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Model and numerical analysis of mechanical phenomena of tools steel hardening

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Abstract

This paper the model hardening of tool steel takes into considerations of mechanical phenomena is presented. Fields stresses and strains are obtained from solutions by FEM equilibrium equations in rate form. The stresses generated during hardening were assumed to result from thermal load, structural deformation, and plastic deformation and transformation plasticity. Thermophysical values in the constitutive relations are depended upon both the temperature and the phase composition. Condition Huber-Misses with the isotropic strengthening for the creation of plastic strains is used. However model Leblond to determined transformations plasticity applied. The analysis of stresses associated of the elements hardening made of tool steel was done.

Keywords: Quenching; Tool steel; Thermo-elestic-plastic finite element analysis

1. Introduction

Representing of mechanical phenomenon in process of heat treatment are mainly stress and their determination is depend on accuracy computing temperature fields and from kinetics of phase transformations in sold state. The kinetics of phase transformations has significant impact on temporary stresses and then on residual stresses [1-3]. Numerical simulations of steel hardening process need therefore to include thermal strains, plastic, and structural strains and transformations plasticity [1-4].

The last decade showed strong evolution of numerical methods in order to in a greater or smaller extent design processes of heat-treatment. Every paper dealing with this topic should contain thermal, microstructural and stress analysis. To implement this type of algorithms one usually applies the FEM, which makes it possible to take into account both nonlinearities and inhomogeneity of thermally processed material [2,4,7-9,14].

In the model of phase transformations diagrams of continuous heating (CHT) and cooling (CCT) are used [4,9,10]. The phase fraction transformed during continuous heating (austenite) is calculated in the model using the Johnson-Mehl and Avrami formula and modification Koistinen and Marburger formula, fractions pearlite or bainite are determined in model by Johnson-Mehl and Avrami formula. The fraction of the martensite formed is calculated using the modified Koistinen equation [1,6,8]

2. Mathematical model

The equilibrium equation and constitutive relations are used in rate form [3,8,9], i.e.:

$$\mathrm{div}\dot{\boldsymbol{\sigma}}(x_\alpha,t)=\mathbf{0},\ \ \dot{\boldsymbol{\sigma}}=\dot{\boldsymbol{\sigma}}^T,\ \ \dot{\boldsymbol{\sigma}}=\mathbf{D}\circ\dot{\boldsymbol{\varepsilon}}^e+\dot{\mathbf{D}}\circ\boldsymbol{\varepsilon}^e \tag{1}$$

where $\boldsymbol{\sigma}=\boldsymbol{\sigma}(\sigma_{\alpha\beta})$ is stress tensor, $\mathbf{D}=\mathbf{D}(\nu,E)$ is the tensor of material constants (isotropic materials), ν is Poisson ratio, $E=E(T)$ is the Young's modulus dependent on the temperature, however $\boldsymbol{\varepsilon}^e$ is tensor elastic strains.

Total strains in the around considered points are result of the sum:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{e} + \boldsymbol{\varepsilon}^{Tph} + \boldsymbol{\varepsilon}^{tp} + \boldsymbol{\varepsilon}^{p} \tag{2}$$

where $\boldsymbol{\varepsilon}^{Tph}$ are isotope of temperature and structural strains, $\boldsymbol{\varepsilon}^{tp}$ are transformations plasticity, and $\boldsymbol{\varepsilon}^{p}$ are plastic strains.

The strains $\boldsymbol{\varepsilon}^{Tph}$ were obtained by solving the rate of the isotropic strain in the processes of heating and cooling [3].

For the Huber-Misses plasticity condition the flow function (*f*) have the form [3,5,9]:

$$f = \sigma_{ef} - Y\left(T, \eta, \varepsilon_{ef}^{\mathrm{p}}\right) = 0 \tag{3}$$

where σ_{ef} is effective stress, $\varepsilon_{ef}^{\mathrm{p}}$ is effective plastic strains, Y is a plasticized stress of material on the phase fraction (η) in temperature (T) and effective strain (ε_{ef}^{p}):

$$Y\left(T, \eta, \varepsilon_{ef}^{\mathrm{p}}\right) = Y_0(T, \eta) + Y_H\left(T, \varepsilon_{ef}^{\mathrm{p}}\right) \tag{4}$$

$Y_0 = Y_0(T, \eta)$ is a yield points of material dependent on the temperature and the phase fraction, however $Y_H = Y_H\left(T, \varepsilon_{ef}^{p}\right)$ is a surplus of the stress resulting from the material hardening.

Using the Leblond model, completed by decreasing functions $(1-\eta)$ which has been proposed by the authors of the work [2,4,10], transformations plasticity are calculated as following:

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{tp}} = \begin{cases} 0, \ \text{dla } \eta_k \le 0.03, \\ -3\sum_{k=2}^{k=5}(1-\eta_k)\varepsilon_{1k}^{ph}\dfrac{\mathbf{S}}{Y_1}\ln(\eta_k)\dot{\eta}_k, \ \text{dla } \eta_k \ge 0.03 \end{cases} \tag{5}$$

where $3\varepsilon_{1i}^{ph}$ are volumetric structural strains when the material is transformed from the initial phase „1" into the *k*-phase, Y_1 is a actual yield points of phase output (in cooling process is austenite).

The equations (1) are solved by means of the FEM [5,8,12]. The system of equations used for numerical calculation is:

$$[\mathbf{K}]\{\dot{\mathbf{U}}\} = \left(\{\dot{\mathbf{R}}\} + \{\dot{\mathbf{t}}^{Tph}\} - \{\dot{\mathbf{t}}^{e}\}\right) + \{\dot{\mathbf{t}}^{ptp}\} \tag{6}$$

where **K** is the element stiffness matrix, **U** is the vector of nodal displacement, **R** is the vector of nodal forces resulting from the boundary load and the inertial forces load, $\mathbf{t}^{Tph}$ is the vector of nodal forces resulting from thermal strains and structural strains, $\mathbf{t}^{e}$ is the vector of nodal forces resulting from the value change of Young's modulus dependent on the temperature, $\mathbf{t}^{ptp}$ is the vector of nodal forces resulting from plastic strains and transformation plasticity.

Have marked rate of displacement solved rate stresses to result to gradient of displacement rate. The final displacements, strains and stress are resulting integration with respect to time, from initial $t=t_0$ to actual time t, i.e.

$$\begin{gathered} \mathbf{U}(x_\alpha, t) = \int_{t_0}^{t} \dot{\mathbf{U}}(x_\alpha, \tau)d\tau \\ \boldsymbol{\varepsilon}(x_\alpha, t) = \int_{t_0}^{t} \dot{\boldsymbol{\varepsilon}}(x_\alpha, \tau)d\tau, \ \boldsymbol{\sigma}(x_\alpha, t) = \int_{t_0}^{t} \dot{\boldsymbol{\sigma}}(x_\alpha, \tau)d\tau \end{gathered} \tag{7}$$

Using one step scheme integration's and marked by index „s" time t, however by index „s+1" - time $t^{s+1} = t^{s} + \Delta t^{s+1}$, summation discrete value functions "**f**" obtain from solutions, in following time steps, carry out following:

$$\mathbf{f}\left(x_\alpha, t^{s+1}\right) = \sum_{k=0}^{k=s} \dot{\mathbf{f}}\left(x_\alpha, \Delta t^{k}\right)\Delta t^{k} + \dot{\mathbf{f}}\left(x_\alpha, \Delta t^{s+1}\right)\Delta t^{s+1} \tag{8}$$

The rate vectors of loads in the brackets in (6) are calculated only once in the increment of the load, whereas the vector $\mathbf{t}^{ptp}$ is modified in the iterative process [12]. In interactions process in following „i" steps are solved the system of equations

$$[\mathbf{K}]\{\delta^{i}\dot{\mathbf{U}}\} = \{\delta^{i}\dot{\mathbf{t}}^{ptp}\} \tag{9}$$

and updating successively displacements, strains and stresses

$$\mathbf{f}\left(x_\alpha, t^{s+1}\right) = \sum_{k=0}^{k=s} \dot{\mathbf{f}}\left(x_\alpha, \Delta t^{k}\right)\Delta t^{k} + \left(\dot{\mathbf{f}}^{Tph}\left(x_\alpha, \Delta t^{s+1}\right) + \sum_{k=1}^{i} \delta^{k}\dot{\mathbf{f}}\right)\Delta t^{s+1} \tag{10}$$

3. Example of numerical calculations

Numerical simulations of hardening of the elements made of the carbon tool steel were performed. The thermophysical coefficients assumed from the works [2,6]. Heat transfer coefficient assumed constant equal α_∞=2000 [W/(m^{2}K)] (heating in fluid layer [13]). The temperature of the heating medium equalled T_∞=1600 K.

Young′s and tangential modulus (E and E^t) were dependent on temperature, whereas the yields stress (Y_0) was dependent on temperature and phase composition. Assumed, that Young′s and tangential modulus are equal 2×10^5 and 4×10^3 [MPa] (E^t*=0.05E*), yield points 150, 480, 700 and 300 [MPa] for austenite, bainite, martensite and pearlite, respectively, in the temperature 300 K. In the temperature of solidus Young′s modulus and tangential modulus equalled 100 and 10 [MPa], respectively, whereas yield points equalled 5 [MPa]. These values were approximated with the use of square functions using the following assumptions based on the work [2,3].

The axisymmetrical object ϕ40×80 mm subjected hardening simulation. After heating the temperature in the point 2 (Fig. 1) was equalled 1400 K and the output phase fractions was austenite and pearlite [6]. The cooling was modelled with the Newton condition and the extreme of heat transfer coefficient assumed equal α_∞=9000 [W/(m^{2}K)] (cooling in the water [3]). The temperature of the cooling medium equalled T_∞=300 K.

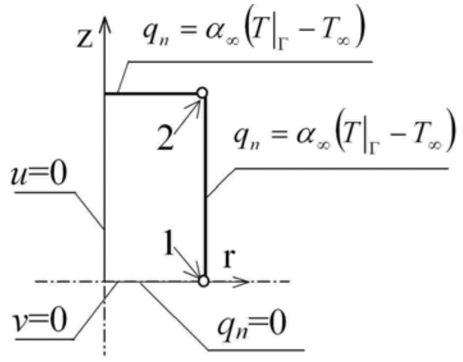

Fig. 1. The scheme of the system and boundary conditions

The kinetic of transformations in the superficial points 1 and 2 of the element are presented in figures 1.

Exemplary residual stresses distributions after hardening, with and without transformation plasticity ($\varepsilon^{tp}=\mathbf{0}$ and $\varepsilon^{tp}\neq\mathbf{0}$) are presented in figures 3-7.

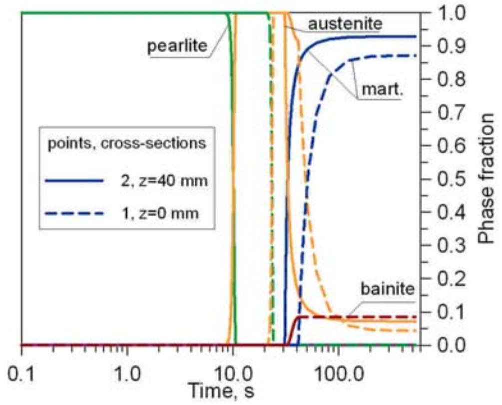

Fig. 2. The kinetic of transformations in the superficial points 1 and 2 of the element (Fig. 1)

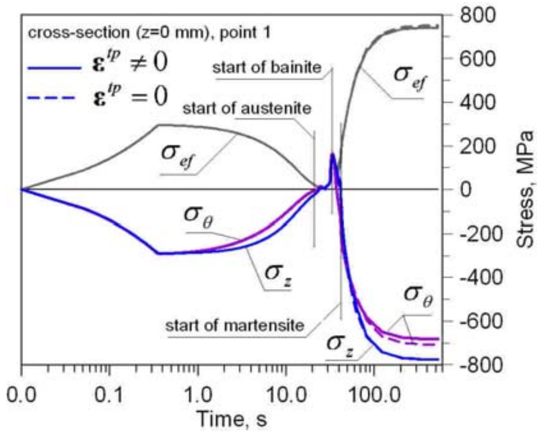

Fig. 3. Stresses according to the time (point 1, Fig. 1), with and without transformation plasticity

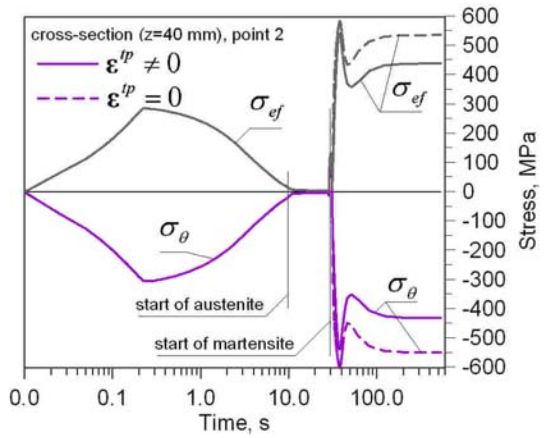

Fig. 4. Stresses according to the time (point 2, Fig. 1), with and without transformation plasticity

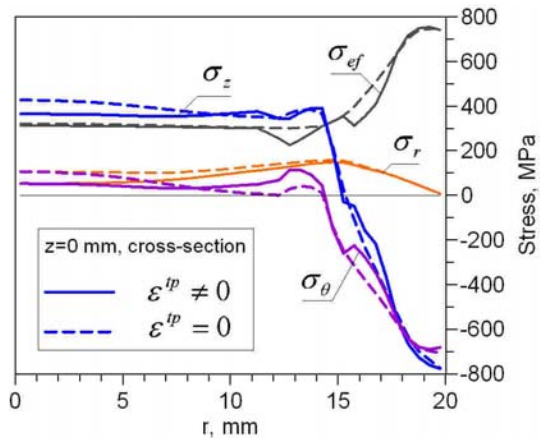

Fig. 5. Residual stresses in the cross sections (Fig. 1), without and with considering transformation plasticity

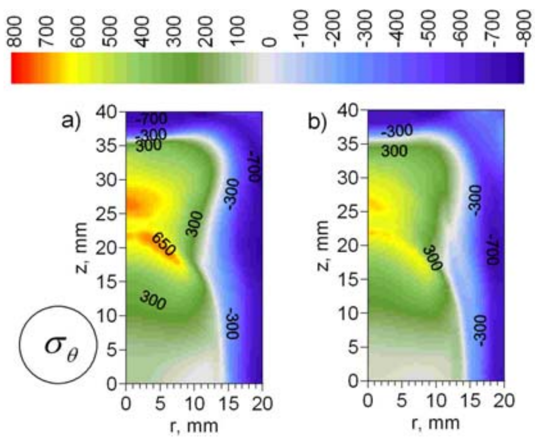

Fig. 6. Residual stresses without a) and with b) transformation plasticity

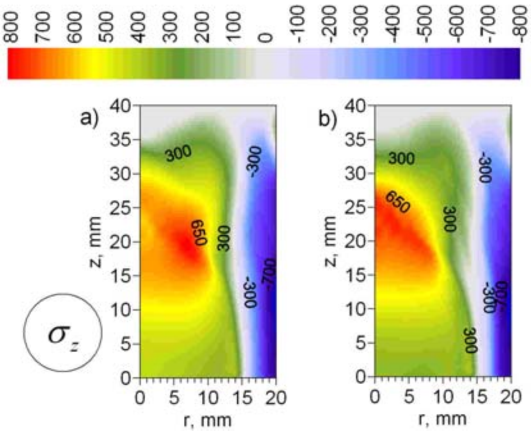

Fig. 7. Residual stresses without a) and with b) transformation plasticity

4. Conclusions

The stresses distributions after such hardening are advantageous. The regular distributions of the stresses are obtained (Figs. 5-7). The extreme values of these stresses are acceptable. Inclusion of transformation plasticity has a influence on distributions and extreme values of stresses in the simulation of the hardening. The deposition of negative circumferential and axial stresses (the most meaningful stresses) is superficial (Figs. 6 and 7), and their extreme values are lower when these stresses are taken into account. It can be claimed that in the numerical simulation of such hardening the fact that transformation plasticity is included in the model of mechanical phenomena brings about the changes in obtained results. These changes encompass smoothing of stresses fields and decrease in their peaks (Figs. 6b and 7b).

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