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THE PREDICTIONS OF STRESS TO TECHNOLOGY IMPROVEMENT OF CARBON STEEL

In work the presented numerical models of tool steel hardening processes take into account thermal, mechanical phenomena and phase transformations. In the model of phase transformations, in simulations heating process continuous heating (CHT) was applied, whereas in cooling process continuous cooling (CCT) of the steel at issue. The phase fraction transformed (austenite) during heating and fractions during cooling of ferrite, pearlite or bainite are determined by Johnson-Mehl-Avrami formulas. The nescent fraction of martensite is determined by Koistinen and Marburger formula or modified Koistinen and Marburger formula. The stress and strain fields are obtained using the solution of the Finite Elements Method of the equilibrium equation in rate form. The thermophysical constants occurring in constitutive relation depend on temperature and phase composite. For determination of plastic strain the Huber-Misses condition with isotropic strengthening was applied whereas for determination of transformation plasticity a modified Leblond model was used.
Keywords*: Phase transformations, hardening, stress, numerical simulations.*

Introduction

Thermal treatment including hardening is a complex technological process aiming to obtain high hardness, high abrasion resistance, high durability of the elements hardened as well as suitable initial structure to be used in the subsequent thermal treatment processes as a result of which the optimum mechanical properties of the elements are received.

Today an intense development of numerical methods supporting designing or improvement of already existing technological processes are observed. The technologies mentioned above include also steel thermal processing comprising hardening. Efforts involving thermal processing numerical models aim to encompass an increasing number of input parameters of such a process [1-2].

As a consequence of analyzing of the thermal processing results many mathematical and numerical models were obtained [1-5]. A basic element of almost all studies regarding transformations of austenite into ferrite, pearlite and bainite is the Avrami equation with respect of the TTT diagram-based models and the general Kolmogorov Johnson-Mehl-Avrami equation with respect to the models using classical nucleation theory [2-4]. The Koistinen and Marburger's equation is, on the other hand, fundamental equation enabling prediction of the kinetics of the martensite transformation [1-4].

The choice of suitable model can by dependent on kinds of lead hardening simulations. It can by parallel simulation of thermal phenomena, phase transformations and mechanical phenomena (Fig. 1), or series block simulations – thermal block, phase transformations, and than mechanical phenomena block.

Models using diagrams of isothermal heating and cooling can be applied both with respect to parallel and block sequential simulation since the transformations starting and ending times are determined at the crossing of the starting and ending curves of the transformations carried out at a fixed temperature [1-3].

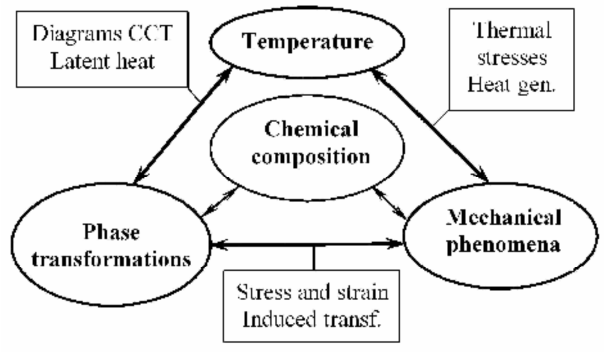

Fig. 1. Scheme of correlation of the hardening phenomena

Models using continuous heating and cooling diagrams can be directly applied only in a block sequential simulation. In this case transformation starting and ending times are determined at the crossing of the starting and ending curves of the transformations and the heating or cooling temperature curves. In the parallel simulation model the transformation starting time is directly determined at the crossing of the transformations starting curve and heating or cooling temperature curves whereas the transformation ending time can be established using the technique of temperature curve approximation within the expected range of the transformation.

Temperature fields

Temperature field are obtain with solved of transient heat equation (Fourier equation) with source unit:

$$\nabla \cdot (\lambda \nabla(T)) - C\frac{\partial T}{\partial t} = -Q \ , \tag{1}$$

where: $\lambda=\lambda(T)$ is the heat conductivity coefficient, $C=C(T)$ is effective heat coefficient, Q is intensity of volumetric internal source (this can also be the phase transformations heat).

Superficial heating investigation in model by boundary conditions Neumann (heat flux q_n), however cooling are modelling by boundary conditions Newton with depend on temperature coefficient of heat transfer:

$$-\lambda\left.\frac{\partial T}{\partial n}\right|_{\Gamma} = q_n = \alpha^T(T)\left(T|_{\Gamma} - T_{\infty}\right). \tag{2}$$

In heating simulation on surfaces except heating source, also radiation through overall heat transfer coefficient was taken into account:

$$-\lambda\left.\frac{\partial T}{\partial n}\right|_{\Gamma} = q_n = \alpha_0\sqrt[3]{T|_{\Gamma} - T_{\infty}}\left(T|_{\Gamma} - T_{\infty}\right) = \alpha^*\left(T|_{\Gamma} - T_{\infty}\right), \tag{3}$$

where: $\alpha_T(T)$ is heat transfer coefficient, α_0 is heat transfer coefficient experimental determine, Γ is surface, from witch is transfer heat, T_{∞} is temperature of medium cooling.

Phase transformations

In the model of phase transformations take advantage of diagrams of continuous heating (CHT) and cooling (CCT) [3,6].

In both case the phase fractions transformed during continuous heating (austenite) is calculated using the Johnson-Mehl and Avrami formula (4) or modified Koistinen and Marburger formula (in relations on rate of heating) (5) [1-4]:

$$\underline{\eta}_A(T,t) = 1 - \exp(-b(t_s,t_f)(t(T))^{n(t_s,t_f)}; \tag{4}$$

$$\underline{\eta}_A(T,t) = 1 - \exp\left(-\ln(\eta_s)\frac{T_{sA}-T}{T_{sA}-T_{fA}}\right),\ \dot{T} \geq 100\,K/s, \tag{5}$$

where: $\underline{\eta}_A$ is austenite initial fraction nescent in heating process, T_{sA} is temperature of initial phase in austenite, T_{fA} – is final temperature this phase.

The coefficient $b(t_s,t_f)$ and $n(t_s,t_f)$ are obtain with (4) next assumption of initial fraction $(\eta_s=0.01)$ and final fraction $(\eta_f=0.99)$ and calculation are by formulas:

$$n(t_s,t_f) = \frac{\ln(\ln(0.01)/\ln(0.99))}{\ln(t_f/t_s)},\ b(t_s,t_f) = \frac{-\ln(0.99)}{(t_s)^n}. \tag{6}$$

Pearlite and bainite fraction (in the model of phase transformations upper and lower bainite is not distinguish) are determine by Johnson-Mehl and Avrami formula.

$$\eta_i(T,t) = \chi\left(1-\exp\left(-b(t(T))^n\right)\right). \tag{7}$$

The nascent fraction of martensite is calculated using the Koistinen and Marburger formula [2].

$$\eta_M(T) = \chi\left(1-\exp\left(\ln(0.01)\frac{M_s-T}{M_s-M_f}\right)\right) \tag{8}$$

or modified Koistinen and Marburger formula [3]:

$$\eta_M(T) = \chi\left(1-\exp\left(-\left(\frac{M_s-T}{M_s-M_f}\right)^m\right)\right), \tag{9}$$

where

$$\chi = \eta_{(.)}^{\%}\underline{\eta}_A \text{ for } \underline{\eta}_A \geq \eta_{(.)}^{\%} \text{ and } \chi = \underline{\eta}_A \text{ for } \underline{\eta}_A < \eta_{(.)}^{\%}, \tag{10}$$

$\eta_{(\cdot)}^{\%}$ is the maximum phase fraction for the established of the cooling rate, estimated on the ground of the continuous cooling graph, m is the constant chosen by means of experiment. For considered steel determine, that m = 3.3 if the start temperature of martensite transformations is equal M_s=493 K, and end this transformations is in temperature M_f=173 K [3,6]. Increases of the isotropic deformation caused by changes of the temperature and phase transformation in the heating and cooling processes are calculated using the following relations:

- heating

$$d\varepsilon^{Tph} = \sum_{\alpha=1}^{\alpha=5} \alpha_\alpha \eta_\alpha dT - \varepsilon_A^{ph} d\eta_A; \tag{11}$$

- cooling

$$d\varepsilon^{Tph} = \sum_{\alpha=1}^{\alpha=5} \alpha_\alpha \eta_\alpha dT + \sum_{\beta=2}^{\beta=5} \varepsilon_\beta^{ph} d\eta_\beta , \tag{12}$$

where: $\alpha_\alpha = \alpha_\alpha(T)$, are coefficients of thermal expansion of: austenite, bainite, ferrite, martensite and pearlite, respectively, ε_A^{ph} is the isotropic deformation accompanying transformation of the input structure into austenite, whereas $\varepsilon_\beta^{ph} = \varepsilon_\beta^{ph}(T)$ are isotropic deformations from phase transformation of: austenite into bainite, ferrite, martensite, or of austenite into pearlite, respectively. These values are usually adopted on the basis of experimental research conducted on a heat cycle simulator [3].

Heat of phase transformations take into account in source unit of conductivity equation (1) calculate by formula:

$$Q = \sum_k H_k^{\eta_k} \dot{\eta}_k , \tag{13}$$

where: $H_k^{\eta_k}$ is volumetric heat *k*- phase transformations, $\dot{\eta}_k$ is rate of change fractions *k*-phase [8]. The methods for calculation of the fractions of the phases created referred to above were used for carbon tool steel represented by C80U steel.

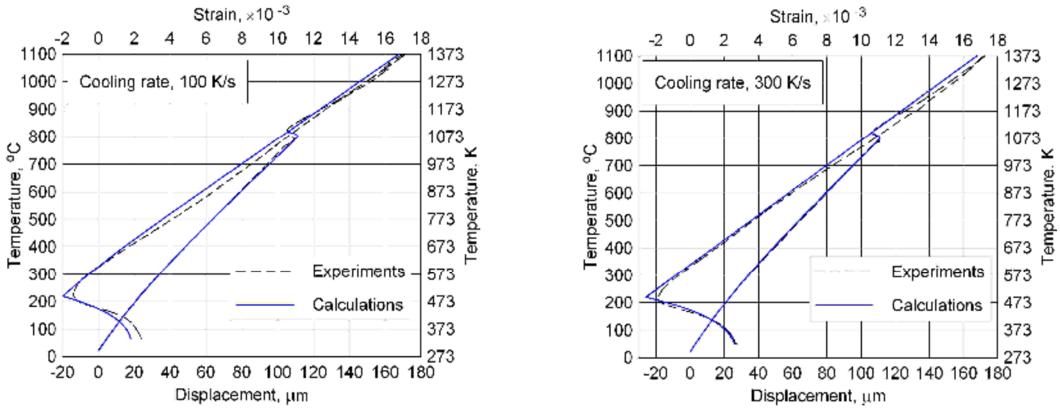

Fig. 2. Experimental and simulating dilatometric curves

The curves of CCT diagrams are introduced into a relevant module of phase fraction determination with supplementary information regarding maximum participation of each phase. However, in the model based upon the diagrams of continuous cooling relevant ranges determine the paces of cooling evaluated to the time when the temperature achieves the transformation starting curve.

In order to confirm the accuracy of the phase transformation model dilatometric tests were carried out on the samples of the steel under consideration. The model was verified by comparing the dilatometric curves received for different cooling paces with simulation curves.

On the basis of the analysis of the results a slight move of CCT diagram was made in order to reconcile the initiation time of the simulation transformation and the times obtained in the experimental research. These moves were presented, for example, in the studies [3].

On the basis of the analysis of simulation and dilatometric curves the values of the thermal expansion coefficient (α(.)) and isotropic structural deformations of each structural component were specified. These coefficients are: 22, 10, 10 and 14.5 ($\times 10^{-6}$) [1/K] and 0.9, 4.0, 8.5 and 1.9 ($\times 10^{-3}$). It was adopted that 1,2,3,4 and 5 refer to austenite, bainite, martensite and pearlite, respectively [2,3]. Exemplary comparisons of the simulation and experiment results are displayed in the figure 2. The transformation kinetics corresponding to the established speeds of cooling was presented in the figure 3.

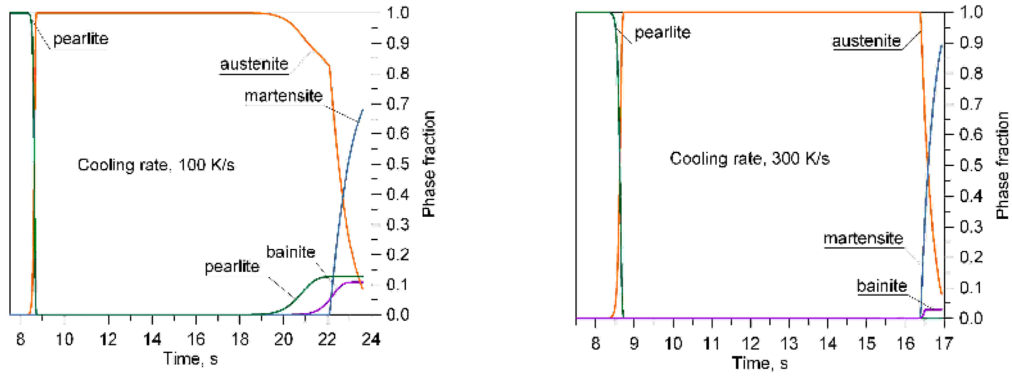

Fig. 3. Kinetics of phases for the fixed rates cooling

Analyse results from the model notice, that advantageous is use in modelling of phase transformations the CCT graph for considered group steel. Accuracy results, particularly in range rate cooling are obtain, in witch forming also bainite (Fig. 3).

Stresses and strains

In the model of mechanical phenomena the equations of equilibrium and constitutive relationship accept in rate form [6,9,10]:

$$\nabla \dot{\boldsymbol{\sigma}}(x_\alpha, t) = \mathbf{0},\ \dot{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}}^T,\ \dot{\boldsymbol{\sigma}} = \mathbf{D} \circ \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} + \dot{\mathbf{D}} \circ \boldsymbol{\varepsilon}^{\mathrm{e}}, \tag{14}$$

where: $\sigma=\sigma(\sigma_{\alpha\beta})$ is stress tensor, $D=D(\nu,E)$ is tensor of material constant (isotropic material), ν is Poisson coefficient, $E= E(T)$ is Young's modulus depend on temperature, whereas ε^e is tensor of elastic strain.

Assumption additives of strains, total strain in environment of considered point are equal:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^{Tph} + \boldsymbol{\varepsilon}^{tp} + \boldsymbol{\varepsilon}^p, \tag{15}$$

where: ε^{Tph} are isotropic temperature and structural strain, ε^{tp} are transformations plasticity, whereas ε^p are plastic strain. To mark plastic strain the non-isothermal plastic law of flow with the isotropic strengthening and condition plasticity of Huber-Misses were used. Plasticize stress is depending on phase fraction, temperature and plastic strain

$$Y\left(T, \eta, \varepsilon_{ef}^{\mathrm{p}}\right) = Y_0(T, \eta) + Y_H\left(T, \varepsilon_{ef}^{\mathrm{p}}\right), \tag{16}$$

where: $Y_0 = Y_0(T,\eta)$ is a yield points of material dependent on the temperature and phase fraction, $Y_H = Y_H\left(T,\varepsilon_{ef}^{p}\right)$ is a surplus of the stress resulting from the material hardening. Transformations plasticity estimate are by Leblond formula, supplement of decrease function (1-η(.)) propose by authors in work [5,8]:

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{tp}} = \begin{cases} 0, \ \eta_k \leq 0.03, \\ -3\sum_{k=2}^{k=5}(1-\eta_k)\varepsilon_{1\_k}^{ph}\dfrac{\mathbf{S}}{Y_1}\ln(\eta_k)\dot{\eta}_k, \ \eta_k \geq 0.03 \end{cases}, \tag{17}$$

where: $3\varepsilon_{1\_k}^{ph}$ are volumetric structural strains when the material is transformed from the initial phase „1" into the k-phase, ***S*** is the deviator of stress tensor, Y_1 is plasticize stress of initial phase (austenite), beside,

$$Y_1 = Y_1^0 + \kappa^Y \varepsilon_{ef}^{tp}, \tag{18}$$

Y_1^0 is yield points of initial phase, $\kappa^Y = \kappa^Y(T)$ is hardening modulus of material, a ε_{ef}^{tp} is effective transformations strain. Equations of equilibrium (14) solve by Finite Elements Method, and in range plasticization of material, iterative process modified method Newton-Raphson are perform.

Example

As it has been already mentioned, the simulations of hardening were subject the fang lathe of cone (axisymmetrical object) made of tool steel. The shape and dimensions considered object was presented on the figure 5. The superficial heating (surface hardening) the section of side surface of cone was modelling Neumann boundary conditions taken Gauss distributions of heating source:

$$q_n = \frac{Q}{2\pi r^2}\exp\left(-\frac{(z-h)^2}{2r^2}\right). \tag{19}$$

The peak value of heating source established on Q=4500 W, radius r=15 mm, angle α=30 (Fig. 7). The cooling of boundary contact with air was modelled boundary conditions (14) taking α_0=30 W/(m^{2}K) [9]. The initial structure was pearlite. The thermophysical values occurrence in conductivity equations (λ,C) was taken constant, averages values from passed in work data [9] suitable assumed: 35 [W/(mK)], 5.0×10^6 [J/(m3K)]. The heat of phase transformations was assumed on the work [9]: $H_{A\text{-}P}$=800×10^6, $H_{A\text{-}B}$=314×10^6, $H_{A\text{-}M}$=630×10^6 [J/(m^{3}K)]. The initial temperature and ambient temperature was assumed equal 300 K.

The heating performed to the moment of cross maximal temperature 1500 K in environment of heat source (point 2, Fig. 4). Provide this obtain requirements austenite zone in parts conic fang lathe. The temperature distributions after heating and obtained zone of austenite presented on the figure 5. The cooling simulated by flux results from the difference of temperature among side surface and cooling medium (Newton condition). The temperature of cooling medium is equal 300 K. The coefficient of thermal conductivity was constant and was equal α_T=4000 [W/(m^{2}K)] (cooling in fluid layer [11]). The cooling performed to obtain by object ambient temperature, and final of structures.

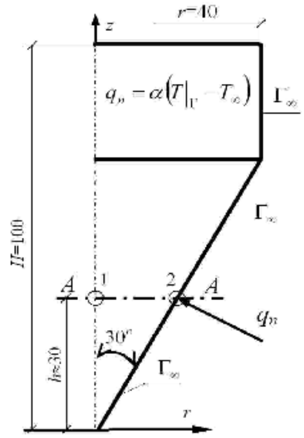

Fig. 4. Form and dimensions of the hardening object

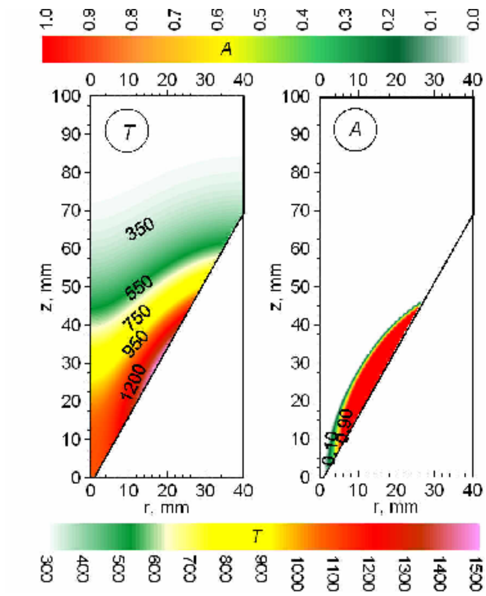

Fig. 5. Distributions: temperature a) and austenite b) after heating

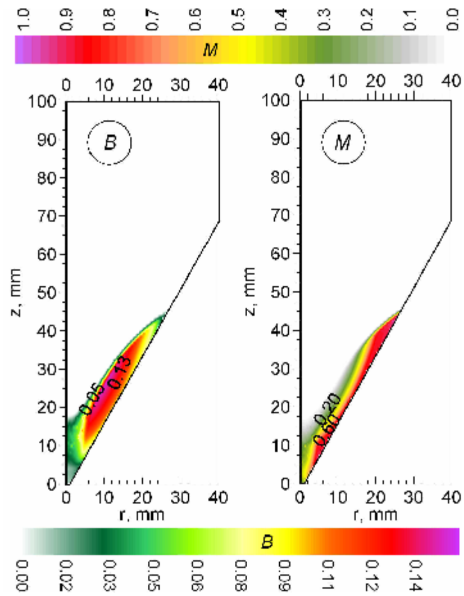

Fig. 6. Zones: bainite a) and martensite b) after quenching

The part of results (Fig. 7) along the radius (r) in cross section A-A and in distinguish points of cross sections (Fig. 4).

As it has been already mentioned, using of CCT diagrams within the cooling rate ranges wherein three transformations are observed: pearlitic, bainitic and martenisitic, guarantees more precise results. The results are shown in figures 8-9. The results of verification simulation of phase transformation kinetics (Fig. 3) prove that application of CCT diagrams enables good precise determination of fractions and kinetics of newly-created phases depending on the cooling rate. Therefore for simulating phase transformations in the object undergoing hardening of the calculation example (fang lathe) a model based upon CCT diagrams was used.

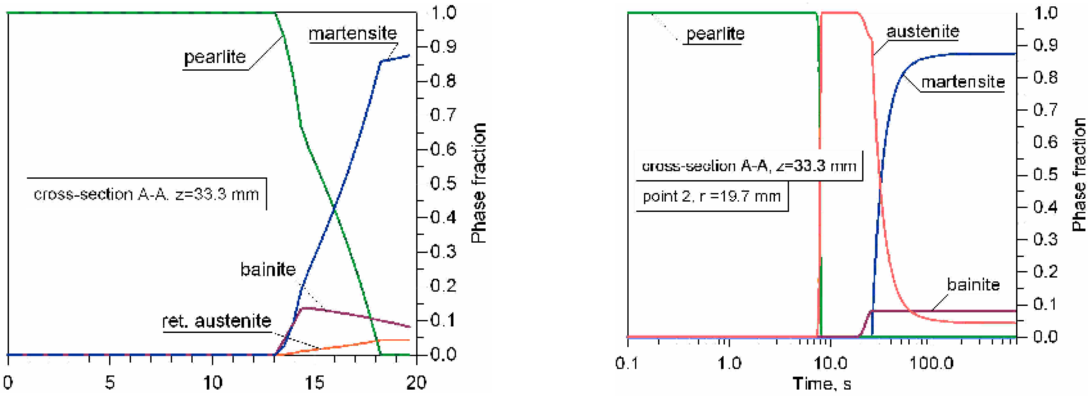

Fig. 7. Phase fractions along radius (cross section A-A) and their kinetics in point 2 (Fig. 4)

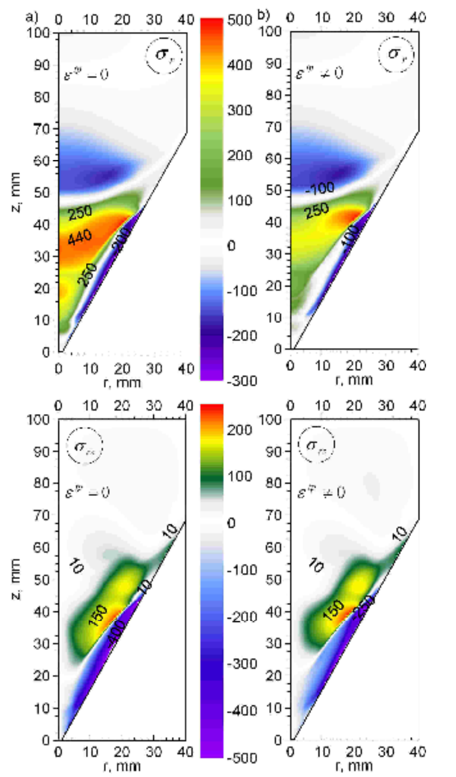

Fig. 8. Distributions of radial and tangential stresses: without a) and with b) transformations plasticity

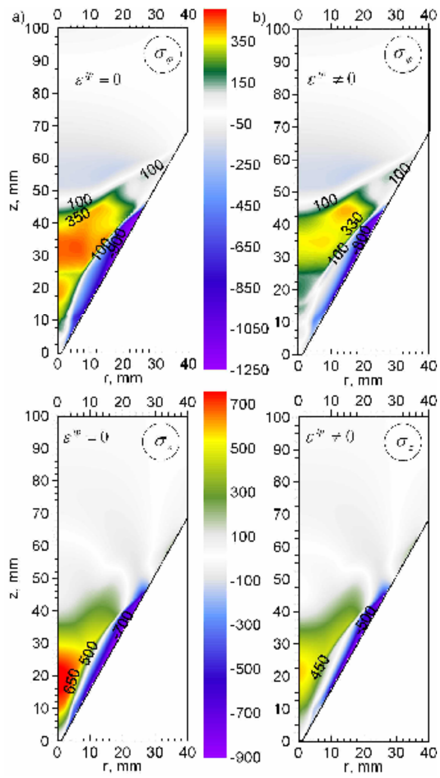

Fig. 9. Distributions of circumferential and axial stresses: without a) and with b) transformations plasticity

The simulations provide to very valuable distribution of temperature and good area of austenite deposition were obtained (Fig. 5). The hardened area after cooling appeared very beneficial, as well, which means that it is very well situated.

The structure of the area after hardening is very good (certain fraction of bainite and significant fraction of martensite) (Fig. 6). In the hardened zone a small fraction of residual austenite (approximately 5%) was received. The point of the lathe was not hardened at all.

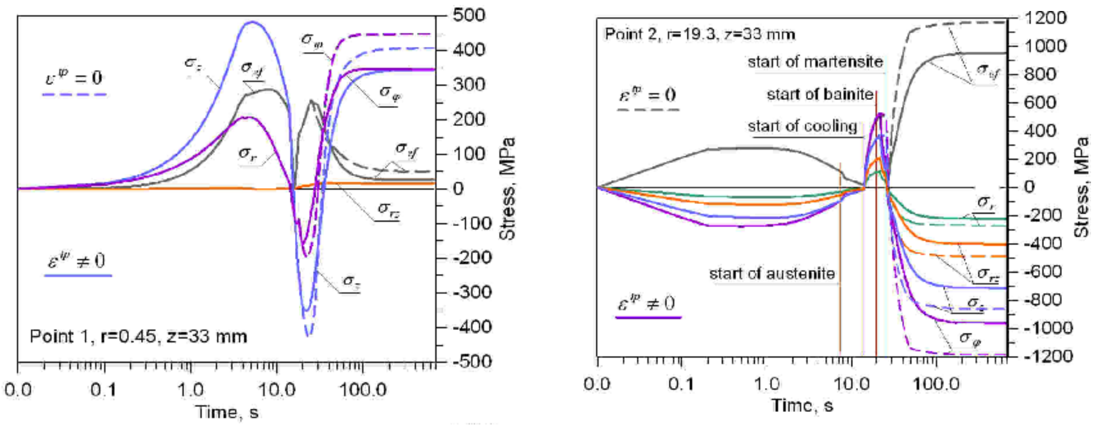

Fig. 10. History of temporary stresses in distinguished points of the cross section A-A

In the modelling of mechanical phenomena the Young's and tangential modulus (E i Et) was depend on temperature however the yield point (Y0) on temperature and phase fractions. The values approximated of square functions assumed: Young's and tangential modulus 2.2×105 and 1.1×104 [MPa] (Et=0.05E), yield points 150, 400, 800 and 270 [MPa] suitably for austenite, bainite, martensite and pearlite, in temperature 300 K. In temperature 1700 K Young's and tangential modulus average 100 and 5 [MPa] siutable, however yield points are equal 5 [MPa] [9].

Obtained results of simulations were presented on following figures. The part of results along the radius (r) in cross section A-A and in distinguish points of cross sections (Fig. 4).

The hardened area after cooling appeared very beneficial, as well, which means that it is very well situated. The structure of the area after hardening is very good (certain fraction of bainite and significant fraction of martensite) (Fig. 6). In the hardened zone a small fraction of residual austenite (approximately 5%) was received [13]. The point of the lathe was not hardened at all. It is very valuable from the practical point of view with respect to the purpose of such a machinery part. Distribution of stresses after such hardening is beneficial. Accumulation of stresses is observed only in the zone undergoing hardening and normal stresses are negative in the subsurface layer (Figs 8-9). There are almost no stresses in the lathe core and point (see Figs 8 and 9).

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ПРОГНОЗИРОВАНИЕ НАПРЯЖЕНИЯ ДЛЯ УЛУЧШЕНИЯ ТЕХНОЛОГИИ ЗАКАЛИВАНИЯ УГЛЕРОДИСТОЙ СТАЛИ

Представленная в работе численная модель процесса закалки инструментальной стали учитывает тепловые и механические явления. Модель фазовых превращений в твердом состоянии базируется на диаграммах непрерывного нагрева и охлаждения стали. Удельный объем фаз определяется по формулам Джонсона-Мэла-Аврами и Коистинена-Марбургера. Доля образующегося мартенсита определяется формулой Коистинена-Марбургера или модифицированной формулой Коистинена-Марбургера. Поля напряжения и деформации получаются из решения уравнения равновесия методом конечных элементов в скоростной форме. При определении временных и остаточных напряжений учитывается связь термофизических параметров между температурой и фазовым составом стали. Для определения пластических деформаций использовано условие Губера-Мизеса с изотропным упрочнением, в то время как для определения трансформационной деформации использовалась модифицированная модель Леблонда.

Ключевые слова: *фазовые превращения, закаливание, напряжения, численное моделирование.*

Т. Доманьскі

ПРОГНОЗУВАННЯ НАПРУГИ ДЛЯ ПОКРАЩЕННЯ ТЕХНОЛОГІЇ ЗАГАРТУВАННЯ ВУГЛЕЦЕВОЇ СТАЛІ

Представлена в роботі чисельна модель процесу загартовування інструментальної сталі враховує теплові явища, механічні та фазові зміни у твердому стані. У моделі фазових змін використовуються графіки безперервного нагрівання, а також графіки безперервного охолодження розглянутої сталі. Частка перетвореної фази (аустеніту) і частки фериту, перліту або бейніту визначаються формулами Джонсона-Мела і Аврамі. Частки утворюваного мартенситу визначаються формулою Коістінена-Марбургера або модифікованою формулою Коістінена-Марбургера. Поля напруги і деформації отримують із рішення рівняння рівноваги методом кінцевих елементів у швидкісній формі. Теплофізичні константи, що входять у конститутивних зв'язках, обумовлені температурою і фазовим складом. Для визначення пластичних деформацій було використано умову Huber-Мізеса з ізотропним зміцненням, в той час як для визначення трансформаційної деформації використовувалась модифікована модель Леблонда.

Ключові слова: *фазові зміни, загартовування, напруженість, чисельне моделювання.*