ANALYSIS OF STRESS CONCENTRATION IN QUENCHING PROCESS OF STEEL CYLINDERS USING FINITE ELEMENT METHOD

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Abstract. *Considerable residual stresses may be formed during quenching process of mechanical components, especially in the presence of geometric discontinuities, and therefore, these stresses may significantly affect industrial processes. Since phenomenological aspects of quenching involve couplings among different physical processes, its description is unusually complex. This study analyzes effects of stress concentration during quenching employing the finite element method associated with an anisothermal constitutive model with two phases (austenite and martensite). Progressive induction hardening of steel cylinders with semi-circular notches is of concerned. Different geometric configurations adopting different radius are treated. This analysis allows one to obtain information about stress concentration during quenching.*

Keywords: *Quenching, Phase Transformation, Thermo-mechanical Coupling, Modeling, Finite Element Method.*

1. INTRODUCTION

Quenching is a heat treatment usually employed in industrial processes and provides a mean to control mechanical properties of steels. Considerable residual stresses may be formed during quenching process of mechanical components, especially in the presence of geometric discontinuities, and therefore, its prediction is an important task (Denis *et al.*, 1985; Denis *et al.*, 1999; Woodard, *et al.*, 1999; Sjöström, 1985; Sen *et al.*, 2000). Nevertheless, the proposed models employed to describe this process are not generic and are usually applicable to simple geometries.

Phenomenological aspects of quenching involve couplings among different physical processes and, therefore, its description is unusually complex. Basically, three couplings are essential: thermal phenomena, phase transformation and mechanical aspects. Pacheco *et al.* (2001) and Silva *et al.* (2004) propose a constitutive model to describe the thermo-mechanical behavior related to the quenching process. This anisothermal model is formulated within the framework of continuum mechanics and the thermodynamics of irreversible processes.

Silva *et al.* (2003) present a finite element method (FEM) to simulate quenching process. Even though the proposed formulation is general, plane elements are adopted allowing the description of axisymmetrical problems. Comparisons between numerical and experimental measures were developed by the authors in previous works in order to validate results (Pacheco *et al.*, 2001; Silva *et al.*, 2004; Oliveira, 2004). In this study, finite element procedure is revisited in order to analyze the effect of stress concentration during quenching. With this aim, steel cylinder bodies with semi-circular notches with different radius are analyzed during quenching. Numerical results estimate residual stresses showing critical situations.

2. FINITE ELEMENT MODEL

The description of quenching process is done with the aid of a constitutive model presented in Pacheco *et al.* (2001) and Silva *et al.* (2004). This model is formulated within the framework of continuum mechanics and the thermodynamics of irreversible processes (Lemaitre & Chaboche, 1990). Thermodynamic forces are defined from the Helmholtz free energy, ψ, and thermodynamic fluxes, defined from the pseudo-potential of dissipation, ϕ. Helmholtz free energy is proposed as a function of observable variables, total deformation, ε_{ij}, and temperature, T; also, internal variables are considered: plastic deformation, ε_{ij}^{p}, volumetric fraction of martensitic phase, β, and another set variable associated with kinematic hardening, α_{ij}:

$$\rho\,\psi(\varepsilon_{ij},\varepsilon_{ij}^{p},\alpha_{ij},\beta,T)=W(\varepsilon_{ij},\varepsilon_{ij}^{p},\alpha_{ij},\beta,T) \tag{1}$$

where $\varepsilon_{ij}^{e}=\varepsilon_{ij}-\varepsilon_{ij}^{p}-\alpha_{T}(T-T_{0})\delta_{ij}-\gamma\beta\delta_{ij}-(3/2)\kappa\sigma_{ij}^{d}\beta(2-\beta)$ is the elastic deformation, α_T is the coefficient of linear thermal expansion and γ and κ are material parameters related to volumetric expansion and plastic deformation induced by martensitic transformation (Sjöström, 1985; Denis et al., 1985). The deviatoric stress component is defined by $\sigma_{ij}^{d}=\sigma_{ij}-\delta_{ij}\,(\sigma_{kk}/3)$.

The potential of dissipation $\phi(\dot{\varepsilon}_{ij}^{p},\dot{\alpha}_{ij},\dot{\beta},q_i)$ is split into two parts:

$$\phi(\dot{\varepsilon}_{ij}^{p},\dot{\alpha}_{ij},\dot{\beta},q_i)=\phi_1(\dot{\varepsilon}_{ij}^{p},\dot{\alpha}_{ij},\dot{\beta})+\phi_2(q_i) \tag{2}$$

A detailed description of this constitutive model may be obtained in Pacheco *et al.* (2001) and Silva *et al.* (2004). This contribution considers long cylindrical bodies as an application of the proposed general formulation. With this assumption, heat transfer analysis may be reduced to a one-dimensional problem in regions far from the cylinder ends. Also, plane stress or plane strain state can be assumed. Under these assumptions, only radial, r, circumferential, θ, and longitudinal, z, components need to be considered. In brief, it is important to notice that tensor quantities may be replaced by scalar or vector quantities. As examples, one could mention: E_{ijkl} replaced by E; H_{ijkl} replaced by H; σ_{ij} replaced by σ_i (σ_r, σ_θ, σ_z).

In order to deal with the nonlinearities of the formulation, an iterative numerical procedure is proposed based on the operator split technique (Ortiz *et al.*, 1983). With this assumption, coupled governing equations are solved from four uncoupled problems: thermal, phase transformation, thermo-elastic and elastoplastic. In this article, finite element method is employed to perform spatial discretization of governing equations. Therefore, the following moduli are considered:

Thermal Problem - Comprises a radial conduction problem with surface convection. Material properties depend on temperature, and therefore, the problem is governed by nonlinear parabolic equations. Classical finite element method is employed to spatial discretization while *Crank-Nicolson* method is used for time discretization (Lewis *et al.*, 1996; Gartling & Hogan, 1994; Segerlind, 1984).

Phase Transformation Problem - Volumetric fraction of martensitic phase is determined in this problem. Evolution equations are integrated from a simple implicit Euler method (Pacheco *et al.*, 2001, 2002; Ames, 1992; Nakamura, 1993).

Thermo-elastic Problem - Stress and displacement fields are evaluated from temperature distribution. Classical finite element method is employed for spatial discretization (Segerlind, 1984).

Elastoplastic Problem - Stress and strain fields are determined considering the plastic strain evolution in the process. Numerical solution is based on the classical return mapping algorithm (Simo & Miehe, 1992; Simo & Hughes, 1998).

As an application of the general procedure technique, classical plane FEM is considered, adopting triangular elements for all finite element moduli.

3. NUMERICAL SIMULATIONS

In order to analyze the effect of stress concentration during quenching process, numerical investigations are carried out simulating a progressive induction (PI) hardening. Progressive induction hardening is a heat treatment process that is done moving a workpiece at a constant speed through a coil and a cooling ring. During heating, a thin surface layer of austenite is formed. After that, this layer is transformed into martensite, pearlite, bainite and proeutectoid ferrite/cementite depending on, among other things, the cooling rate. A hard surface layer with high compressive residual stresses, combined with a tough core with tensile residual stresses, is often obtained.

This article considers progressive induction hardening simulations in a cylindrical bar with radius R = 45mm and a thickness of induced layer, e_{PI} = 5mm. The specimen is heated to 1120K (850°C) for 5s and then, immersing in a liquid medium at 294K (21°C) for 10s. After that, air-cooling is assumed until a time instant of 60s is reached.

Material parameters for numerical simulation are presented in Table 1. Other parameters depend on temperature and are interpolated from experimental data as follows (Melander, 1985a; Melander, 1985b; Hildenwall, 1979; Camarão, 1998; Pacheco *et al.*, 2001):

Table 1 – Material parameters (SAE 4140H).

k = 1.100 x 10^{-2} K^{-1}	κ = 5.200 x 10^{-11} Pa^{-1}	M_s = 748 K
γ = 1.110 x 10^{-2}	ρ = 7.800 x 10^3 kg/m^3	M_f = 573 K

$$E = E_A\,(1-\beta) + E_M\,\beta \qquad \begin{cases} E_A = 1.985x10^{11} - 4.462x10^7 T - 9.909x10^4 T^2 - 2.059T^3 \\ E_M = 2.145x10^{11} - 3.097x10^7 T - 9.208x10^4 T^2 - 2.797T^3 \end{cases} \tag{3}$$

$$H = \begin{cases} 2.092x10^6 + 3.833x10^5 T - 3.459x10^2 T^2, & \text{if } T \le 723K \\ 2.259x10^9 - 2.988x10^6 T, & \text{if } 723K < T \le 748K \\ 5.064x10^7 - 3.492x10^4 T, & \text{if } T > 748K \end{cases} \tag{4}$$

$$\sigma_Y = \begin{cases} 7.520x10^8 + 2.370x10^5 T - 5.995x10^2 T^2, & \text{if } T \le 723K \\ 1.598x10^{10} - 2.126x10^7 T, & \text{if } 723K < T \le 748K \\ 1.595x10^8 - 1.094x10^5 T, & \text{if } T > 748K \end{cases} \tag{5}$$

$$\alpha_T = \begin{cases} 1.115x10^{-5} + 1.918x10^{-8} T - 8.798x10^{-11} T^2 + 2.043x10^{-13} T^3, & \text{if } T \le 748K \\ 2.230x10^{-5}, & \text{if } T > 748K \end{cases} \tag{6}$$

$$c = 2.159x10^2 + 0.548T \tag{7}$$

$$\Lambda = 5.223 + 1.318x10^{-2} T \quad (8)$$

Heat transfer coefficient for cooling fluid (Ucon E 2.8%) and air are respectively given by (Camarão *et al.*, 2000; Pacheco *et al.*, 2001; Hildenwall, 1979; Melander, 1985a; Melander, 1985b):

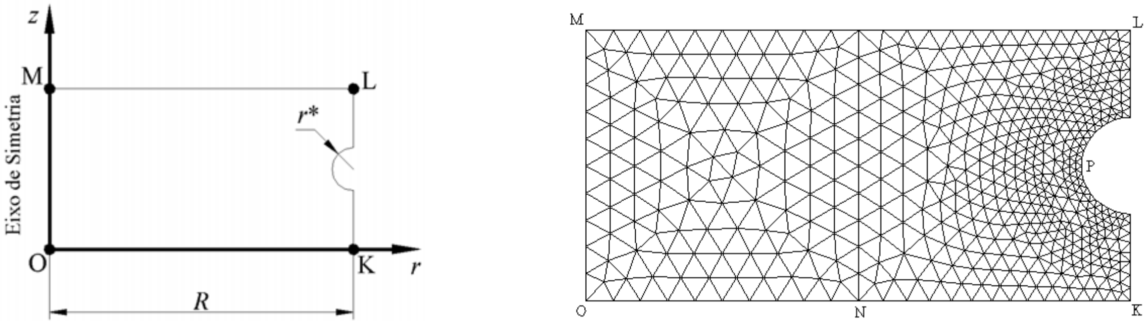
$$h_{fluid} = \begin{cases} 6.960x10^2, & \text{if } T \le 404K \\ 2.182x10^4 - 1.030x10^2 T + 1.256x10^{-1} T^2, & \text{if } 404K < T \le 504K \\ -2.593x10^4 + 5.500x10^2 T, & \text{if } 504K < T \le 554K \\ -9.437x10^4 + 4.715x10^2 T - 7.286x10^{-1} T^2 + 3.607x10^{-4} T^3, & \text{if } 554K < T \le 804K \\ 1.210x10^3, & \text{if } T > 804K \end{cases} \quad (9)$$

$$h_{air} = \begin{cases} 2.916 + 6.104x10^{-2} T - 1.213x10^{-4} T^2, & \text{se } T \le 533K \\ 6.832 + 1.837x10^{-2} T - 1.681x10^{-5} T^2 + 6.764x10^{-9} T^3, & \text{if } 533K < T \le 1200K \\ 3.907x10^1 - 2.619x10^{-2} T, & \text{if } 1200K < T \le 1311K \\ -2.305x10^1 + 3.366x10^{-2} T, & \text{if } T > 1311K \end{cases} \quad (10)$$

FEM analysis is performed exploiting axisymmetrical geometry and a single strip is considered for simulations (Gür & Tekkaya, 1996). This assumption is employed since the passage of the moving workpiece through the heating and cooling rings induces their effects in this single strip while adjacent material, above and below this strip, is at lower temperatures. The material at lower temperatures prevents the axial strain and, as a consequence, plane strain condition may be adopted. Moreover, radial heat flux is assumed.

Stress concentration is introduced by semi-circular notch with different radius, r^*. Basically, 6 situations are analyzed: 0, 0.5mm, 0.75mm, 1.0mm, 1.50mm and 2.0mm. Figure 1 shows a mesh for r^* = 2.0mm and similar meshes are generated for other configurations. Table 2 presents mesh characteristics of each configuration.

In Fig. 1, the segment *OM* is at the cylinder center axis while *LK* is at the cylinder surface. Null displacements are imposed in *OK* and *ML*. Moreover, thermal boundary conditions impose convection condition in *KL* while other faces have adiabatic conditions.



(a) (b)

Figure 1 – (a) Cylinder with stress concentrator; (b) FEM mesh for r^* = 2.0mm.

Table 2 – Mesh information for different radius r^*.

r^* (mm)	Nodes	Elements
0	377	672
0.50	716	1323
0.75	487	880
1.00	503	904
1.50	417	740
2.00	535	972

At first, volumetric phase fraction of martensite is of concern. Figure 2 shows the final time instant considering different radius, r^*. Notice that phase transformations tends to follow the geometry of the specimen. On the other hand, numerical simulations show that temperature distribution tends to be homogeneous for all configurations.

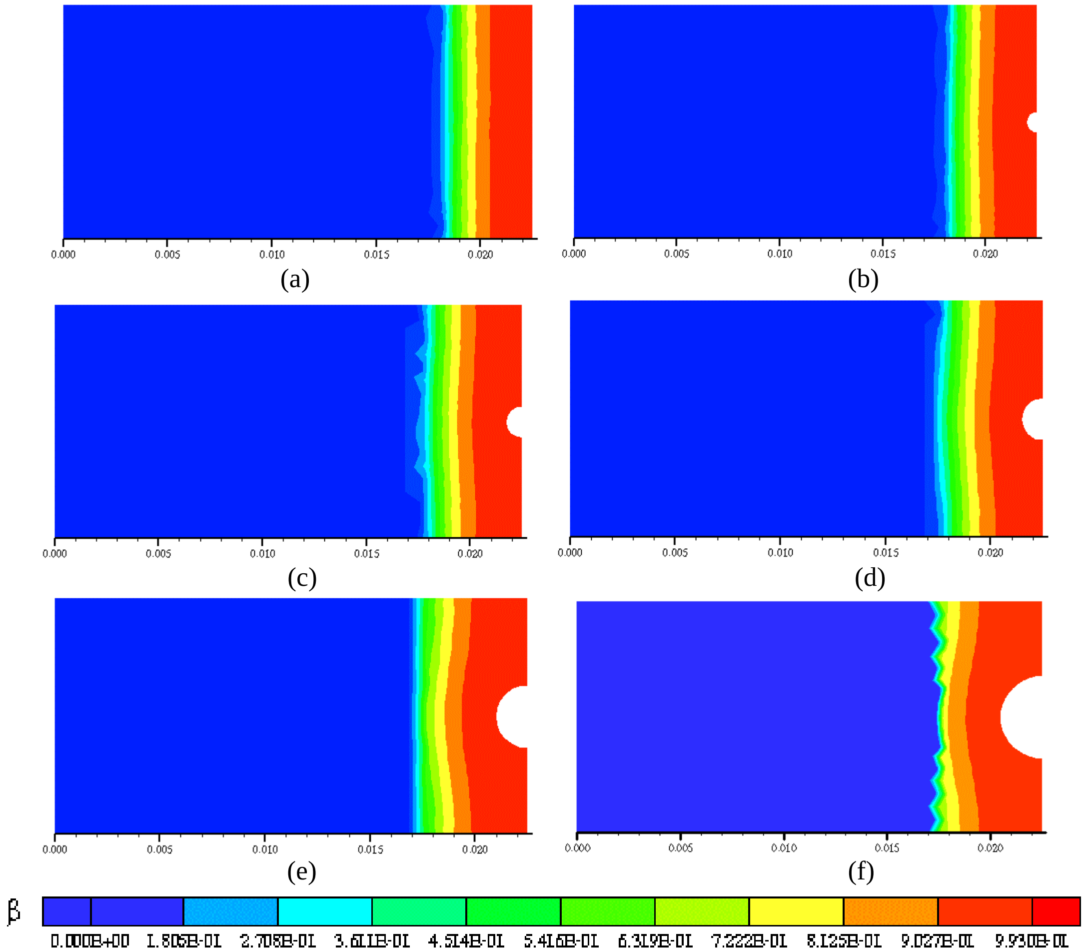


Figure 2 – Volumetric fraction of martensite for the final time instant.
(a) $r^* = 0$; (b) $r^* = 0.5$ mm; (c) $r^* = 0.75$ mm; (d) $r^* = 1.0$ mm; (e) $r^* = 1.5$ mm; (f) $r^* = 2.0$.

Residual stresses are now focused. In general, residual stresses σ_r and σ_z are compressive in cylinder surface. Figure 3 shows that residual radial stresses, σ_r, the increase stress concentrator radius r^* causes the increase of the region related to maximum tensile stresses.

Figure 4 shows residual stresses σ_θ for the final time instant and different radius r^*. Notice a well defined tensile stress region in the range 12mm $< r <$ 18mm. The larger value (in magnitude) of compressive stresses is observed for $r^* = 1.5$ mm. In order to evaluate the effect of stress concentration during quenching it is interesting to compare the maximum compressive stress value (in magnitude) when $r^* = 1.5$mm, $\sigma_\theta = -996.5$MPa, and when $r^* = 0$mm (without stress concentrator), $\sigma_\theta = -667.9$MPa, which is 47% of difference.

Figure 5 shows residual stresses σ_z presenting similar behavior of σ_θ. Notice that compressive stress region in the core decreases when the stress concentrator radius increases. Evaluating the effect of stress concentrator it is possible to observe a difference of 78% ($\sigma_z = -955.5$MPa when $r^* = 0.5$mm, and $\sigma_z = -536.4$MPa when $r^* = 0$).

Shear residual stresses σ_{rz} also has extreme values near stress concentrator (Figure 6). Notice that greater values occur for $r^* = 1.0$mm.

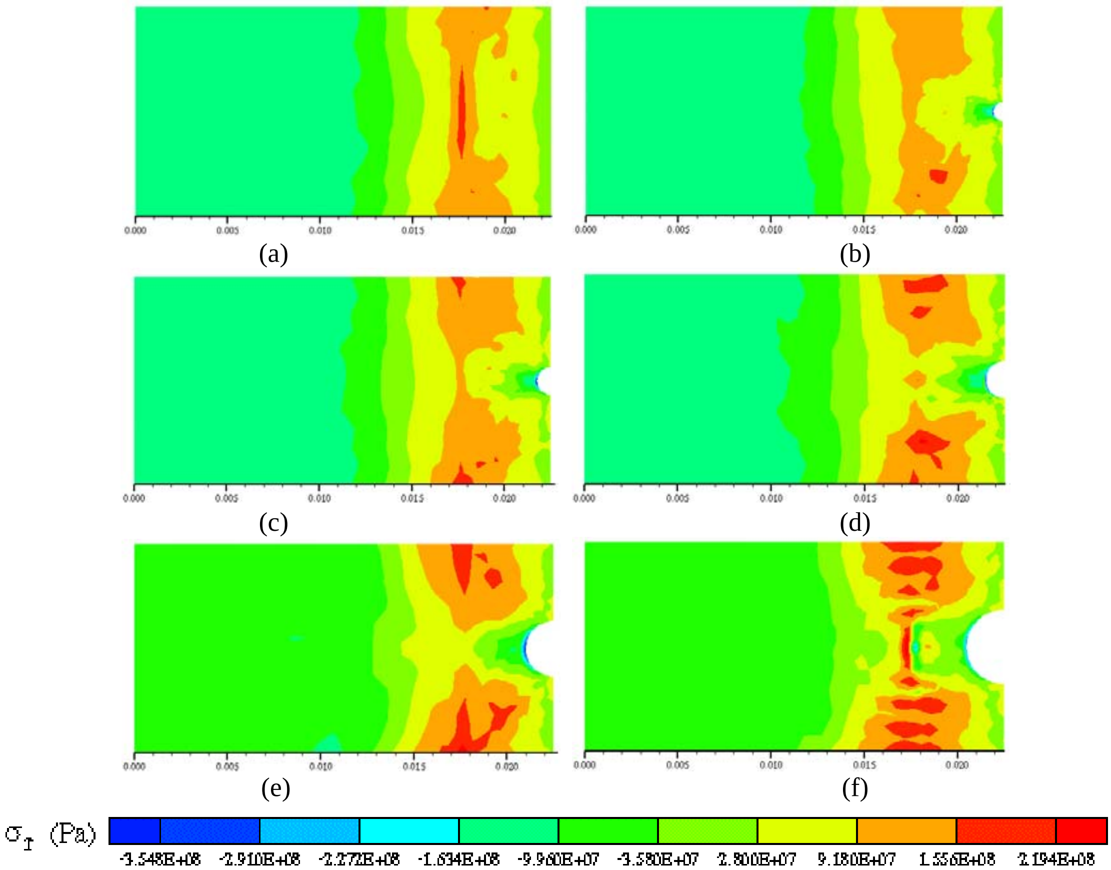


Figure 3 – Residual stress σ_r for the final time instant.
(a) $r^* = 0$; (b) $r^* = 0.5$ mm; (c) $r^* = 0.75$ mm; (d) $r^* = 1.0$ mm; (e) $r^* = 1.5$ mm; (f) $r^* = 2.0$ mm.

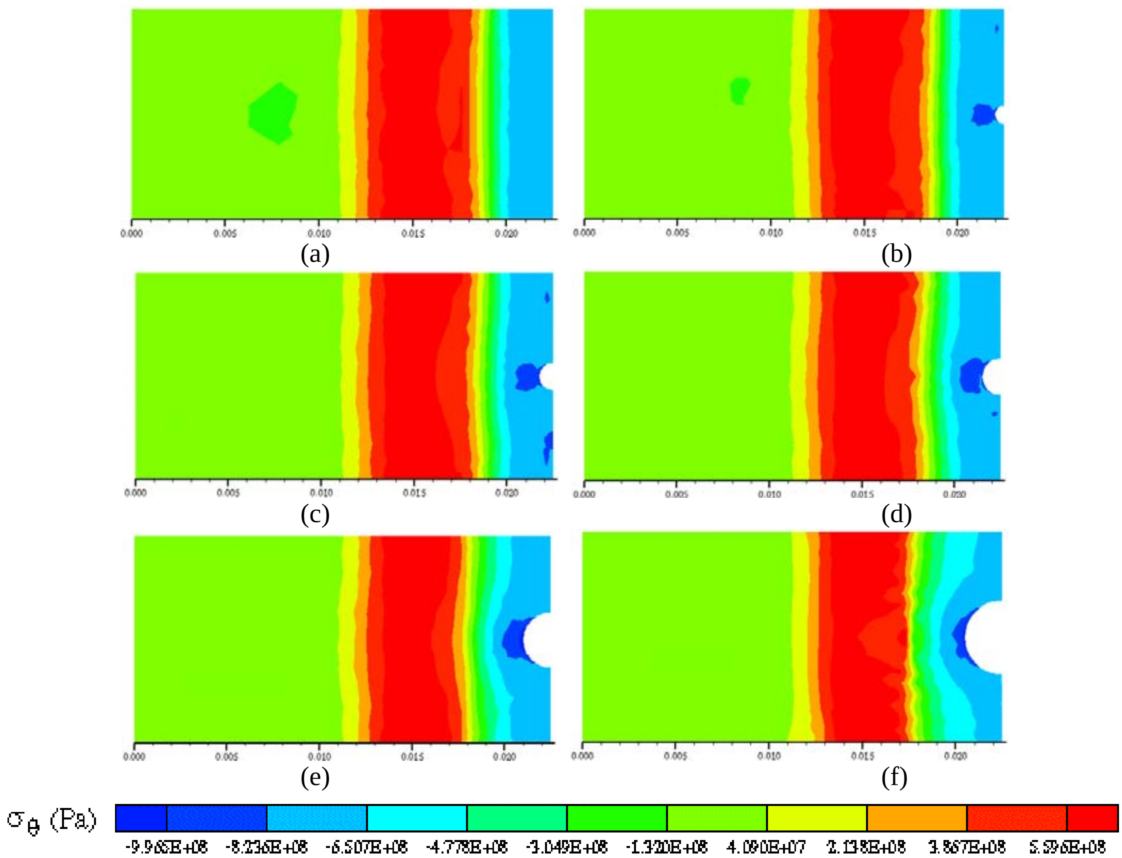


Figure 4 – Residual stress σ_θ for the final time instant.
(a) $r^* = 0$; (b) $r^* = 0.5$ mm; (c) $r^* = 0.75$ mm; (d) $r^* = 1.0$ mm; (e) $r^* = 1.5$ mm; (f) $r^* = 2.0$ mm.

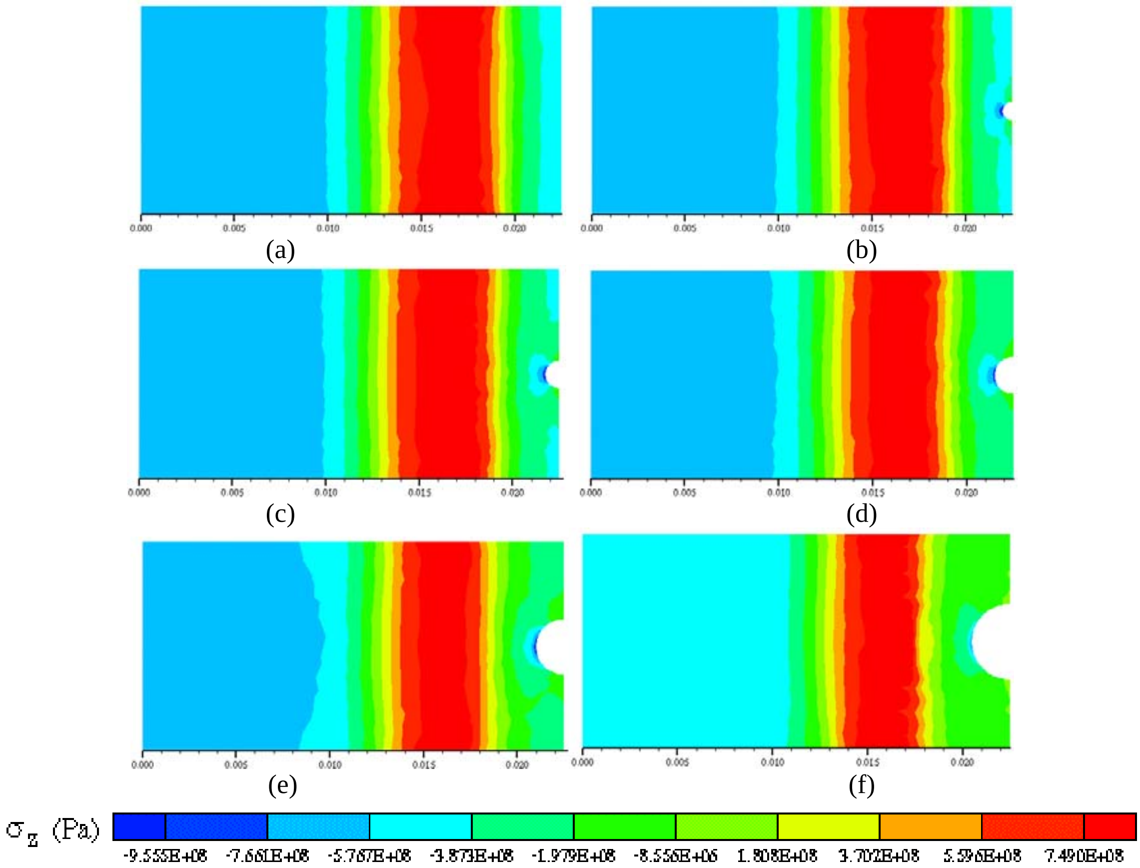


Figure 5 – Residual stress σ_z for the final time instant.
(a) $r^* = 0$; (b) $r^* = 0.5$ mm; (c) $r^* = 0.75$ mm; (d) $r^* = 1.0$ mm; (e) $r^* = 1.5$ mm; (f) $r^* = 2.0$ mm.

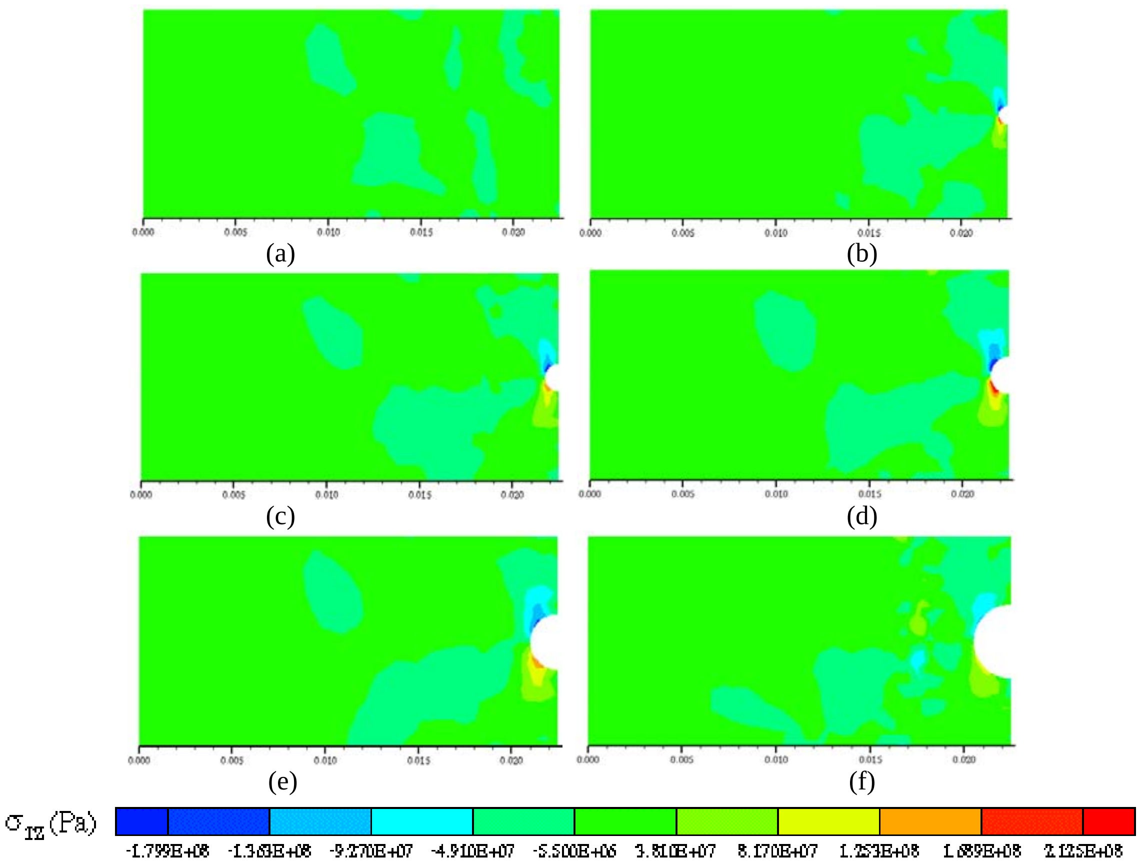


Figure 6 - Residual stress σ_{rz} for the final time instant.
(a) $r^* = 0$; (b) $r^* = 0.5$ mm; (c) $r^* = 0.75$ mm; (d) $r^* = 1.0$ mm; (e) $r^* = 1.5$ mm; (f) $r^* = 2.0$ mm.

Figure 7 shows an alternative way to observe the previous results using von Mises stresses. These stresses are important for the evaluation of the structural integrity of mechanical components, as in the case of yielding and fatigue design. A peak for the maximum stress value is observed for 0.75mm and a non-monotonic behavior is observed when the residual stress is plotted against r^*/R. It is worth to note that the stress concentration factor for this geometry considering usual shaft loading, as axial, torsion or bending loading, rises as the relation r^*/R decreases. Therefore, a different behavior is observed for residual and operational stresses.

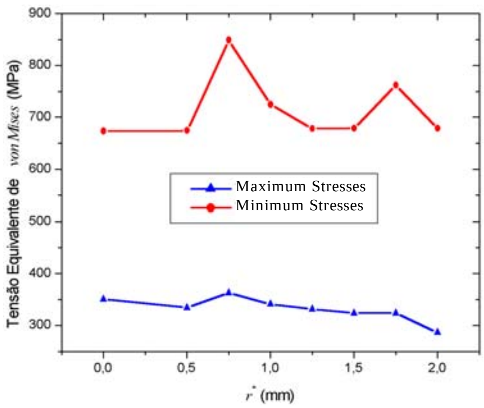


Figure 7 – von Mises stresses as a function of radius r^*.

4. CONCLUSIONS

This article reports on the modeling and simulation of quenching process, considering finite element method associated with an anisothermal constitutive model with two phases (austenite and martensite). A numerical procedure based on operator split technique associated with an iterative numerical scheme is employed in order to deal with nonlinearities in the formulation. Progressive induction hardening of a steel cylindrical body with a semi-circular notche is considered. The effect of stress concentration is of concerned, analyzing different configurations defined by the radius of the semi-circular notches, r^*. Numerical simulations show that, in general, there is a critical value of this radius where residual stress is larger and non-monotonic behavior is observed. The authors agree that this kind of analysis may be useful to evaluate critical situation for quenching process.

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6. REFERENCES

Ames, W.F., 1992, "*Numerical Methods for Partial Differential Equations*", Academic Press.

Boley, B.A. & Weiner, J.H., 1985, "*Theory of Thermal Stresses*", Krieger.

Camarão, A.F., 1998, "*A Model to Predict Residual Stresses in the Progressive Induced Quenching of Steel Cylinders*", PhD thesis, Department of Metallurgical and Materials Engineering, Universidade de São Paulo (in Portuguese).

Camarão, A.F., da Silva, P.S.C.P. & Pacheco, P.M.C.L., 2000, "Finite Element Modeling of Thermal and Residual Stresses Induced by Steel Quenching", In Seminário de *Fratura, Desgaste e Fadiga de Componentes Automobilísticos*, Brazilian Society of Automotive Engineering, Rio de Janeiro (in Portuguese).

Denis, S., Gautier, E., Simon, A. & Beck, G., 1985, "Stress-Phase-Transformation Interactions – Basic Principles, Modelling and Calculation of Internal Stresses", *Material Science and Technology*, v.1, October, pp.805-814.

Denis, S., Archambault, S., Aubry, C., Mey, A., Louin, J.C. & Simon, A., 1999, "Modelling of Phase Transformation Kinetics in Steels and Coupling with Heat Treatment Residual Stress Predictions", *Journal de Physique IV*, v.9, September, pp.323-332.

Gartling D.K. and Hogan R.E., 1994, COYOTE – "A Finite Element Computer Program for Nonlinear Heat Conduction Problems/Part I", Enginnering Sciences Center, Sandia National Laboratories. in: http://sandia.gov [captured in January 12, 2002].

Gür, C.H. and Tekkaya, A.E., 1996, "Finite Element Simulation of Quench Hardening", Steel Research, 67, No.7, pp.298-306.

Hildenwall, B., 1979, "*Prediction of the Residual Stresses Created During Quenching*", Ph.D. thesis, Linkoping University.

Lemaitre, J. & Chaboche, J.L., 1990, "*Mechanics of Solid Materials*", Cambridge Press.

Lewis, R.W., Morgan, K., Thomas, H.R. and Seethramu, K.N., 1996, "The Finite Element Method in Heat Transfer Analysis", John Wiley & Sons, USA.

Melander, M., 1985a, "*A Computational and Experimental Investigation of Induction and Laser Hardening*", Ph.D. thesis, Department of Mechanical Engineering, Linkoping University.

Melander, M., 1985b, "Computer Predictions of Progressive Induction Hardening of Cylindrical Components", Materials Science and Technology, 1 October, pp. 877-882.

Nakamura, S., 1993, "*Applied Numerical Methods in C*", Prentice-Hall, Englewood Cliffs, New Jersey.

Oliveira, W.P., 2004, *"Modeling the Quenching Process of Steel Cylinders using a Constitutive Multi-Phase Model"* (in portuguese), M.Sc. Dissertation, Mestrado em Tecnologia – CEFET/RJ.

Ortiz, M., Pinsky, P.M. & Taylor, R.L., 1983, Operator Split Methods for the Numerical Solution of the Elastoplastic Dynamic Problem, *Computer Methods of Applied Mechanics and Engineering*, v. 39, pp.137-157.

Pacheco, P.M.C.L., Camarão, A.F. & Savi, M.A., 2001, "Analysis of Residual Stresses Generated by Progressive Induction Hardening of Steel Cylinders", *Journal of Strain Analysis for Engineering Design*, v.36, n.5, pp.507-516.

Segerlind, L.J., 1984, "Applied Finite Element Analysis", 2nd Edition, John Wiley & Sons, USA.

Sen, S., Aksakal, B. & Ozel, A., 2000, "Transient and Residual Thermal Stresses in Quenched Cylindrical Bodies", *International Journal of Mechanical Sciences*, 42, pp.2013-2029.

Silva, E.P., Pacheco, P.M.C.L. & Savi, M.A., 2004, "On the Thermo-Mechanical Coupling in Austenite-Martensite Phase Transformation Related to The Quenching Process", *International Journal of Solids and Structures*, v.41, n.3-4, pp.1139-1155

Silva, E.P., Pacheco, P.M.C.L. & Savi, M.A., 2003, "Simulation of Quenching Process Using the Finite Element Method", *COBEM 2003 - 17th International Congress of Mechanical Engineering*, São Paulo.

Simo, J.C. & Hughes, T.J.R., 1998, "*Computational Inelasticity*", Springer.

Simo, J.C. & Miehe, C., 1992, "Associative Coupled Thermoplasticity at Finite Strains: Formulation, Numerical Analysis and Implementation", *Computer Methods in Applied Mechanics and Engineering*, v.98, pp.41-104.

Sjöström, S., 1985, "Interactions and Constitutive Models for Calculating Quench Stresses in Steel", *Material Science and Technology*, v.1, pp.823-829.

Woodard, P.R., Chandrasekar, S. & Yang, H. T. Y., 1999, "Analysis of Temperature and Microstructure in the Quenching of Steel Cylinders", *Metallurgical and Materials Transactions B*, v. 30B, August, pp.815-822.