Papers submitted to the Conference "Applications of Physics in Mechanical and Material Engineering"

Analysis of Physical and Structural Properties during Modelling of the Heating and Cooling Process of the Steel Ring

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The paper describes the physical aspects of modelling a moving heat source on the outer surface of a steel ring. The work concerns numerical modelling of thermal and structural phenomena in spiral laser heating and cooling in any coolants. The numerical analysis performed in the Abaqus/FEA software was developed to predict the size and quality of the hardened zone. The power distribution and spiral motion of the moving heat source are implemented in an additional DFLUX subroutine (Fortran). The results of the numerical simulation include the temperature field and the predicted zone hardened at different cooling rates. They are the starting point for the analysis and selection of parameters when modelling the hardening process, taking into account phase transformations in the solid state.

topics: hardening, Abaqus, phase transformations

1. Introduction

The paper presents the results of a numerical simulation of the circumferential hardening of the side surface of the ring made in accordance with DIN 988 of S355 steel with a heat source simulating laser heating. Numerical tests were carried out in the Abaqus FEA program. The program includes a discrete model of the analysed heated zone. In the material module of the Abaqus CAE program, thermal properties that vary with temperature are defined [1]. The implementation of additional numerical procedures made it possible to model the movement of the laser beam along the perimeter of the object. On the basis of the performed numerical calculations, the temperature distribution in the heated zone and the thermal cycles in the characteristic points of the cross-section were determined. The results of the phase composition kinetics for two cooling conditions, in the air medium and in water, are presented.

2. Model of phase transformations

The cooling diagram (CCT) was used in the phase transformation model. Initial phase transformation in the austenite is diffusive. The kinetics of the transformation is well defined the Johnson–Mehl–Avrami formula [2, 3], i.e.,

$$\eta_A^H\,(T,t) = 1 - \exp\Big[-b\,(t_s,t_f)\;t^{n(t_s,t_f)}\,(T)\Big], \qquad (1)$$

where η_A^H is the austenite initial fraction nascent in heating process, $b(t_s,t_f)$ and $n(t_s,t_f)$ are coefficients determined from the transformation (1) assuming the initial fraction ($\eta_s(t_s)=0.01$) and final fraction ($\eta_f(t_f)=0.99$) forming a phase, and t_s and t_f are the initial and final times of the transformations. Pearlite and bainite fractions (in the model of phase transformations upper and lower bainite is not distinguish) are determined by the Johnson–Mehl–Avrami formula, taking into account the fraction of the austenite phase formed in the heating process, i.e.,

$$\begin{aligned} \eta_{(\cdot)}\,(T,t) = {}& \psi\Big(1-\exp\big(-b\,t^n(T)\big)\Big)\psi = \eta_{(\cdot)}^{\%}\eta_A^H \\ & \text{for } \eta_A \geq \eta_{(\cdot)}^{\%} \\ \psi = \eta_A^H \quad & \text{for } \eta_A^H < \eta_{(\cdot)}^{\%} \end{aligned} \qquad (2)$$

where $\eta_{(\cdot)}^{\%}$ is the maximum phase fraction for the established value of the cooling rate, estimated on the base of the continuous cooling graph [4].

The fraction of martensite forming below the temperature M_s is determined by the Koistinen and Marburger formula [5]

$$\eta_M\,(T) = \psi\Big(1-\exp\big(-k(M_s-T)^m\big)\Big), \qquad (3)$$

where m is a constant chosen by means of experiment (for the considered steel $m = 1$), whereas the constant k is determined from (3) at the end of transformation condition at the temperature M_f (for $\psi = 1$), i.e.,

$$k = -\frac{\ln\left(1-\eta\left(M_f\right)\right)}{M_s - M_f} = -\frac{\ln\left(0.01\right)}{M_s - M_f} \tag{4}$$

With respect to the considered steel, for which $M_s = 413$ K, $M_f \approx 255$ K, the constant k resulting from (4) is $k = 0.0144$. The obtained coefficient is comparable to the value given in literature [4] with respect to carbon steels ($k \approx 0.011$).

3. Mathematical and numerical model

The heat flow equation in the Abaqus program is found on the basis of the energy conservation equation and Fourier law, expressed by the criterion of weighted residuals method. The equation is as follows [5, 6]

$$\int_V \mathrm{d}V\,\rho\frac{\partial U}{\partial t}\delta T + \int_V \mathrm{d}V\,\frac{\partial \delta T}{\partial x_j}\cdot\left(\lambda\frac{\partial T}{\partial x_j}\right) = \int_V \mathrm{d}V\,\delta T\,q_V + \int_S \mathrm{d}S\,\delta T\,q_S, \tag{5}$$

where λ is thermal conductivity [W/(m °C)], $U = U(T)$ is internal energy [J/kg], q_v is laser beam heat source [W/m^3], $T = T(x_j, t)$ is temperature [°C], q_s is boundary heat flux [W/m^2], δT is variational function, ρ is density [kg/m^3], V is volume [m^3], S is surface [m^2], $T = T(x_j, t)$ is temperature [°C], and $j = 1, 2, 3$

It is worth noting that (5) is completed by the initial conditions and boundary conditions of the Dirichlet and Neumann types [6], while the heat exchange with the environment is governed by Newton's law, which takes into account the loss of heat by convection, radiation and evaporation. In the literature on the numerical modelling of the laser beam hardening process, the Gaussian mathematical model [7] of the volumetric heat source is most often adopted to describe the power distribution of the welding source (6). This model takes into account the linear decrease of energy density along material penetration depth

$$q_v(r,z) = \frac{Q}{\pi\,r_0^2 h}\left(1-\frac{z}{h}\right)\,\mathrm{e}^{(1-r^2/r_0^2)}, \tag{6}$$

where Q is laser beam power [W], h is the laser heat source penetration depth [m], z is actual depth [m], r_0 is beam radius, and r is actual radius [m], where $r = \sqrt{x^2+y^2}$.

In Abaqus FEA, the moveable heating source is simulated using an additional DFLUX numerical subroutine written in the Fortran programming language. The subroutine takes into account the power distribution of the beam, its location, beam translation and of motion direction. The location of the centre of the source is determined for each time step depending on the adopted source velocity. The three-dimensional discrete model (Fig. 1) of the analysed object was developed in the Abaqus FEA program. The considered object is a ring made of S355 steel, with an outer diameter of 20 mm, an inner diameter of 14 mm, and height $h = 2$ mm. The study analysed the influence of cooling parameters on the size of the hardened zone and the structural composition in the cross-section. For the heating process, the following values were taken: beam power $Q = 500$ W and source speed $v = 1.775$ m/min. Based on the numerical verification, in the case of heating, the beam radius was taken to be $r = 1.0$ mm, and the penetration depth — $h = 2$ mm. The location of the heating source on the outer surface of the ring depends on the adopted heating velocity and time. The analysis is carried out in polar coordinates transposed into the Cartesian system

$$\begin{cases} x = R_z\sin(\phi_0 + \omega\,t), \\ y = R_z\cos(\phi_0 + \omega\,t), \\ z = z_0, \end{cases} \tag{7}$$

where R_z is outer radius of the shaft [m], t is time [s], ϕ_0 is the angle of the initial position of heat source on the outer shell, ω is angular velocity, and z_0 is initial position on the axis z.

Figure 2 shows the numerical model with finite element mesh, cross-section points 1–6 are marked. Numerical calculations were performed using the finite element method. First, calculations of thermal

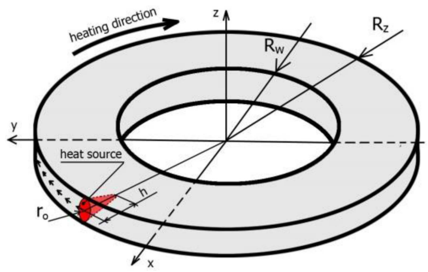

Fig. 1. Diagram of the analysed object.

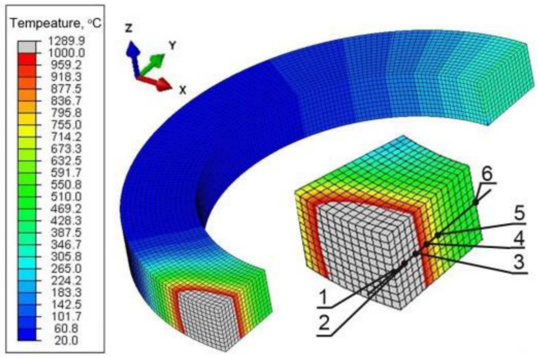

Fig. 2. The distribution of temperature after time 2 s.

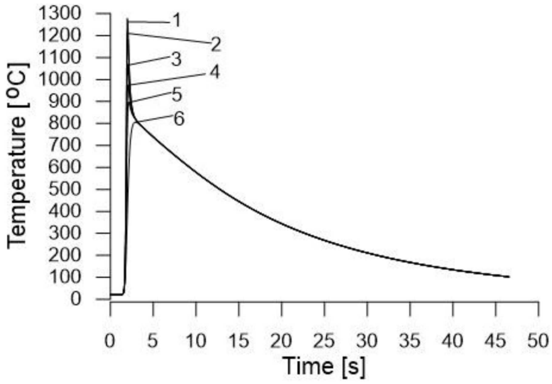

Fig. 3. Thermal cycle in cross-sectional points-cooling in air.

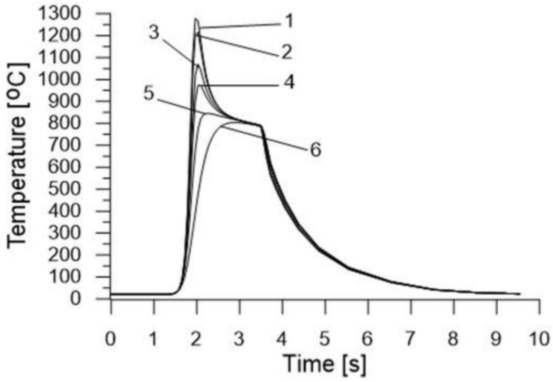

Fig. 4. Thermal cycle in cross-sectional points-cooling in water.

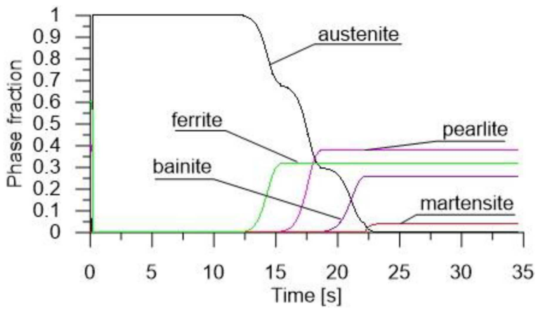

Fig. 5. Kinetics of phase transformations, cooling in air — point 1.

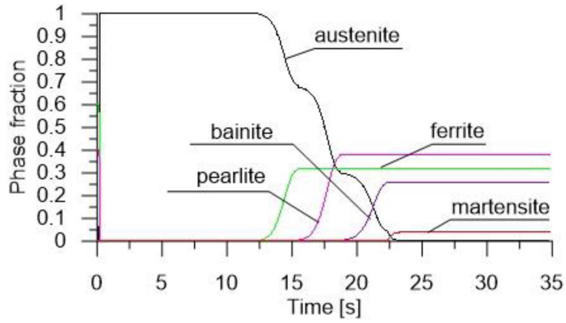

Fig. 6. Kinetics of phase transformations, cooling in air — point 6.

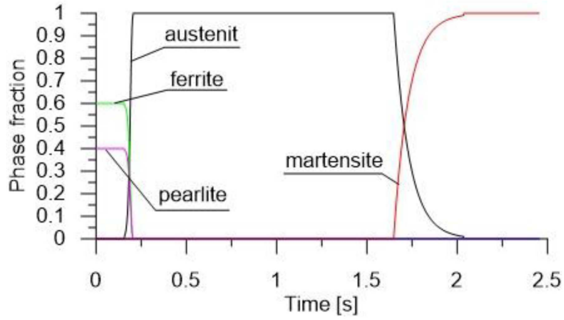

Fig. 7. Kinetics of phase transformations, cooling in water — point 1.

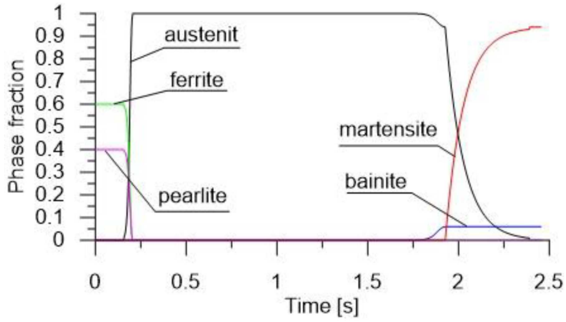

Fig. 8. Kinetics of phase transformations, cooling in water — point 6.

phenomena were performed and then the kinetics of phase changes were estimated. The temperature distribution in the middle of the heating process is shown. The area above the A_{c3} austenitization temperature is presented in gray.

4. Results and discussion

The 355 steel material model was included in the Abaqus material module. The calculations took into account variables such as temperature and thermo-mechanical properties of the adopted steel grade. The ambient temperature was $T_0 = 20$°C and the assumed heat transfer coefficient in the air was $\alpha = 0.15$ W/(cm^2 K), and in the water environment — $\alpha = 0.55$ W/cm^{2}K.

Figures 3 and 4 show the temperature distribution over time in the characteristic points of the cross-section for cooling in air and in water, respectively.

Figures 5 and 6 show the kinetics of phase transformations for the extreme points of the cross-section.

Figures 7 and 8 show the kinetics of phase transformations for the extreme cross-sectional points when the cooling medium was water.

5. Conclusions

From the comparison of the calculated phase fractions in the points during cooling in different mediums (Figs. 5–8), it can be seen that the model showed well and precisely the differences in the final structure. On the basis of the developed model, it is possible to estimate the temperature and phase change distributions in hardened objects of any diameter. The presented results are the basis for the development of a model that allows the estimation of the mechanical properties of hardened elements. The parameters of the heating source simulating laser heating, adopted during the analysis, allowed to obtain appropriate temperature distributions enabling the surface layer to harden at a depth of 2 mm. The developed model can be successfully used in modelling the structural and mechanical phenomena in thermal processes of steel.

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