ARCHIVES of FOUNDRY ENGINEERING

ISSN (1897-3310)
Volume 10
Issue 1/2010

31 – 34

6/1

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Numerical modelling of tools steel hardening. A thermal phenomena and phase transformations

T. Domański[a]*, A. Bokota[b]
[a] Institute of Mechanics and Machine Design, Czestochowa University of Technology
[b] Institute of Computer and Information Sciences Czestochowa University of Technology
42-200 Częstochowa, 73 Dąbrowskiego str., Poland
*Corresponding author. E-mail address: domanski@imipkm.pcz.czest.pl

Received 22.07.2009; accepted in revised form 27.07.2009

Abstract

This paper the model hardening of tool steel takes into considerations of thermal phenomena and phase transformations in the solid state are presented. In the modelling of thermal phenomena the heat equations transfer has been solved by Finite Elements Method. The graph of continuous heating (CHT) and continuous cooling (CCT) considered steel are used in the model of phase transformations. Phase altered fractions during the continuous heating austenite and continuous cooling pearlite or bainite are marked in the model by formula Johnson-Mehl and Avrami. For rate of heating >100 K/s the modified equation Koistinen and Marburger is used. Modified equation Koistinen and Marburger identify the forming fraction of martensite.

Keywords: Heat treatment; Phase transformation, Numerical modelling

1. Introduction

Heat treatment is a technological process, in which thermal phenomena, phase transformations and mechanical phenomena are dominant. Models, which describe processes mentioned above, do not take into consideration many important aspects. As a result of the complexity of phenomenon of heat treatment process, there are many mathematical and numerical difficulties in its modelling. For this reason there is no model which would include phenomenon accompanying heat treatment, and therein and hardening.

The correct prediction of the final proprieties is possible after defining the type and the property of the nascent microstructure of the steel - element in the process of heating, and then the cooling treated thermally. Recently, many research works have been made on the analysis of quenching process with the help of finite element simulation technique [1-3].

In this paper the numerical model of phase transformation such as Johanson-Mehl-Kolmogorov model for the diffusional transformation and modified Koistinen and Marburger model for the difusionless transformation were employed to investigate a phase fraction during the heating and quenching process. For rate of heating >100 K/s the modified equation Koistinen and Marburger is used [4,5].

2. Mathematical models

Fields of the temperature determined from equation solution of the transient heat:

$$\operatorname{div}(\lambda \operatorname{grad} T) - C\frac{\partial T}{\partial t} = -q^{v} \tag{1}$$

where $\lambda=\lambda(T)$ is the heat conductivity coefficient, $C=C(T)$ is an effective heat capacity, q^{v} is intensity of internal sources (one takes into account in him heat of phase transformations).

Superficial heating and cooling are realised in the model with the boundary condition of the Newton boundary condition with temperature dependent a convection coefficient:

$$-\lambda\frac{\partial T}{\partial n}\bigg|_{\Gamma} = q_n = \alpha_{\infty}(T|_{\Gamma} - T_{\infty}) \tag{2}$$

where $\alpha^{T}(T)$ is the heat transfer coefficient, Γ is surface, from which the heat is taken over, T_{∞} is temperature of the cooling medium.

The finite element method in the Bubnov-Galerkin formulation is used to solve the problem [6].

In the model of phase transformations diagrams of continuous heating (CHT) and cooling (CCT) are used (Fig. 1) [7-9]. The phase fraction transformed during continuous heating (austenite) is calculated in the model using the Johnson-Mehl and Avrami formula and modified Koistinen and Marburger formula, for rate heating >100 K/s, fractions pearlite or bainite are determined in model by Johnson-Mehl, Avrami and Kolmogorov formula. The fraction of the martensite formed, is calculated using the modified Koistinen and Marburger formula [4,5,10]:

$$\begin{aligned}
&\eta_A(t) = 1-\exp(-b(t_s,t_f)(t-t_{sA})^{n(t_s,t_f)}\\
&\eta_A(t) = 1-\exp\left(-\left(\frac{t_{sA}-T}{T_{sA}-T_{fA}}\right)^{5/2}\right),\ \dot{T}\geq 100\,K/s\\
&\eta_M(T) = \eta_m\left(1-\exp\left(-\left(\frac{M_s-T}{M_s-M_f}\right)^{m}\right)\right),\quad m=3.3\\
&\eta(t) = \eta_m(1-\exp(-b(T)^{n}))
\end{aligned} \tag{3}$$

where $\eta_m = \eta_C^{\%}\eta_A$ for $\eta_A \geq \eta_C^{\%}$ and $\eta_m = \eta_A$ for $\eta_A < \eta_C^{\%}$, $b(t_s,t_f)$ and $n(t_s,t_f)$ are coefficients calculated assuming the initial fraction ($\eta_s(t_s)$=0.01) and the final fraction ($\eta_f(t_f)$=0.99), $\eta_C^{\%}$ is maximal phase fraction for established cooling rate estimated with CCT diagrams, η_A is a fractions of the initial austenite, T_{sA} is temperature start austenite transformations, T_{fA} – final temperature of this transformations, m is constant from experiment; for considered steel m = 3.3 if for the temperature start transformations martensite amount M_s=493 K, and final this transformations is in assumed temperature M_f=173 K [7,8].

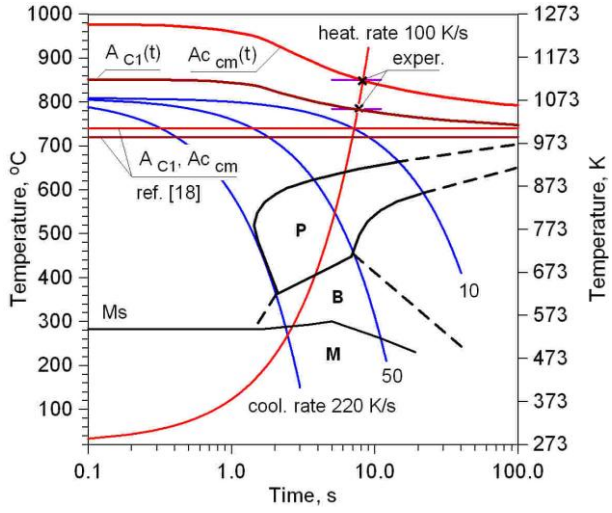

Fig. 1. The Time-Temperature-Transformation graphs (CHT) and (CCT) for tools steel [8,9]

Latent heat, which was generated due to phase transformation, led to increase of the temperature within the material treatment heating. This internal heat source could be handled by enthalpy change. Thus, the following enthalpy changes for the diffusional and diffusionless transformations were used ([J/m^3]) [1,5,9]:

$$\Delta H_B = 314\times10^6,\ \Delta H_M = 630\times10^6,\ \Delta H_P = 800\times10^6 \tag{4}$$

where ΔH_B, ΔH_M and ΔH_P indicate the enthalpy changes during austenite-bainite, austenite-martensite and austenite-pearlite transformations, respectively.

Heat of phase transformations is considered in the term source of the conductivity equation (1) and is calculated with the example [1,8,11]:

$$q^{v} = \sum_k H_k\dot{\eta}_k \tag{5}$$

where H_k is volumetric heat (enthalpy) k- phase transformations, $\dot{\eta}_k$ is the rate of change k- phase fraction.

In this way the derived model for evaluating phase fraction and kinetics of transformation in heating and cooling processes were verified. The purpose of the dilatometric research was to analyse phase transformations during heating and continuous cooling of steel considered [8,9]. Dilatometric research was done in the Institute for Ferrous Metallurgy in Gliwice by means of a dilatometer DIL805 produced by Bähr Thermoanalyse GmbH.

The coefficient of thermal expansion for pearlitic structure depends not linear on the temperature (see. Fig. 2), and an approximation of this coefficient using the square function [9]:

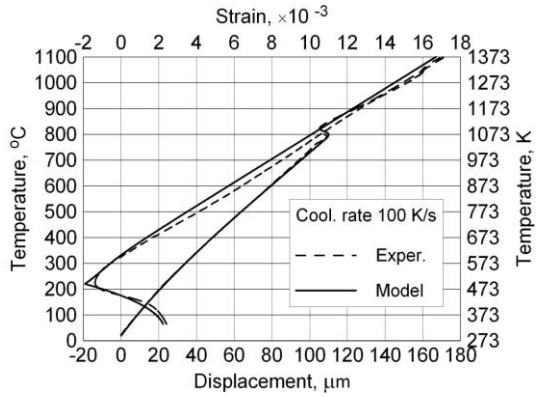

Fig. 2. Experimental and simulated dilatometric curves

Based on comparisons of experimental and simulator dilatometric curves for the examined steel, values of thermal expansion coefficients and isotropic structural strains of each micro-constituents were determined. They equal: 22, 10, 10 and 14.5 ($\times 10^{-6}$) [1/K] and 1.9, 4.5, 8.3 and 1.5 ($\times 10^{-3}$) for austenite, bainite, martensite and pearlite respectively [9,12].

Results of these simulations and appropriate comparisons to the experiment results are presented in the papers [8,9]. The example comparisons are presented the figure 2, the kinetic of transformations established cooling rate are presented on the figure 3 (see [9]).

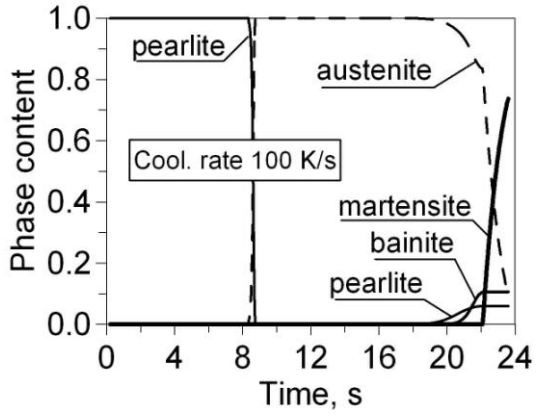

Fig. 3. The kinetic of transformations for established cooling rate

The simulated dilatometric curves were obtained by solving the increment of the isotropic strain in the processes of heating and cooling [8,9].

3. Example of numerical calculations

Numerical simulations of hardening of the elements made of the carbon tool steel were performed. The thermophysical coefficients λ and C were assumed as constants: 35 [W/(mK)], and 5.0×10^6 [J/(m^3K)]. These are the average values calculated on the basis of the data in the work [3]. Heat transfer coefficient assumed constant equal α_∞=2000 [W/(m^2K)] (heating in fluid layer [9]). The temperature of the heating medium equalled T_∞=1600 K. The cooling was modelled with the Newton condition and the extreme of heat transfer coefficient assumed equal α_∞=9000 [W/(m^2K)] (cooling in the water [9]). The temperature of the cooling medium equalled T_∞=300 K.

The axisymmetrical object with the following size ϕ40×80 mm (Fig. 4) underwent hardening simulation (cf. [1]). After heating it had an even temperature in the point 2 (Fig. 4) equalling 1400 K, and the output microstructure was austenite and pearlite (see Fig. 5).

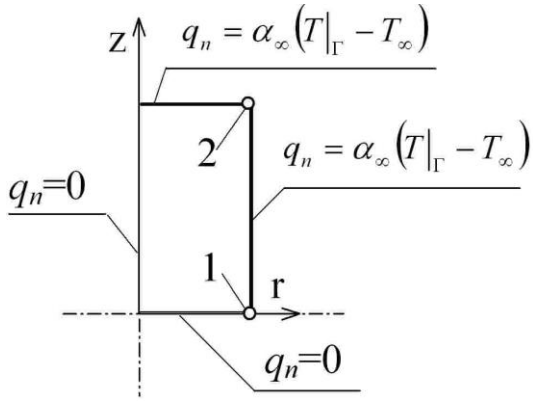

Fig. 4. The scheme of the system and boundary conditions

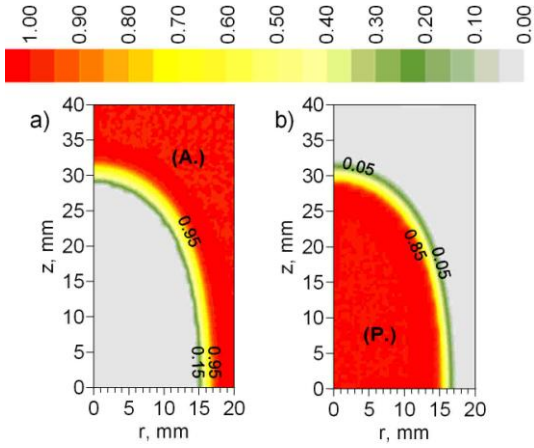

Fig. 5. Distributions of the austenite a) and pearlite b) after heating

Hardened zones in the cross sections of the element are presented in figures 6. Distributions of the simulated fractions in a microstructure after hardening of the object are presented in figure 7.

4. Conclusions

The results of the verification of the phase transformations model are satisfactory and confirm the correctness of the designed

model of phase transformations for the carbon tool steel (Figs. 6 and 7).

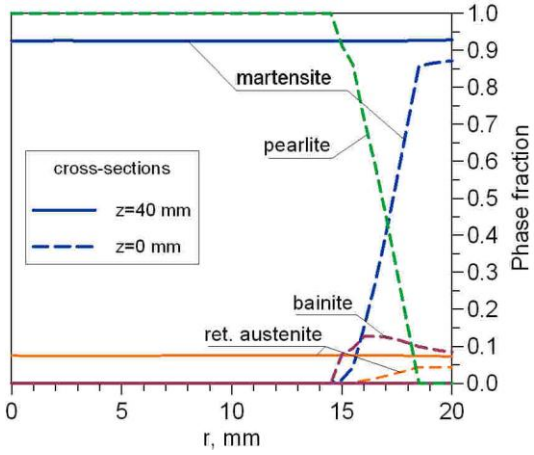

Fig. 6. Hardened zones in the cross sections

Hardened zones in the cross and longitudinal sections are presented in figures 6 and 7.

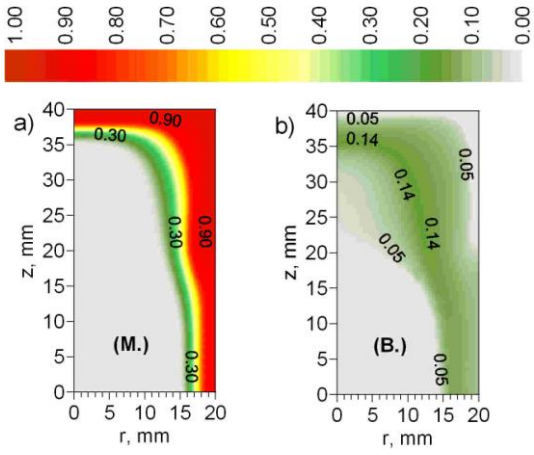

Fig. 7. Distributions of martensite a) and bainite b)

References

[1] S.H. Kang, Y.T. IM, Three-dimensional thermo-elestic-plastic finite element modeling of quenching process of plain carbon steel in couole with phase transformation. Intenational Journal of Mechanical Sciences 49, (2007), 13-16.

[2] L. Huiping, Z. Guoqun, N. Shanting, H. Chuanzhen, FEM simulation of quenching process and experimental verification of of simulation results, Material Science and Engineering A 452-453 (2007), 705-714.

[3] M. Coret, A. Combescure, A mesomodel for the numerical simulation of the multiphasic behavior of materials under anisothermal loading (application to two low-carbon steels), International Journal of Mechanical Sciences, 44 (2002), 1947-1963.

[4] A. Bokota, A. Kulawik, Model and numerical analysis of hardening process phenomena for medium-carbon steel. Archives of Metallurgy and Materials, 52(2), (2007), 337-346.

[5] E.P. Silva, P.M.C.L. Pacheco, M.A. Savi, On the thermo-mechanical coupling in austenite-martensite phase transformation related to the quenching process, International Journal of Solids and Structures, 41 (2004), 1139-1155.

[6] O.C. Zienkiewicz, R.L. Taylor, The finite element method, Butterworth-Heinemann, Fifth edition, vol. 1,2,3, 2000.

[7] M. Białecki, Characteristic of steels, seria F, tom I, Editor Silesia 1987, 108-129, 155-179, (in Polish).

[8] T. Domański, Numerical modelling of surface hardening elements of steel. PhD Thesis, Częstochowa 2005, (in Polish).

[9] A. Bokota, T. Domański, Numerical analysis of thermo-mechanical phenomena of hardening process of elements made of carbon steel C80U. Archives of Metallurgy and Materials, 52(2), (2007), 277-288.

[10] L. Taleb, F. Sidoroff, A micromechanical modelling of the Greenwood-Johnson mechanism in transformation induced plasticity, International Journal of Plasticity, 19 (2003), 1821-1842.

[11] S. Serejzadeh, Modeling of temperature history and phase transformation during cooling of steel, Journal of Processing Technology, 146 (2004), 311-317.

[12] T. Domański, A. Bokota, Numerical model of phase transformation of steel C80U. Archives of Foundry Engineering, 4(4) (2007), 39-42.