



Deyneko L.,
Kobasko N.

SIMPLIFIED METHOD OF FORECASTING THE INFLUENCE OF COOLING INTENSITY DURING HARDENING ON THE MECHANICAL PROPERTIES OF STEEL PRODUCTS

The object of research is the structure and mechanical properties of steel at the central points of hardened products. In this work, a technique has been developed based on comparing the cooling rate in the central region of the product with the cooling rate of a test sample with a diameter of 5–6 mm, investigated in laboratory conditions. By this time, this approach was not possible, since two main problems had not been resolved. The transition from a small sample to a real product during quenching was scientifically unreasonable due to the great complexity of the problem. There were no known mathematical relationships for calculating the cooling rate when quenching products of arbitrary shape in liquids. Recently, these problems have been solved and steel with optimal hardenability has appeared, which can be cooled very quickly. This simplified the solution to this problem. The technique developed in this work helps to temper metal products in such a way that there are large compressive residual stresses on the surface, and in the middle there is a bainite structure of high strength and increased toughness. This allows to increase the service life of hardened products, reduce the percentage of alloying elements, and also maintain a clean environment. In this regard, based on the achievements of science in recent decades, a method is proposed for predicting the structure and mechanical properties of steel during quenching of real parts. This technique can be used to increase the durability of machine parts and tools. The work also notes the prospects of using aqueous solutions of low-concentration polymers for intensive hardening of steel products. In this case, when simulating the cooling rate during quenching of real products, test samples are quenched in aqueous solutions of the same polymers of increased concentration in order to form a stable vapor film. The stable vapor film ensures a stable heat transfer coefficient. This increases the accuracy of modeling and expands the capabilities of the proposed calculation method.

Keywords: method of modeling the structure formation, bainitic and martensitic transformations, heat treatment, high strength.

Received date: 30.04.2020

Accepted date: 26.05.2020

Published date: 31.08.2020

Copyright © 2020, Deyneko L., Kobasko N.

This is an open access article under the CC BY license

(<http://creativecommons.org/licenses/by/4.0>)

1. Introduction

The main idea of this work is to combine advances in the fields of bainitic and martensitic transformations based on effective control of phase transformations in the core of hardened products. Great achievements have been obtained in the strengthening of rolled products, where the main emphasis is on achieving a high-strength and plastic bainitic structure [1, 2]. At present, special attention is paid to bainitic transformations, since the bainitic structure provides higher strength and plastic properties of the material than the martensitic structure of the material can provide [3]. When discussing this important problem with the author of [3], it turned out that to obtain a bainitic structure, it is necessary to apply rapid cooling in order to avoid pearlite transformations. As a rule, upon rapid cooling, martensite immediately appears on the surface of the items to be hardened instead of bainite. Therefore, in most cases, to obtain a viscous bainitic structure, expensive isothermal quenching in baths is carried out at a temperature equal to or higher than

the temperature of the onset of the martensitic transformation M_s . In this case, alloyed and high-alloyed steels are used. The bainitic structure along the entire section of the product under conditions of rapid cooling can be obtained by quenching steels in liquid media under pressure [4]. But such a process is expensive and requires the manufacture of special equipment. This problem is easily solved by combining both directions. As is known, during the quenching of steels with low hardenability, a thin layer of martensite appears on the surface of products, while the core remains viscous, consisting of bainite and pearlite [5–7]. This leads to the creation of compressive stresses on the surface of hardened parts [8, 9]. Moreover, the authors of [10–12] have shown by computer simulation that intense hardening creates high compressive stresses on the surface of products and super-strengthens the material. Very important experiments by the authors of [13–15] have confirmed this. This leads to significant savings in alloying elements. Therefore, in studies [16, 17], a steel with optimal hardenability was developed and a quenching medium for its hardening was proposed, which

is a 1 % aqueous solution of a polymer of reverse solubility. These achievements have been discussed internationally in leading physics journals [18, 19].

When choosing a cooling mode for metal products in the implementation of hardening heat treatment, the following main criteria are traditionally guided by the choice of a cooling medium:

- requirement for the absence of any vapor film during the hardening process, which creates a uniform and intensive cooling of steel products [10];
- economic feasibility of implementing the selected development, which is primarily due to the cost of the cooling medium and its operation;
- manufacturability of the cooling medium, which is determined by the following main parameters: operating temperature; acceptable concentration of components (for various aqueous cooling media); the ability to monitor the cooling capacity of the medium;
- environmental safety of the cooling medium during its preparation, operation and disposal;
- fire safety during storage and operation.

An increase in the degree of metal alloying or the use of additional technologies for surface hardening of the working surfaces of metal products (in addition to traditional types of heat treatment) significantly increases the cost and complicates the technology of their manufacture. Saving metal became possible due to the discovery of the phenomenon of super-hardening of steel during intense hardening [17, 18]. And also the formation of high compressive residual stresses on the surface of heat-strengthened products has been proven [19, 20].

To control the microstructure and mechanical properties of steel in the center of hardened products, it is necessary to cut the hardened part and make test samples from the core of the material. This is a very expensive and painstaking job. Therefore, it is relevant to accurately predict the structure and mechanical properties in the center of hardened products.

Long-term studies of the authors [3, 17, 20] have created the basis for the implementation of such forecasts. Thus, *the object of research* is the structure and mechanical properties of steel at the central points of hardened products. *The aim of this research* is to develop a technique for modeling the processes of phase transformations in the center of hardened large products in laboratory conditions.

2. Methods of research

During the study, samples with a diameter of 5–6 mm are used, which are cooled in the laboratory at a rate equal to the cooling rate in the center of large items during quenching.

This paper discusses studies in relation to technologies of hardening heat treatment of various metal products, in which water or aqueous solutions of polymers of very low concentration are used as a quenching medium. To optimize the proposed approach, the authors propose a new

simplified technique for studying the effect of cooling intensity under conditions of hardening heat treatment on the mechanical properties of steel products. The essence of the new technique is outlined below.

3. Research results and their discussion

3.1. Simplified method for predicting the mechanical properties of the material in the core of hardened products.

To predict the strength properties of the material in the core of large products, it is necessary to create conditions for cooling test samples equal to those for cooling the core of products. It is enough to calculate the cooling rate of the core of large products and the cooling rate of samples and create conditions for their equality.

The proposed calculations are based on the theory of thermal conductivity and the theory of regular thermal regime [21, 22].

To carry out such calculations Tables 1–3 show the thermophysical properties of copper, silver and supercooled austenite, which are used in this research.

Table 1

Thermal conductivity λ of supercooled austenite depending on temperature

$T, ^\circ\text{C}$	100	200	300	400	500	600	700	800	900
Present value $\lambda, \text{W/mK}$	17.5	18	19.6	21	23	24.8	26.3	27.8	29.3
Average value $\bar{\lambda}, \text{W/mK}$	17.5	17.75	18.55	19.25	20.25	21.15	21.90	22.65	23.4

Table 2

Thermal conductivity λ of copper and silver as a function of temperature

$T, ^\circ\text{C}$	0	100	200	400	600	800	900
Copper, W/mK	393.1	384.9	380	365	353.5	340.8	333
Silver, W/mK	410.5	392	372	362	374.5	–	–

Table 3

Thermal diffusivity of subcooled austenite depending on material temperature

$T, ^\circ\text{C}$	100	200	300	400	500	600	700	800	900
$a \times 10^{-6} \text{ m}^2/\text{s}$	4.55	4.63	4.70	4.95	5.34	5.65	5.83	6.19	6.55
$\bar{a} \times 10^{-6} \text{ m}^2/\text{s}$	4.55	4.59	4.625	4.75	4.95	5.10	5.19	5.37	5.55

To calculate the cooling rate of test samples and real parts, let's use the generalized dependence (1), which is valid for any size and shape of products [11, 21, 22]:

$$v = \frac{aKn}{K}(T - T_m), \quad (1)$$

where v – cooling rate; a – coefficient of thermal diffusivity of steel; Kn – Kondratiev number; K – Kondratiev form factor in m^2 ; T – current temperature; T_m – temperature of the quenching bath.

Since the cooling process must be interrupted, below is also a generalized relationship (2) for calculating the cooling time for products of various configurations under different heat transfer conditions [11, 12]:

$$\tau = \left[\frac{kBi_v}{2.095 + 3.867Bi_v} + \ln \frac{T_0 - T_m}{T - T_m} \right] \frac{K}{aKn}, \quad (2)$$

where

$$Bi_V = \frac{\alpha}{\lambda} K \frac{S}{V},$$

where τ – cooling time in seconds; Bi_V – dimensionless generalized Biot number; $k=1, 2, 3$ – coefficients for bodies of plate, cylindrical and spherical shape; α – heat transfer coefficient; λ – thermal conductivity of steel; S – surface; V – volume.

$$Kn = \frac{Bi_V}{(Bi_V^2 + 1.437Bi_V + 1)^{0.5}} \tag{3}$$

The author of [20] proposes a criterion for intense cooling (4), at which both film boiling and unsteady nucleate boiling during quenching in liquid media are absent:

$$Bi = \frac{2(\vartheta_o - \vartheta_I)}{\vartheta_I + \vartheta_{uh}}, \tag{4}$$

where

$$\vartheta_I = \frac{1}{\beta} \left[\frac{2\lambda(\vartheta_o - \vartheta_I)}{R} \right]^{0.3}, \tag{5}$$

where $\vartheta_I = T_I - T_S$; $\vartheta_o = T_o - T_S$; $\beta = 3.41$; R – radius; T_I – surface temperature at the beginning of nucleate boiling; T_o – initial temperature; T_S – saturation temperature.

When quenching sheet metal, well-known data on the effect of pressure in a sprayer on the intensity of convective heat transfer can be used (Fig. 1) [23].

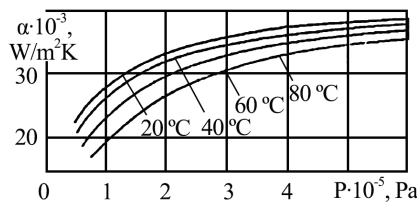


Fig. 1. Convective heat transfer coefficient versus pressure in a sprayer for water at temperatures of 20 °C, 40 °C, 60 °C and 80 °C [23]

Let’s consider the cooling rate of 20 mm thick sheet products. To do this, first determine the value ϑ_I :

$$\vartheta_I = \frac{1}{3.41} \left[\frac{2 \cdot 23(760 - \vartheta_I)}{0.01} \right]^{0.3} = 27 \text{ }^\circ\text{C}.$$

Then let’s determine the criterion for direct convective heat transfer during quenching of a 20 mm thick sheet:

$$Bi = \frac{2(\vartheta_o - \vartheta_I)}{\vartheta_I + \vartheta_{uh}} = \frac{2 \cdot (760 - 27)}{(27 + 80)} = 14.$$

According to this criterion, film and nucleate boiling will be absent if the convective heat transfer coefficient is 32000 W/m²K:

$$\alpha = \frac{\lambda Bi}{R} = \frac{23 \cdot 14}{0.01} = 32200 \text{ W/m}^2\text{K}.$$

Having these data, let’s determine the generalized Biot number and the Kondratiev number, which are equal:

$$Bi_V = 0.346Bi = 0.346 \cdot 14 = 4.83;$$

$$Kn = 0.86.$$

The cooling rate of the sheet core at 700 °C with a thickness of 20 mm is:

$$v = \frac{aKn}{K}(T - T_m) = \frac{5.37 \cdot 10^{-6} \text{ m}^2/\text{s} \cdot 0.86}{40.52 \cdot 10^{-6} \text{ m}^2} (680 \text{ }^\circ\text{C}) = 78 \text{ }^\circ\text{C/s}.$$

Now let’s find out the cooling rate of a small sample when it is quenched in various environments.

When quenched in oil with an average heat transfer coefficient of 1000 W/m²K, the cooling rate is calculated in the same way:

$$Bi = \frac{1000 \text{ W/m}^2\text{K} \cdot 0.003 \text{ m}}{23 \text{ W/mK}} = 0.13;$$

$$Bi_V = 0.4053 \cdot 0.13 = 0.053; \quad Kn = 0.05;$$

$$K = 1.56 \cdot 10^{-6} \text{ m}^2;$$

$$v = \frac{aKn}{K}(T - T_m) = \frac{5.19 \cdot 10^{-6} \text{ m}^2/\text{s} \cdot 0.05}{1.56 \cdot 10^{-6} \text{ m}^2} \cdot 640 \text{ }^\circ\text{C} = 106 \text{ }^\circ\text{C/c}.$$

When quenching a sample 6 mm in diameter in hot water at a temperature of 60 °C with a heat transfer coefficient of 750 W/m²K:

$$Bi = \frac{750 \text{ W/m}^2\text{K} \cdot 0.003 \text{ m}}{23 \text{ W/mK}} = 0.0975;$$

$$Bi_V = 0.4053 \cdot 0.0975 = 0.0395; \quad Kn = 0.0388;$$

$$v = \frac{aKn}{K}(T - T_m) = \frac{5.19 \cdot 10^{-6} \text{ m}^2/\text{s} \cdot 0.0388}{1.56 \cdot 10^{-6} \text{ m}^2} \cdot 610 \text{ }^\circ\text{C} = 79 \text{ }^\circ\text{C/c}.$$

According to the proposed method, this means that the sheet core has the same mechanical properties as the 6 mm sample after quenching in water at 60 °C.

To facilitate similar calculations in relation to the semi-axes of trucks in Tables 4, 5 show comparable cooling rates of semi-axes and samples.

Table 4

The cooling rate of the core of the semi-axes, depending on their size and heat transfer conditions

Diameter, mm	$K, \text{ m}^2$	Cooling rate in °C/s at $Kn=0.8$	Cooling rate in °C/s at $Kn=1$
48	$99.6 \cdot 10^{-6}$	28	35
50	$108.1 \cdot 10^{-6}$	25.7	32.2
52	$116.9 \cdot 10^{-6}$	24	30
60	$155.6 \cdot 10^{-6}$	18	22.3
62	$166.2 \cdot 10^{-6}$	16	20.3

Table 5

Cooling rate of cylindrical samples with a diameter of 6 mm depending on the value of the heat transfer coefficient

α , W/m ² K	Kn	Cooling rate in °C/s (700 °C)
200	0.0092	20
300	0.0139	31
400	0.018	40
500	0.023	51
600	0.027	60
700	0.029	63
1000	0.041	100
2000	0.092	204

It should be noted that along with the improvement of the mechanical properties of the core of the semi-axes of cars, high compressive stresses arise on their surface, increasing the service life of the semi-axes. Some experimental data are given in Table 6.

Table 6

Residual circumferential compressive stresses in MPa on the surface of different products after their intense hardening [11]

No.	Product	Circumferential compressive stresses in MPa on the surface of intensely hardened products
1	Bearing rollers 75 mm thick, made of steel 11X15 (52100)	-840
2	Cylindrical samples 72.9 mm thick made of 1547 steel	-626
3	40 mm pivots made of 4140 steel	-563

Thus, the mechanical properties of the core of an intensely cooled 20 mm thick sheet correspond to the mechanical properties of a cylindrical sample 6 mm in diameter quenched in a hot hearth with a heat transfer coefficient of 750 W/m²K. To simulate the process of cooling the core of the semi-axes, cooling of the samples is required at lower heat transfer coefficients.

It should also be noted that it is very incorrect and erroneous to attempt to use the heat transfer coefficients obtained when testing a 20 mm diameter silver ball on any steel samples. The thermal conductivity of silver is 20 times higher than the thermal conductivity of steel, which means that silver will have a more developed vapor film and a different heat transfer coefficient compared to steel.

3.2. Prediction of mechanical properties in the core of large products by quenching and laboratory testing of small test samples. Prediction of the structure of steel and its hardness at the central points of products can be carried out using the Jominy method, which has been discussed many times in the literature [24–26]. Let's propose a simpler forecasting technique, which consists in comparing the cooling rates obtained when testing small samples in hot water and the calculations performed to calculate the cooling rate of the core of a real part when it is quenched in real conditions.

It is known from the technical literature that the cooling capacity of water significantly depends on its tempera-

ture during the quenching cooling of parts. The results of experiments [27] carried out on a silver ball 20 mm in diameter are shown in Fig. 2.

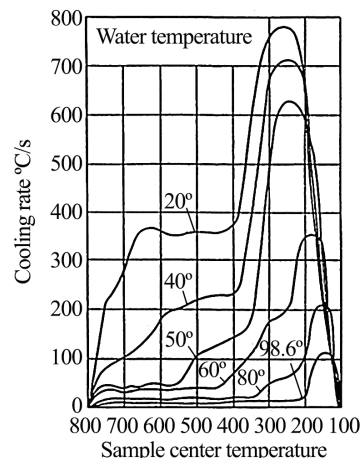


Fig. 2. Curves of changes in the cooling rate of a 20 mm diameter silver ball when it is cooled in water with different temperatures depending on the temperature of the center of the thermal probe [27]

The work [28] investigates the uniformity of cooling of a steel strip from a temperature of 800 °C according to the values of the ultimate strength along its thickness depending on the water temperature. Digits on the curves in Fig. 3 show the water temperature in °C.

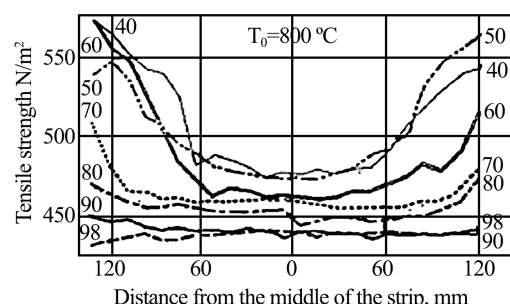


Fig. 3. The uniformity of metal cooling from a temperature of 800 °C according to the values of the ultimate strength along the width of the steel strip, depending on the temperature of the quenching medium [28]

This is an extremely costly and painstaking work that takes a long time, measuring the mechanical properties of materials over the entire section of the steel strip. Therefore, let's suggest the opposite procedure. By quenching cylindrical samples 6 mm in diameter in various quenching media and measuring their cooling rate, as well as their mechanical tests, it is possible to restore the distribution of strength in the steel strip using the proposed method of simplified calculations. More detailed information on the quenching of steels in liquid media, taking into account modern mathematical models, is discussed in [29]. In the calculations, one can use experiments carried out on cylindrical samples with a diameter of 6 mm, which are shown in Fig. 4 and in Table 7. Research can also be used [26, 27, 30].

In Fig. 4 the following designations are adopted: σ_B – tensile strength, MPa; σ_T – yield point, MPa; δ – relative extension, %; KCV^{-20} – impact toughness, determined when testing Charpy samples (with V concentrator) at a temperature of minus 20 °C, MJ/m².

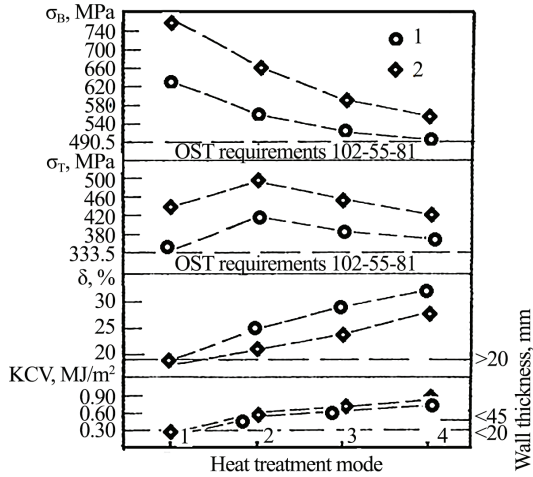


Fig. 4. Mechanical properties of 15XCHD steel, depending on the mode of heat treatment and grade chemical composition:

1 – melting has a grade chemical composition in terms of carbon concentration, close to the lower; 2 – melting has a brand chemical composition in terms of carbon concentration, close to the average; Mode 1 – hardening volumetric heat treatment (TH) with austenitizing temperature of 980 °C in water (TB>90 °C) according to the mode of complete cooling of the metal to the ambient temperature; Modes 2, 3, 4 – TH+tempering 30 min. at 500, 600, 700 °C, respectively

Table 7

Effect of the cooling intensity of low-carbon low-alloy steel 09G2S (δ=8 mm) in the low-temperature region on the level of crystal lattice defects and microdeformations

No.	Metal processing mode	Microdeformation level, $L, \times 10^{-4}$	Dislocation density, $\rho, \text{cm}^{-2} \times 10^{10}$
1	Thermal hardening (TH) in hot water until the metal is completely cooled	5.6/5.1	3.4/3.0
2	TH in hot water with interruption of cooling at metal temperature ≈250 °C	1.1/4.3	2.6/2.1
3	TH in hot water with interruption of cooling at metal temperature ≈350 °C	0.8/3.6	1.9/1.2
4	Quenching in oil (+40 °C)	6.1	5.04
5	Quenching in water (+20 °C)	24.6	1.01×10^{11}

Note: the numerator shows the values for heat-strengthened metal, and the denominator – after heat-strengthening and subsequent tempering at 500 °C

To implement the proposed technique, let's experimental data on testing the mechanical properties of steel and its fine structure after quenching small samples in hot water (Fig. 4, Table 7). As seen from Fig. 4, even within the same steel grade, the mechanical properties of the steel vary greatly, which the Jominy method does not take into account. In addition, the known method does not operate with such concepts as the plastic properties of the material, the level of microdeformations and the density of dislocations (Fig. 4, Table 7). The proposed technique makes it possible to transfer the obtained studies to real parts, in

which the cooling rate during quenching is the same as the cooling rate of small samples.

In recent decades, in the practice of heat treatment, aqueous solutions of polymers have been actively used as cooling media. The results of recent studies show the promise of using aqueous solutions with a low concentration of polymers, which provide intense and uniform cooling of various steel metal products during quenching [18, 19].

Additional information concerning uniform cooling and predicting the structure and mechanical properties of the material in the volume of heat-strengthened products is presented in [18, 19].

The algorithm of the developed technique is demonstrated by the example of intensive hardening of steel products of a ring shape (Fig. 5). Let's suppose that at the enterprise the specified products are cooled with water jets (Fig. 1) under conditions $Bi \rightarrow \infty$.

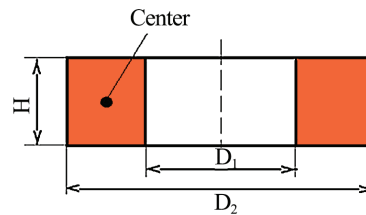


Fig. 5. Sketch of ring-shaped products selected for predicting mechanical properties and structure at central points

Table 8 shows the cooling rates of ring-shaped products at a temperature of 700 °C depending on the dimensions of the products that are hardened under conditions. Let's suppose that it is necessary to study the structure and measure the mechanical properties in the center of a large ring, which has the following dimensions: outer diameter $D_2=0.1$ m, inner diameter $D_1=0.02$ m, and ring height 0.04 m (Table 8). The cooling rate in the center of such a ring at a temperature of 700 °C is 42 °C/s.

Table 8

Cooling rate in the center of ring-shaped products depending on the size of the rings

D_1	D_2	H	$K \cdot 10^{-6} \text{ m}^2$	$v, \text{ °C/s}$
0.02	0.06	0.02	20.6	172
0.02	0.08	0.03	46.6	76
0.02	0.10	0.04	83.4	42

Similarly, Table 9 shows the cooling rates of small samples for rupture depending on their dimensions and cooling conditions, that is, the heat transfer coefficient. Comparing Table 8 and Table 9, it is necessary to find equal cooling rates and thus figure out what the small sample should be for testing and under what conditions it should be cooled. For the case under consideration, a small sample with a diameter of 5 mm is suitable, which must be cooled with a coefficient of 300 (Table 9).

The proposed method, in comparison with the Jominy method, is simpler and allows one to obtain broader and more important information about the tested steel (Fig. 4, Table 7).

Table 9

Cooling rate of prototypes for strength testing depending on their size and heat transfer coefficients

α , W/m ² K	150	300	400	500	1000
v , °C/s. Sample 10 mm	6	12	16	21	42
v , °C/s. Sample 6 mm	16	32	44	59	118
v , °C/s. Sample 5 mm	23	46	63	85	170

This work continues the development of the method for predicting the structure and mechanical properties of steel in the core of hardened products in a more simplified version, which was described in [26]. Especially this method is very important when using steel with optimal hardenability and the method of its choice depending on the shape and size of the hardened products, which were patented in [16].

As a rule, such steel is subjected to intense quenching, which provides for the creation of high compressive stresses in the surface martensite layer and a softer core consisting of a mixture of pearlite and bainite or pure bainite of increased strength and ductility [16, 17]. In this regard, it is important to have a simple and easily realizable technique for studying the mechanical properties of the core of hardened products without resorting to their destruction.

At present, there are already ready-made developments for the large-scale introduction of intensive technologies and steels with optimal hardenability into world practice on the basis of existing equipment or simple new equipment. It is planned to use low concentrations of aqueous solutions of polymers of reverse solubility as a quenching medium. Employees of Intensive Technologies LTD (ITL, Kyiv, Ukraine) have developed computer programs for calculating cooling modes in quenching media for parts of various configurations and sizes. Also, a quenching medium for intensive quenching based on aqueous solutions of polyacrylamide of very low concentration (0.001–0.005 %) has been proposed [31, 32].

It should be borne in mind that the proposed calculation technique is very approximate. At the modern level, when calculating temperature fields and cooling rates, it is necessary to solve the hyperbolic equation of heat conduction and use computer simulation [33, 34]. It is also important to use modern methods of testing quenching media [35–37]. All this should be taken into account in further research.

4. Conclusions

The paper proposes a simple technique for modeling the formation of the structure and mechanical properties of the material in the core of various steel products during their quenching in liquid media. The essence of the technique is that first, the rate of cooling of the core of the hardened products is calculated at temperatures of 700 °C and 300 °C. Then the calculation of the cooling rate of small samples with a thickness of 5–6 mm is carried out, which are cooled under conditions where similar cooling rates are achieved for small test samples at temperatures of 700 °C and 300 °C. It is also proposed to combine the achievements in the field of bainitic and

martensitic transformations during quenching in order to maximize hardening of the quenched products.

Acknowledgement

Dedicated to the 116th anniversary of the birth of Academician K. Starodubov.

References

- Starodubov, K. F., Uzlov, I. G., Savenkov, V. Ia. et. al. (1970). *Termicheskoe Uprochnenie Prokata*. Dnepropetrovsk: Metallurgiya, 368.
- Deineko, L. N., Bolshakov, V. I. (2000). *Termicheskoe uprochnenie soedinitelnykh detalei magistralnykh neftegazoprovodov*. Dnepropetrovsk, 120.
- Bhadeshia, H. K. D. H. (2015). *Bainite in Steels: Theory and Practice*. Money Publishing, 616.
- Liscic, B., Tensi, H., Canale, L., Totten, G. (Eds.) (2010). *Quenching Theory and Technology*. CRC Press, 725. doi: <http://doi.org/10.1201/9781420009163>
- Shepeliakovskii, K. Z. (1972). *Uprochnenie detalei mashin po-verkhnostnoi zakalkoi TVCH*. Moscow: Mashinostroenie, 288.
- Shepeliakovskii, K. Z., Ushakov, B. K. (1990). Induction surface hardening-progressive technology of XX and XXI centuries. *Proc. 7th Int. Congress on Heat treatment and technology of surface coatings*, 33–40.
- Ouchakov, B., Shepeljakovskii, K. (1998). *New Steels and Methods for Induction Hardening of Bearing Rings and Rollers*. Bearing Steels: Into the 21st Century, 307. doi: <http://doi.org/10.1520/stp12136s>
- Shepeliakovskii, K. Z., Bezmenov, F. V. (1998). New Induction Hardening Technology. *Advanced Materials & Processes*, 154 (4), 225–227.
- Ushakov, B. K., Efremov, V. N., Kolodjagny, V. V., Skryagin, V. I., Dub, L. G. (1991). New Compositions of Bearing Steels of Controlled Hardenability. *Stal*, 10, 62–65.
- Liscic, B., Tenzi, H. M., Luty, W. (1992). *Theory and Technology of Quenching*. Berlin, New York: Springer-Verlag, 534. doi: <http://doi.org/10.1007/978-3-662-01596-4>
- Kobasko, N. I., Aronov, M. A., Powell, J. A., Totten, G. E. (2010). *Intensive Quenching Systems: Engineering and Design*. ASTM International, 234. doi: <http://doi.org/10.1520/mnl64-eb>
- Kobasko, N. (2017). A method for optimizing chemical composition of steels to reduce radically their alloy elements and increase service life of machine components. *EUREKA: Physics and Engineering*, 1, 3–12. doi: <http://doi.org/10.21303/2461-4262.2017.00253>
- Rath, J., Lübben, T., Hunkel, M., Hoffmann, F., Zoch, H.-W. (2010). Grundlegende Untersuchungen zur Erzeugung von Druckeigenspannungen durch Hochgeschwindigkeits-Abschrecken. *HTM Journal of Heat Treatment and Materials*, 64 (6), 338–350. doi: <http://doi.org/10.3139/105.110037>
- Rath, J., Lübben, T., Hoffmann, F., Zoch, H.-W. (2010). Generation of compressive residual stresses by high speed water quenching. *International Heat Treatment and Surface Engineering*, 4 (4), 156–159. doi: <http://doi.org/10.1179/174951410x12851626812970>
- Zoch, H. W., Schneider, R., Lübben, T. (2014). *Proc. of European Conference on Heat Treatment and 21st IFHTSE Congress*. Munich, 566.
- Kobasko, N. (2013). Pat. No. 114174 UA. *Alloyed Low Hardenability Steel and Method of its Composing*. MPK: C22C 38/40, C22C 38/08, C21D 1/18, C22C 38/24, C22C 38/46, C21D 9/00, C22C 38/12. No. a 2013 11311. declared: 23.09.2013; published: 10.05.2017, Bul. No. 9.
- Kobasko, N. (2018). *Optimal Hardenability Steel and Method for Its Composing*. Lambert Academic Publishing, 122.
- Kobasko, N. I. (2019). Uniform and Intense Cooling During Hardening Steel in Low Concentration of Water Polymer Solutions. *American Journal of Modern Physics*, 8 (6), 76–85.
- Kobasko, N. I. (2020). Mechanism of Film Boiling Elimination and IQ Process Design for Hardening Steel in Low Concentration of Water Polymer Solutions. *Global Journal of Science Frontier Research*, 20 (7), 39–56. doi: <http://doi.org/10.34257/gisfravol20is7pg39>

20. Pat. No. 6,364,974 B2 US (2002). *Quenching apparatus and method for hardening steel parts*. Assignee: IQ Technologies, Inc. Appl. No. 09/551,082. Filed: 18.04.2000.
21. Lykov, A. V. (1967). *Teoriya teploprovodnosti*. Moscow: Vysshaya shkola, 600.
22. Kondratev, G. M. (1954). *Regulyarnyi Teplovoy Rezhim*. Moscow: Gostekhizdat, 364.
23. Kondratev, G. M. (1957). *Teplovye Izmereniya*. Moscow: Mashgiz, 250.
24. Kadinova, A. S., Kheifets, G. N., Taitis, N. Iu. (1963). O kharaktere teploobmena pri struinom okhlazhdenii. *Inzhenerno-fizicheskii zhurnal*, 6 (4), 46–50.
25. Xie, L., Funatani, K., Totten, G. (Eds.) (2004). *Handbook of Metallurgical Process Design*. CRC Press, 957. doi: <http://doi.org/10.1201/9780203970928>
26. Totten, G. E., Bates, C. E., Clinton, N. A. (1993). *Handbook of quenchants and quenching technology*. ASM international, 513.
27. Kobasko, N., Guseynov, Sh., Rimshans, J. (2019). *Core Hardness and Microstructure Prediction in Any Steel Part*. Lambert Academic Publishing, 104.
28. Aronov, M. A., Kobasko, N. I., Powell, J. A., Totten, G. E. (2010). *Intensive Quenching of Steel Parts. ASM Handbook. Vol. 4A. Steel Heat Treating Fundamentals and Processes*, 198–212.
29. Eshar, W. et. al. (1987). Technology of cooling at heat treating of materials. *Chernyye metally*, 6-7, 3–12.
30. Buikis, A. (2020). *Multidimensional Mathematical Models for Intensive Steel Quenching*. Lambert Academic Publishing, 136.
31. Petrash, L. V. (1959). *Zakalochnye Sredy*. Moscow-Leningrad: Mashgiz, 112.
32. Kobasko, N. (2018). New approach in modifying quenching processes based on possibility of controlling steel's surface temperature by insulating layer. *EUREKA: Physics and Engineering*, 6, 54–62. doi: <http://doi.org/10.21303/2461-4262.2018.00788>
33. Bobinska, T., Buike, M., Buikis, A. (2010). Hyperbolic heat equation as mathematical model of steel quenching of L-shape samples. *Proc. of the 5th IASME/WSEAS Int. Conf. on Continuum Mechanics, Fluids, Heat*. Cambridge: WSEAS Press, 21–26.
34. Mayinger, F. (1992). Thermo- and Fluiddynamic Principles of Heat Transfer During Cooling. *Theory and Technology of Quenching*, 41–72. doi: http://doi.org/10.1007/978-3-662-01596-4_3
35. Liscic, B. (2016). Measurement and Recording of Quenching Intensity in Workshop Conditions Based on Temperature Gradients. *Materials Performance and Characterization*, 5 (1), MPC20160007. doi: <http://doi.org/10.1520/mpc20160007>
36. Felde, I. (2015). Liquid Quenchant Database – Determination of Heat Transfer Coefficient during Quenching. *IDE 2015*. Bremen, 265–274.
37. Narazaki, M., Osawa, K., Shirayoshi, A., Fuchizawa, S. (1999). Influence of validity of heat transfer coefficients on simulation of quenching process of steel. *Proceedings of the 19th ASM Heat Treating Society Conference. ASM International*. Materials Park, 600–607.

Deyneko Leonid, Doctor of Technical Sciences, Professor, Department of Heat Treatment of Metals, National Metallurgical Academy of Ukraine, Dnipro, Ukraine, e-mail: leonid_deyneko@i.ua, ORCID: <http://orcid.org/0000-0002-1177-3055>

Kobasko Nikolai, PhD, Consultant, Intensive Technologies Ltd, Kyiv, Ukraine, e-mail: nkobasko@gmail.com, ORCID: <http://orcid.org/0000-0002-7636-5298>