NUMERICAL MODEL OF PROGRESSIVE HARDENING PROCESS WITH TEMPERING FOR C45 STEEL

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Abstract. The paper deals with numerical model of thermal phenomena and phase transformation in solid state with tempering. To modeling the process heat transfer equation and macroscopic model of phase change based on CCT and CHT diagrams are used. The numerical solution of heat conductivity equation is introduced to estimate the temperature field during the heating and cooling processes. To solve this equation finite element method (FEM) derived on the base of Bubnov-Galerkin formulation is applied.

Introduction

Heat processing is often used in modern branches of the industry. Surface processing, particulary progressive hardening processing becomes very popular. The constructed model contains of heating-cooling phenomena and phase transformations with tempering (Fig. 1) during progressive hardening.

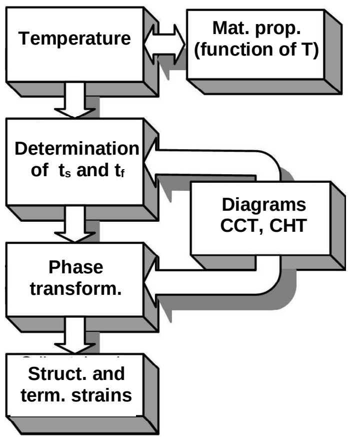

Fig. 1. The flow diagram of the model

1. Temperature field

During phase transformation in the solid state heat transfer is governed by the partial differential equation in Lagrange's coordinates:

$$\nabla \cdot (\lambda \nabla T) - C \frac{\partial T}{\partial t} + q_V = 0 \tag{1}$$

where $C = C(T)$ is the thermal capacity, $\lambda = \lambda(T)$ is the thermal conductivity coefficient and ρ is the density.

In order to solve the Fourier-Kirchhoff equation finite element method based on Galerkin scheme is applied. The model is completed by the Dirichlet and Neumann conditions. This model is built for 3D space. The cubic finite elements with three-linear shape functions are used in presented numerical model [2, 5, 6].

2. Phase transformations

Proposed method of the calculation of phase transformation during continuous cooling and heating uses data from two CCT diagrams and CHT diagram respectively. In every step the fraction of new phase is calculated on the basis of kinetics of the transformation modelled according to Johnson-Mehl-Avrami or Koistinen-
-Marburger laws.

The volume fraction of austenite appeared during heating process is determined by the Avrami expression [1, 2, 6]:

$$\tilde{\eta}_A(T,t) = 1 - \exp\left(-b(T) t^{n(T)}\right) \tag{2}$$

or modified Koistinen-Marburger equation [4]:

$$\tilde{\eta}_A(T,t) = 1 - \exp\left(-k_A (T_{sA} - T)\right),\ k_A = \frac{4.6051702}{T_{sA} - T_{fA}} \tag{3}$$

where $b(T)$ and $n(T)$ are coefficients depend on time of the start and the finish transformation, T_{sA} and T_{fA} are the time of the start and the finish of austenite transformation. The modified KM equation is used for cooling rate upper 100 K/s.

The volume fractions appeared during diffusional transformations (austenite to ferrite, pearlite and bainite) can be written as [1, 2]:

$$\eta_{(i)}(T,t) = \left(\tilde{\eta}_A - \sum_{\alpha \neq i} \eta_\alpha \right) \left(1 - \exp\left(-b(T) t^{n(T)}\right)\right) \tag{4}$$

The phase transformation during the high-speed cooling (austenite to martensite) is determined by classical form of KM equation, for T < Ms:

$$\eta_M(T,t)=\left(\tilde{\eta}_A-\sum_{\alpha\neq M}\eta_\alpha\right)\left(1-\exp\left(-k\left(M_S-T\right)\right)\right),\ k=\frac{-\ln\left(\sum_\alpha \eta_\alpha\right)}{\left(M_s-M_f\right)} \qquad (5)$$

In the model of phase transformations the influence of austenitisation temperature on the kinetics of transformations is taken into account.

The increment of isotropic strain resulting from the temperature and phase transformation is determined by formula [2, 6]:

$$d\varepsilon^T=\sum_i \alpha_i(T)\eta_i dT,\quad d\varepsilon^{ph}=\sum_i \gamma_i(T)d\eta_i \qquad (6)$$

where α_i is a thermal expansion coefficients for „*i*” phase, γ_i is a structural expansion coefficients for „*i*” transformation.

Table 1

Structural and thermal expansion coefficients [6]

	α_i, 1/K	γ_i		α_i, 1/K	γ_i
Austenite	$2{,}178 \cdot 10^{-5}$	$1{,}986 \cdot 10^{-3}$	Bainite	$1{,}171 \cdot 10^{-5}$	$4{,}0 \cdot 10^{-3}$
Ferrite	$1{,}534 \cdot 10^{-5}$	$1{,}534 \cdot 10^{-3}$	Martensite	$1{,}36 \cdot 10^{-5}$	$6{,}85 \cdot 10^{-3}$
Pearlite	$1{,}534 \cdot 10^{-5}$	$1{,}534 \cdot 10^{-3}$	Sorbite	$1{,}534 \cdot 10^{-5}$	$-1{,}0 \cdot 10^{-3}$

3. Numerical results

The numerical simulation of the hardening process was made for the cubicoid steel element (Fig. 2) which was heated by progressive heat source with gaussian distribution [3, 7]. The heat source was moved along parallel pathes. The distance between them was equal to 0.005 m. The maximum intensity of the source reached Q = 4800 W, the radius was equal to 0.005 m, time step Δt = 0.017 s, velocity of the heat source V_x = 0.02 m/s.

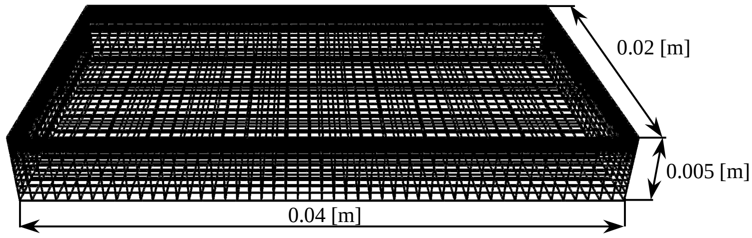

Fig. 2. The mesh used for hardening element

The temperature field and volume fraction of the phases on the upper surface are presented in Figures 3-5. Isotropic strains connected to phase transformations and phase kinetics in two points lying on the upper surface are showed in Figures 6-7.

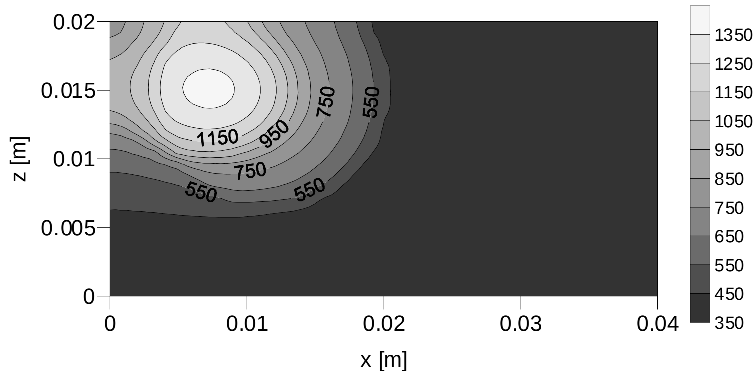

Fig. 3. Field of temperature [K], upper surface - time of process 13.32 s

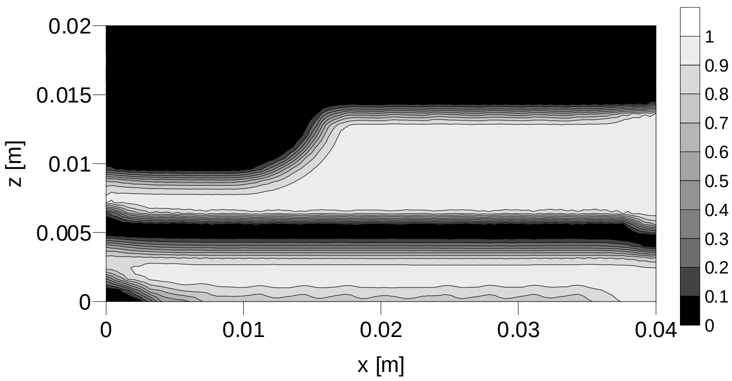

Fig. 4. Distribution of martensite, upper surface - time of process 13.32 s

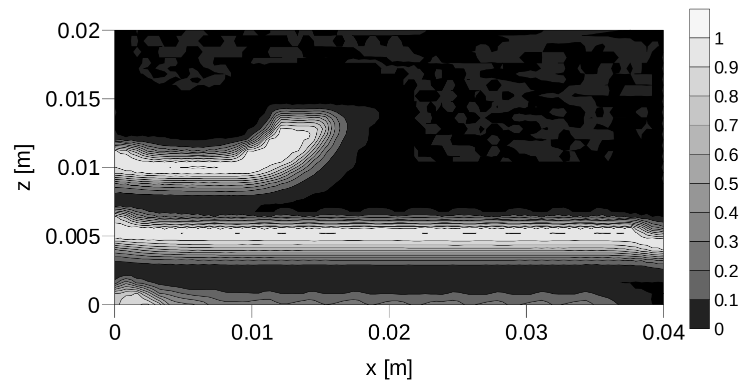

Fig. 5. Distribution of sorbite, upper surface - time of process 13.32 s

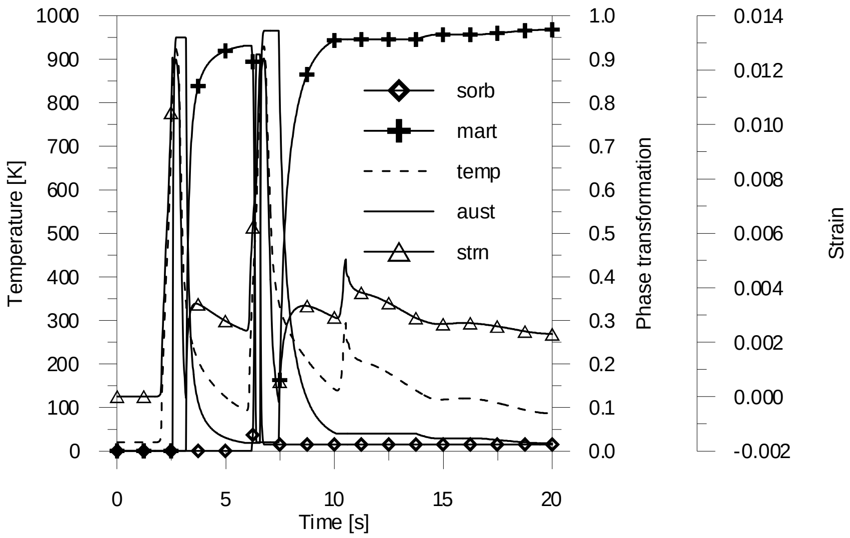

Fig. 6. The kinetic of phase transformations, structural and thermal strain and temperature, node nr 1

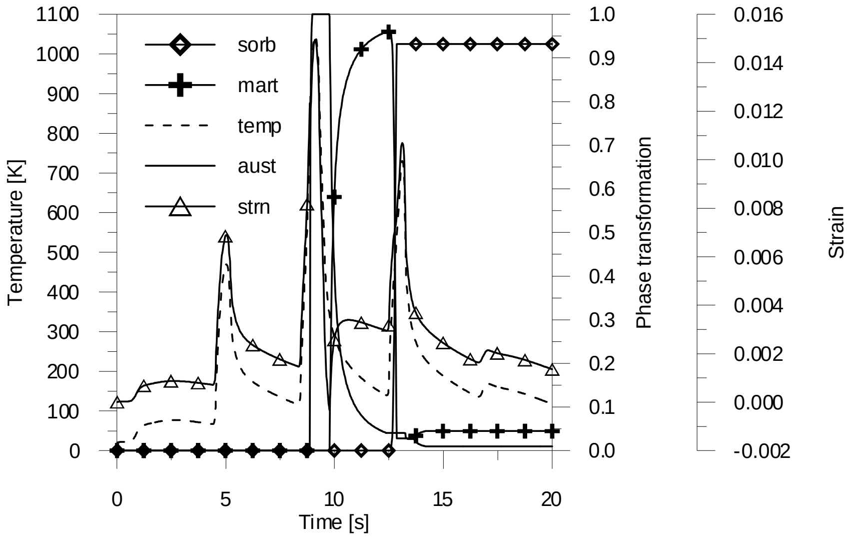

Fig. 7. The kinetic of phase transformations, structural and thermal strain and temperature, node nr 2

Conclusions

The tempering process considered in the presented model has the great influence on the structural strain distributions and the level of stresses in the element. The macroscopic model of the phase transformation may be very useful in the practice, however it needs experimental verification.

References

[1] Avrami M., J. Chem. Phys. 1939, 7, 1103.

[2] Bokota A., Kulawik A., Trójwymiarowy model zjawisk termicznych determinowanych źródłem ruchomym, Archives of Foundry 2002, 2, 4 (2/2), 74-78.

[3] Klobčar D., Tušek J., Taljat, B., Finite element modeling of GTA weld surfacing applied to hot-work tooling, Computational Materials Science 2004, 31, 368-378.

[4] Koistinen D.P., Marburger R.E., A general equation prescribing the extent of the autenite--martensite transformation in pure iron-carbon alloys and plain carbon steels, Acta Mettalica 1959, 7, 59-60.

[5] Kulawik A., Bokota A., Makroskopowy model przemian fazowych w stali C45, Archives of Foundry 2006, 6, 22 (2/2), 286-291.

[6] Kulawik A., Analiza numeryczna zjawisk cieplnych i mechanicznych w procesach hartowania stali 45, Praca doktorska, Częstochowa 2005.

[7] Zhang, L., Michaleris P., Investigation of Lagrangian and Eulerian finite element methods for modeling the laser forming process, Finite Elements in Analysis and Design 2004, 40, 383-405.