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Application of JM®-Test in 3D simulation of quenching

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Analysis and modelling

ABSTRACT

Purpose: Simulation of hardness distribution in quenched steel specimen has been investigated using 3D numerical formulation. Structural mesh has been used in numerical simulation. Numerical calculations of hardness distribution in specimen made of high hardenability steel have been performed in order to define appropriate steel for manufacturing of machine part. Possibility of application of numerical model based on experimental results in steel quenching has been investigated.
Design/methodology/approach: Numerical simulation of the steel quenching is consisted of computation of cooling curve during the quenching and prediction of hardness at specimen points after the quenching. Hardness at specimen points is estimated by the conversion of cooling time results to hardness. Conversion is provided by the relation between cooling time and distance from the quenched end of Jominy-specimen. In this way the numerical simulation has been combined with experimental Jominy-test.
Findings: Structure transformation and hardness distribution can be successfully estimated based on time, relevant to structure transformation. Relevant time for quenching results for most structural steels is cooling time from 800 to 500 °C (t8/5).
Research limitations/implications: Since high hardenability of investigated steel there are limits in application of original Jominy-specimen in simulation of quenching of steels. The modified Jominy-test enables cooling time, t8/5 higher than Jominy-test.
Practical implications: The simulation of quenching based on modified Jominy-test can be applied for steels with higher hardenability. This method of simulation is especially suitable for tools and dies steels. 3D numerical simulation of quenching is more confident in practical implementation and provides more information than 2D formulation.
Originality/value: Using the results of simple experimental test, i.e., modified Jominy-test in numerical modeling of steel quenching it is possible to achieve better results of hardness simulation.
Keywords: Numerical techniques; 3D modeling; Steel quenching

1. Introduction

Mathematical modelling of hardness distribution in quenched steel specimens is consisted of numerical simulation of specimen cooling, numerical simulation of specimen hardening and respectively prediction of mechanical properties [1]. For the simulation of specimen cooling which is thermodynamical problem, it is necessary to establish the appropriate algorithm which describes cooling process, and it is necessary to accept appropriate input data.

The accuracy of mathematical modelling of quenching directly depends on the correctness of input variables applied in the model. Experimentally acquired heat transfer data have advantages in specific conditions but numerical simulation of quenching with the application of calibrated heat transfer data is a generalized way of simulation and is largely applicable. Calibrated data are not as precise as experimentally acquired data but they are useful for large spectra of specimen dimensions [2].

Structure composition can be defined by kinetic equations of prior structure transformation or can be estimated by using CCT diagrams [3]. Structure transformation and hardness distribution can be also estimated based on time, relevant to structure transformation [4]. Mechanical properties of quenched steel can be estimated according to prediction of structure composition.

2. Simulation of specimen cooling

The temperature field change in an isotropic rigid body with coefficient of heat conductivity λ, density ρ and specific heat capacity c, without heat sources [5], can be described by Fourier's law of heat conduction:

$$\frac{\delta(c\rho T)}{\delta t} = \mathrm{div}\lambda\ \mathrm{grad}T \quad (1)$$

Characteristic initial condition is:

$$-\lambda \left.\frac{\delta T}{\delta n}\right|_s = \alpha(T_s - T_f) \quad (2)$$

where: T_s is surface temperature (K), T_f is quenchant temperature (K), α is heat transfer coefficient ($Wm^{-2}K^{-1}$).

The discretization equation for a 3D situation was established by using the final volume method [6] and is equal:

$$T^1_{ijk}\left[\sum_{m=1}^{2} b_{(i,i+n)jk} + \sum_{m=1}^{2} b_{i(j,j+n)k} + \sum_{m=1}^{2} b_{ij(k,k+n)} + b_{ijk}\right] = \sum_{m=1}^{2}\left(b_{(i,i+n)jk}T^1_{(i,i+n)jk} + b_{i(j,j+n)k}T^1_{i(j,j+n)} + b_{ij(k,k+n)}T^1_{ij(k,k+n)} + b_{ijk}T^0_{ijk}\right) \quad (3)$$

$$i=1,2,\dots i_{max};\quad j=1,2,\dots j_{max};\quad k=1,2,\dots k_{max} \quad n=3-2m$$

3. Computer simulation of hardness based on cooling time (t8/5)

Numerical calculations of hardness distribution in specimen made of steel X210Cr12 (DIN) have been performed in order to define appropriate steel for manufacturing of machine part. Steel specimen is shown in Figure 1.

The specimen was quenched in oil with Grossman's H-value H=0.25 with austenitization temperature 850 °C.

Experimentally evaluated Jominy results of investigated steel X210Cr12 are shown in Table 1 [4].

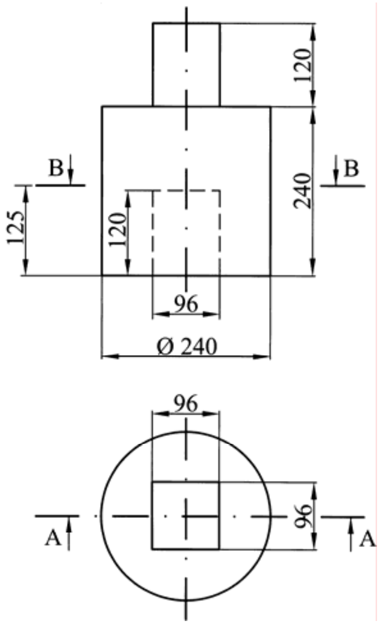

Fig. 1. Steel specimen

The correlation between coefficients of heat transfer and temperature is appointed by Crafts-Lamont's diagrams [7].

Table 1.
Jominy Test Results of Steel X210Cr12

Distance, mm	2,5	5	10	15	20	30	40	60
Hardness, HRC	64	64	64	64	64	64	63	63

Values of heat conductivity coefficient vs. surface temperature are shown in Figure2.

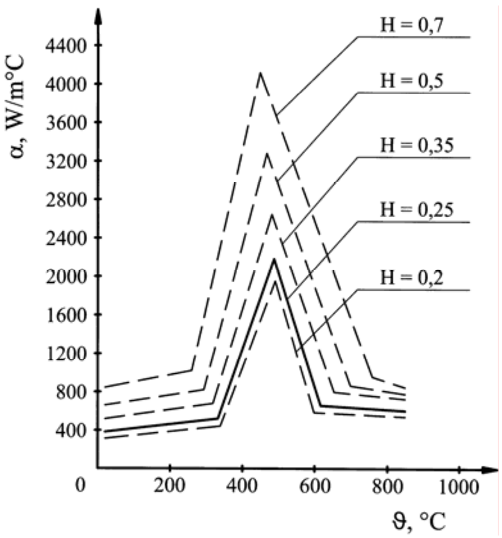

Fig. 2. Calibrated values of heat transfer coefficient α vs. temperature

4. Hardness distribution in quenched steel specimen

The structural transformations and hardness distribution can be estimated based on time, relevant for structure transformation. The characteristic cooling rate, i.e., cooling time from 800 to 500 °C, $t_{8/5}$ is very important for most structural steels [4]. Usually, if the cooling time from 800 to 500 °C, $t_{8/5}$ is equal in two different specimens, hardness of two these specimens are equal. Hardness at specimen points is estimated by the conversion of cooling time results to hardness. This conversion is provided by the relation between cooling time and distance from the quenched end of Jominy-specimen (Figure 3) [4].

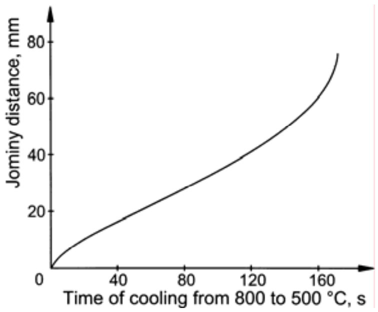

Fig. 3. Distance from the quenched end of Jominy-specimen vs. cooling time from 800 to 500 °C

Jominy-test is suitable for application in computer simulation of quenching when maximal cooling time, $t_{8/5}$ is lower than 200 s [8]. Since high hardenability of investigated steel and since maximal cooling time, $t_{8/5}$ in investigated specimen is higher than 200 s, Jominy-test is not suitable for application in computer simulation of quenching.

To achieve cooling times, $t_{8/5}$ higher than 200 s, the JM® - specimen is designed for high hardenability steel [9] [10]. The JM® - specimen can be used in similar manner for hardness prediction in simulation of quenching of high hardenability tool steel as Jominy-specimen in simulation of quenching of structural low alloyed steels [11] [12]. JM® - specimen is shown in Figure 4.

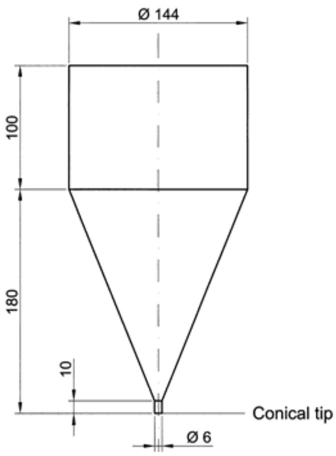

Fig. 4.- Modified JM®-specimen

JM® results of investigated steel X210Cr12 are shown in Table 2.

Table 2.
JM®-test result of Steel X210Cr12

Distance, mm	2	11	21	32	59	89	115	160
Hardness, HRC	64	63	62	59	49	42	39	39

If the hardness of quenched steel workpieces could be estimated using the time of cooling, $t_{8/5}$ in actual location of investigated workpiece and JM® - specimen, kinetics of microstructure transformation during the cooling must be similar in the JM® - specimen and actual steel workpieces for which the hardness is to be determined [13] [14]. Figure 5 shows the cooling times from 800 to 500 °C at the depth of 0.8 mm from the surface of the JM®-specimen [15].

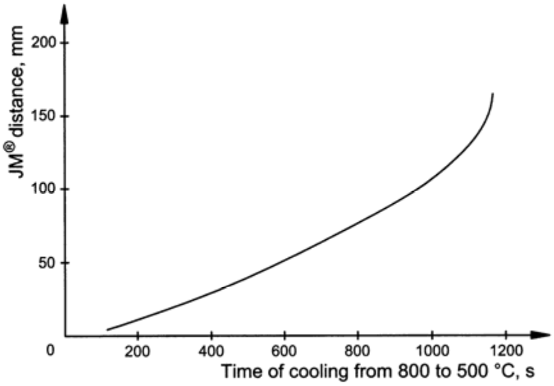

Fig. 5. Distance from the conical tip of JM®- specimen vs. cooling time from 800 to 500 °C

Hardness distribution on transversal view B-B and longitudinal view A-A are shown in Figures 6 and 7 for steel X210Cr12. Hardness values are expressed in HRC. Figures are accompanied with legend which shows relation between hardness and adequate colour.

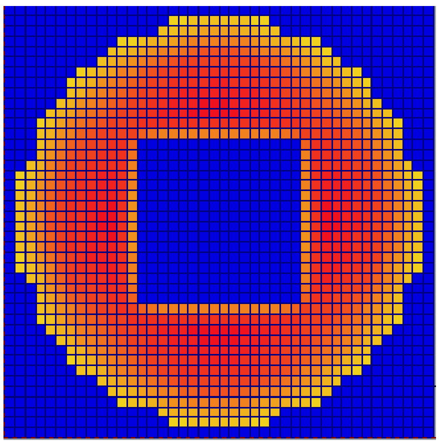

Fig. 6. Hardness distribution on view B-B (Steel X210Cr12)

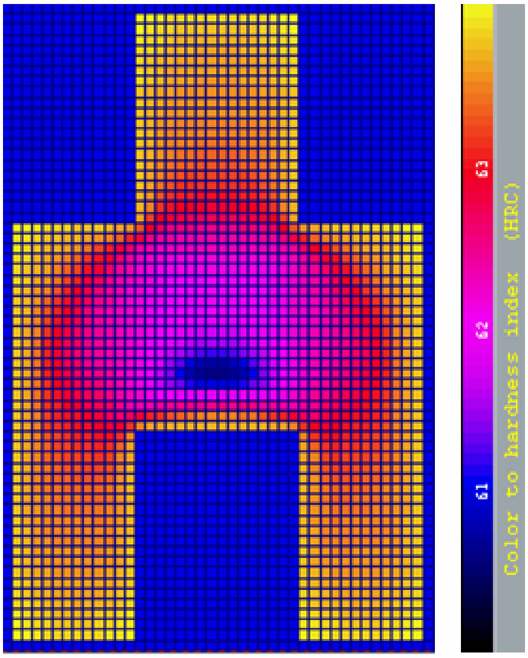

Fig. 7. Hardness distribution on view A-A (Steel X210Cr12)

Numerical simulation of as-quenched hardness distribution in specimens made of steel X210Cr12 shows that investigated specimen is completely quenched.

5. Conclusions

3D mathematical model of hardness distribution in steel specimen is developed in order to define hardness distribution in steel specimen with complex shape. Model is based on control volume method and consisted of numerical simulation of heat transfer during the cooling and of numerical simulation of specimen hardening. Input variables are estimated by inverse method. Heat transfer data estimated in such way are suitable for computer simulation of quenching of steel before selecting optimal material and processes.

The modified Jominy-test enables higher cooling time, $t_{8/5}$ and enable application in simulation of quenching for steel with higher hardenabilty. The modified Jominy-test can be applied in simulation of quenching of steel with higher hardenability rather than original Jominy-test.

Numerical simulation of as-quenched hardness distribution in specimens made of steel X210Cr12 shows that investigated specimen is completely quenched. According to these results it can be concluded that the steel X210Cr12 is good choice for manufacture of investigated machine part by quenching in oil.

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