1*b*) for the one-dimensional bar, without phase transformation, clamped at both ends model. This is indicates that a similar restriction condition is achieved in both situations.

The results obtained with the proposed model show that the behavior is very complex as involves several coupled phenomena. Meanwhile, 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.

4. CONCLUSION

This work presents a study of residual stresses due thermal effect in welded repaired steel plates. A bidimensional finite element thermo-elastoplastic model is developed in order to estimate the residual stress distribution after the welding process and before operation. Numerical simulations show that there are high values of residual stresses (of the initial yield strength magnitude) at the end of welding process, and therefore before the mechanical component enters in operation. Residual stresses can influence significantly the structural integrity of the mechanical component, as they are added to the operational stresses due external operational loadings.

The proposed methodology can be used as a powerful tool to study the effects of welding parameters, like heat input or welding velocity, in the residual stresses of welded mechanical components. The finite element approach permits the direct application of the model to more complex geometries. Its worth to mention that important effects as the phase transformation that occurs during welding, must be addressed in a more detailed analysis using a model with phase transformation in future works. Moreover, an experimental program to measure residual and operational stresses must be established.

5. ACKNOWLEDGEMENTS

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