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The numerical analysis of the hardening phenomena of the hot-work tool steel

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Abstract

In the paper, to the numerical analysis of quenching phenomena, the complex model of hardening of the hot-work tool steel is used. The numerical algorithm of the thermal phenomena is based on the solving of the heat transfer equation, which takes into account the heat of phase transformations in the solid state, using the finite element method. Model of estimation of phase fractions and their kinetics is based on the continuous cooling diagram (CCT). Phase fractions which occur during the continuous heating and cooling (austenite, pearlite or bainite) are described by Johnson-Mehl-Avrami (JMA) formula. To determine of the formed martensite the modified Koistinen-Marburger (KM) equation is used. The stress and strain are determined by the solution of the equilibrium equations in the rate form using finite element method. The Young's and tangent modulus were dependent on temperature, whereas the yields stress was function of temperature and phase composition of the hardened element. In the model the thermal, structural, plastic strains and transformation plasticity are taken into account. Thermophysical properties occurring in the constitutive relations depended on the temperature and phase composition of the material. To calculate the plastic strains the Huber-Mises plasticity condition with isotropic hardening is used. Whereas to determine transformations induced plasticity the modified Leblond model is applied. Based on the implemented algorithms of the volumetric hardening process (assuming the various temperatures of the cooling medium) the numerical analysis of the phase content, strains and stresses for the hot-work steel (W360) element is performed.

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1. Introduction

The numerical analysis of the heat treatment phenomena is the important problem for the modern lab which designs for the industry. The research works including the issue of the heat treatment can be divided into those that in the complex way analyze the presented phenomena, as well as those that focus only on the one phenomena of the heat treatment process. The phenomena occurring during the heat treatment are very complex and still incompletely described. The model of the heat treatment process, which is hardening, should contain at least with three coupling elements: thermal, structural and mechanical [1-6]. In the heat treatment process the significant stresses are generated and cause, in most cases, the plasticize of the material. Determination of the kinetics of phases and kind of obtained structures during the heating or cooling process of iron alloys is necessary to calculate the stresses for the hardening process. Additionally, to ensure the reliability of the results of numerical simulations of mechanical phenomena, except thermal, structural and plastic strains the transformation induced plasticity should be taken into account. The element which has the significant influence on the results of numerical simulation of the hardening is the appropriate choice of the heating and cooling conditions which are modeled by the boundary conditions. This is important in the case of quenching the hot-work tool steel, which is easily hardened [7-9].

Therefore, in the paper paid attention to this problem by comparing the results from numerical simulation of the hardening of hot-work tool steel (W360) for the two method of hardening: the volumetric cooling in the room temperature and cooling, in the recommended, higher temperature.

2. Model of thermal phenomena

In the heat transfer phenomena model the heat transfer equation is used in the following form:

$$\mathrm{div}\left(\lambda \mathrm{grad}\left(T\right)\right) - C_{ef}\frac{\partial T}{\partial t} = -Q,\ T = T\left(x_\alpha, t\right) \tag{1}$$

where $\lambda=\lambda(T)$ is the thermal conductivity coefficient [W/(mK)], $T=T(x_\alpha,t)$ is temperature [K], $C_{ef}=C(T)$ is an effective heat capacity [J/(m^{3}K)], Q is intensity of internal sources in which the heat of phase transformations are taken into account [W/m^3], x_α are the coordinates [m] and t is time [s].

The equation (1) is supplemented by initial conditions ($T(x_\alpha,t_0)=T_0(x_\alpha)$, $Q(x_\alpha,t_0)=Q_0(x_\alpha)=0$) and appropriate boundary conditions: Neumann and Newton (are described in the examples).

Heat of phase transformations $\left(Q^{ph}\right)$ take into account in source unit of conductivity equation (1) calculate by formula:

$$Q = \dot{Q}^{ph} = \sum_k \dot{Q}_k^{\eta_k} = \sum_k H_k^{\eta_k}\dot{\eta}_k$$

where $H_k^{\eta_k}$ is volumetric heat k - phase transformations [J/m^3] (k=2..5 respectively for the bainite, ferrite, martensite and pearlite), $\dot{\eta}_k$ is rate of k – phase transformation [1,10,11].

The following enthalpy changes for the diffusional and diffusionless transformations were used [2,4,6,16]: $\Delta H_B = 314\times10^6$, $\Delta H_M = 630\times10^6$, $\Delta H_P = 800\times10^6$ J/m^3. ΔH_B, ΔH_M and ΔH_P indicate the enthalpy changes during austenite-bainite, austenite-martensite and austenite-pearlite transformations, respectively.

3. Model the kinetics of phase transformation in the solid state

To calculate the kinetic of phase transformations during cooling the offset continuous cooling diagram (CCT) is used (Fig. 1).