Steel Quenching in Liquid Media under Pressure

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Abstract: - The paper deals with the regularities of steel quenching under pressure. It has been shown that in conditions $Bi \rightarrow \infty$ it is possible to control the surface temperature during nucleate boiling, which expands the potentialities of the low-temperature thermomechanical treatment and steel quenching in water under pressure. There are also illustrations of the implementations of such process. The technology can be used for strengthening of tools, forgings, and others components of machines.

Key-Words:- Quenching under pressure, Nucleate boiling, Low temperature thermomechanical treatment, Environment.

1 Introduction

It is known that during non-stationary nucleate boiling the self-regulated thermal process is observed. The temperature of a surface of a part at this time is kept above the level of boiling of a boundary liquid layer and differs from it very little. In this connection there is opportunity to affect the process of martensite transformations, detaining or accelerating it. There are two opportunities to make such effect. The first opportunity consists of using superfluous pressure that raises the boiling temperature of a boundary liquid layer. The second opportunity consists of using high-concentration aqueous solutions which increase boiling temperature. The use of both approaches is effective when quenching high-carbon steels and the martensite start temperature is below 200°C, i.e., $M_S \leq 200$°C. This paper presents results of experimental studies of the effect of superfluous pressure upon the character of temperature distribution at the surface of steel parts during martensite transformation

Detaining the process of transformation of the supercooled austenite into martensite, there is opportunity to apply effectively low-temperature thermomechanical treatment with the purpose of increase in mechanical and plastic properties of steels. It allows also decreasing the probability of quench crack formation and distortion of the hardened parts.

The creation of superfluous pressure increases critical heat flux densities q_{cr1} and q_{cr2} therefore the probability of the occurrence of the full film and transitive boiling decreases. All these factors can be used for the development of new technologies. However, from the scientific point of view, the most important is the opportunity to control (regulate) the temperature field of a part to be quenched, when $Bi \rightarrow \infty$. It is generally accepted that at $Bi \rightarrow \infty$ the temperature of a surface of a part to be quenched becomes equal to the temperature of the quenchant, therefore, it is impossible to change the temperature field of a part. In our case during boiling the surface temperature decreases sharply to the boiling temperature of a boundary liquid layer and for a long time (during self-regulated process) is kept approximately at the same level. As in high-carbon steels the martensite start temperature M_S is below 200°C, it is possible to raise temperature of boiling of a boundary liquid layer to M_S and, due to it, to detain the process of the transformation of austenite into martensite during self-regulated thermal process.

Thus, the new concept about the opportunity to control the temperature field of a part to be quenched at $Bi \rightarrow \infty$ has been suggested. It expands potentialities of low-temperature thermomechanical treatment, and is a basis for the development of new intensive and environmentally clean technologies.

2 Installations for Study Process of Quenching under Pressure and Results of Experiments

The steel quenching process in water and aqueous solutions under superfluous controlled pressure was studied on the test installation shown in Fig. 1. The installation consists of induction heating device 5, tightly closed chamber 2, the vacuum pump for pumping air out for creation of low pressure in the

chamber, a cylinder 7 with the compressed neutral gas for creation high pressure, measuring devices 8, 9, 10 for registration of temperature fields in test specimens and pressure in the chamber [1].
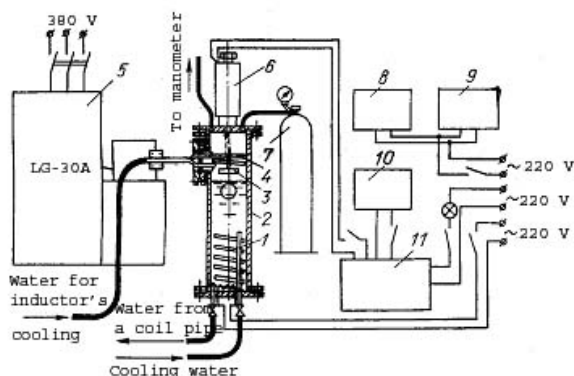
Fig. 1 The basic scheme of the installation for quenching steel specimens in the liquid media under controlled pressure: 1 is a coil pipe; 2 is the case of the chamber; 3 is a test specimen; 4 is inductor; 5 is induction installation; 6 is a solenoid; 7 is a bulb with compressed gas; 8, 9 are potentiometers; 10 is a data recorder; 11 is rectifier.

Inside the chamber there were inductor 4 of induction installations, coil pipe 1 for cooling a quenchant, electric heaters and test specimen 3 suspended on a mobile rod, which moves upwards and downwards by means of turning on and off solenoid 6. There were observation windows on lateral walls for visual monitoring over the process of the formation of vapor films. The compressed air was brought to the chamber from a bulb for cooling specimens under superfluous pressure, and also the vacuum pump is connected for the creation of low pressure above a mirror of a bath and for cooling in vacuum of test specimens. Temperature of the quenchant was measured at different points of the tank by means of the thermocouples delivered through a bottom of the chamber to potentiometer EPP-098. Temperature of the specimen was determined by means of the chromel-alumel thermocouples delivered inside of the chamber through the seal in the top cover of the chamber. Temperature fields were registered by means of measuring devices 8, 9, 10 [1].

The tests were made with a cylinder-shaped specimen of 20-mm diameter, made of austenite steel Kh18N9T or Kh18N10T. The choice of the specimen material was stainless steel because during quenching in the beginning of cooling process all steel parts consist of the supercooled austenite, which thermal and physical properties

differ very little from thermal and physical properties of steel Kh18N9T.

Differential chromel-alumel thermocouples were made of 0.2-mm-diameter wire. Junctions of thermocouples were welded in inner points of the specimen and at the surface the extensions of thermocouples were recessed in grooves of a specimen and also covered by a foil. To prevent the possibility of quenchant penetration into apertures at the end face of a specimen, a tube was welded, which isolated inner thermocouples from liquid. Such a specimen was fixed at a mobile rod, which, when the solenoid was turned on, pulled the specimen into the inductor for its heating.

The use of aqueous solutions of electrolytes of optimal concentration together with the high pressure significantly increases the critical heat flux density. The manufactured stand (see Fig. 1) is intended for the study of the effect of pressure upon steel quenching process. In particular, it can be used for the study of the effect of pressure upon the process of quench crack formation, deformation, distortion, hardening, hardenability of steel parts, and also on the values of residual stresses that arise during quenching. The quenchants were motionless, i.e., during steel quenching only natural circulation of the quenchant was observed.

The effect of pressure upon distribution of temperature fields was studied on a cylindrical specimen of 20-mm diameter. Experiments were carried out at atmospheric pressure and superfluous pressure $(3; 6; 9) \times 10^5$ Pa. Results of measurements of temperature at various points of a specimen are presented in Fig. 2. During cooling in water under atmospheric pressure non-uniform cooling of the surface of a specimen was observed due to the formation of local vapor films. When the pressure above a mirror of a quench tank increases, the process of film boiling disappears and temperature of the part's surface quickly goes down to saturation temperature of the quenchant, a little exceeding it. Then, for quite a long time during nucleate boiling, remains approximately at the same level insignificantly approaches the saturation temperature of the quenchant. These regularities were used at developing new methods of two – step quenching. At the first step transformation from austenite to martensite is delayed and at the second step cooling within the martensite range is produced very rapidly to achieve effect of steel superstrengthening phenomenon. At the first step cooling is provided in plain water or water solutions of optimal concentration. At the second step rapid cooling and

washing of steel parts are the same technological process.
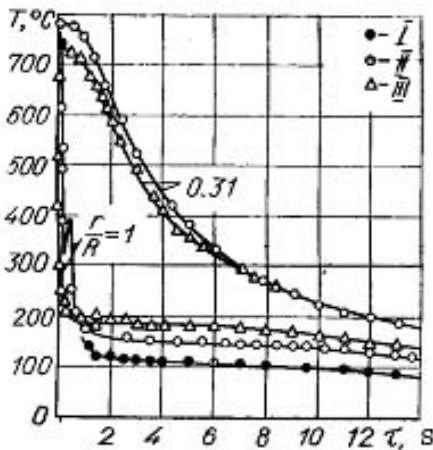
Fig. 2 Effect of pressure upon the temperature field of a cylindrical specimen of 20-mm diameter made of steel Kh18N9T: I - 10^5 Pa; II - $4 \cdot 10^5$ Pa; III - $7 \cdot 10^5$ Pa.

So, at atmospheric pressure during nucleate boiling for 10 s the temperature at the surface of a specimen changes from 120 to 100°C while at the center of the specimen the temperature changes for this time from 730 to 250°C. At high pressure, in particular, $7 \cdot 10^5$ Pa, the temperature at the surface sharply falls to 190°C and then, for 8 s, reduces to approximately 170°C. For this time the temperature at the distance of r/R = 0.31 is reduced from 730 to 220°C. With the increase pressure the temperature of the specimen's surface increases too. During nucleate boiling this temperature changes insignificantly, and with increase in pressure the duration of nucleate boiling decreases a little, transforming earlier into the single-phase convection.

The presented results are important from the practical point of view. The point is that the process of transformation of the supercooled austenite into martensite for the majority of steel grades, in particular, for high-carbon steels, starts at 200°C and below. For low-carbon and medium-carbon steels in this case the point M_s is characteristic, below which with increase in cooling rate, intensive transformation of a greater part of austenite into martensite starts. For medium-carbon steels the specified temperature is approximately within the range of 150 - 200°C. Therefore, for these steels by means of small pressure it is possible to detain the process of transformation of a greater part of austenite into martensite, and for high-carbon steels this transformation can be detained completely. Such delay is feasible only in

the field of nucleate boiling where there is a minor alteration of temperature of a surface and essential change of temperature of inner points of the body.
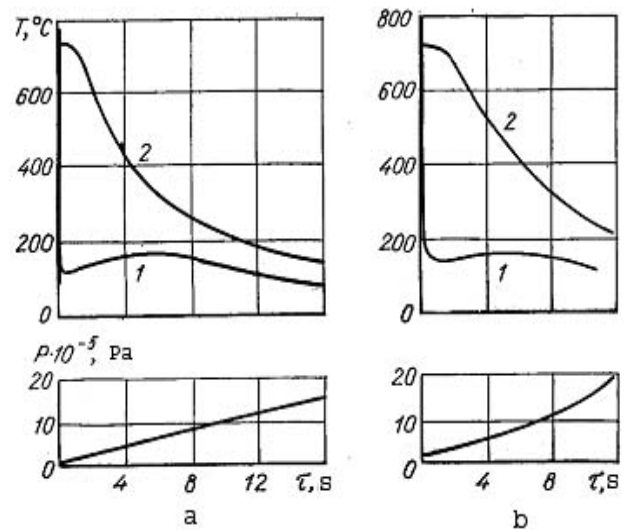
Fig. 3 Effect of variable pressure upon a course of change in temperature at the surface and a core point of a cylindrical specimen of 20-mm diameter made of steel Kh18N9T during its cooling in water at 20°C: a – numerical calculation; b – experimental data; 1 – a surface; 2 – a point at distance of 6.2 mm from the center

The use of variable pressure is of great interest, as in practice it is difficult to support pressure at a constant level. When loading and unloading of parts into and out of the quench chamber the pressure drops towards atmospheric one.

To study the effect of variable pressure upon change in temperature at a part's surface special experiment was made at a testing installation (see Fig. 1). Pressure in the chamber from the time of immersing the heated specimen into a quenchant increased from atmospheric one to $9 \cdot 10^5$ Pa. Fig. 8.4 presents temperature at the surface of a cylindrical 20-mm diameter specimen versus pressure changing by the linear law. Inner points of the specimen during nucleate boiling are intensively cooled, while with increase of pressure the temperature of the surface of the specimen at first increases a little, and then goes down to the quenchant temperature.

Slight increase of temperature at the surface of the specimen is explained by the fact that by the end of nucleate boiling the pressure in the chamber increased insignificantly and only in the area of convection it reached $9 \cdot 10^5$ Pa. One can control by pressure the temperature of a surface of a part to be quenched only in the area of nucleate boiling; at the convection it is practically impossible to control the temperature of a surface.

Table 1 Water saturation temperature versus pressure

$P \cdot 10^{-5}$,Pa	T_S,°C	$P \cdot 10^{-5}$,Pa	T_S,°C
1	99.64	11	184.05
2	120.23	12	187.95
3	133.54	13	191.60
4	143.62	14	195.04
5	151.84	15	198.28
6	158.84	16	201.36
7	164.96	17	204.30
8	170.42	18	207.10
9	175.35	19	209.78
10	179.88	20	212.37

Table 2 Temperature of isothermal keeping for various steel grades at which no more than 25 % of martensite in the supercooled austenite is formed

Steel grade	T_o, °C	C, %	Temperature, °C	
			M_s	25% martensite
45	880	0.44	350	310
U8	850	0.8	235	150
U10	780	1.1	200	130

Thus, changing pressure one can effectively control the temperature at the surface of a part to be quenched under any given law. It can be used for controlling the process of transformation of the supercooled austenite into martensite. Having CCT diagrams (continuous cooling transformation diagrams), one can design optimal steel quenching processes.

3   Duration of Non –Stationary Nucleate Boiling

The equation for determining the duration of non-stationary nucleate boiling (self-regulated thermal process) is presented below [1].

$$\tau = \left[\Omega + b \ln \frac{\vartheta_I}{\vartheta_{II}}\right]\frac{K}{a}, \qquad (1)$$

where b=3.21; K is Kondratjev form factor; *a is* thermal diffusivity;

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3}; \qquad (2)$$

$$\vartheta_{II} = \frac{1}{\beta}[\alpha_{conv}(\vartheta_{II} + \vartheta_{uh})]^{0.3} \qquad (3)$$

$$\beta = \frac{75\lambda'(\rho' - \rho'')^{0.5} g^{0.5}}{\delta^{0.5}(\rho'' r^* \overline{W}'')^{0.7} \Pr^{0.2}}. \qquad (4)$$

Pr is Prandtle criterion (number); α is heat transfer coefficient; λ is thermal conductivity; σ is a factor of surface tension; g is a gravity factor (m/s^2); ρ' is liquid density (kg/m^3); ρ'' is steam density (kg/m^3); q is heat flux density (W/m^2); r^* is heat of steam formation (J/kg); W'' is steam bubble growth rate (m/s).

It is this equation that is a generalized dependence for the determination of the time of non-stationary nucleate boiling, i.e., self-regulated thermal process

For the specimens studied a boundary liquid boiling layer is formed for a quite short time which we call the first period of cooling. For example, during cooling a cylindrical specimen of 30-mm diameter from 850°C in water at temperature of 20°C the time of the first period during which the maximum of heat flux density is reached is equal to approximately 0.2 s, while the time of nucleate boiling for this specimen is equal to 22 s. The time of the first period makes about 1 % of the total time of nucleate boiling. It means that full fill boiling is absent and main mode is nucleate boiling. To prevent film boiling the initial heat flux density should be less than the first critical heat flux density q_{cr1}. Some experimental data for q_{cr1} are shown in Fig. 4 which can be used at quenching in water under pressure. In some cases the time of the first period can be neglected, considering that nucleate boiling is established immediately upon immersing a part into a quenchant. Such approach is approximate; however, when there is no film boiling, it provides satisfactory agreement between computed data and experimental results.
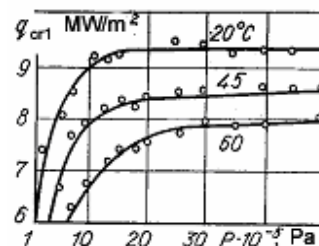

Fig. 4 The qcr1 *versus* pressure and temperature of water [2, 3].

4 Practical Use of the New Method of Quenching

Basic scheme of the automated process of steel quenching in water and aqueous solutions under pressure is shown on Fig. 5. The quenching process is carried out as follows. When the platform is at starting position I, the part 5 heated to austenization temperature is delivered to tray 1. At this time the driving mechanism is turned on, and the platform occupies work position II, hermetically closing the top part of the quench tank. The compressed air moves through aperture 2, creating necessary pressure between a quenchant and the platform (cover). Pressure is delivered such a way that the quenchant saturation temperature should be equal to M_S, i.e., martensite start temperature.

During quenching in water under pressure at nucleate boiling there is a delay of transformation of austenite into martensite, therefore, in the period of the effect of high thermal stresses the part consists of the supercooled austenite. Quench cracks in these conditions are not formed. The method of steel quenching in water and aqueous solutions under superfluous controlled pressure can be effectively applied for those steel grades that have martensite start temperature M_S no more than 200°C.
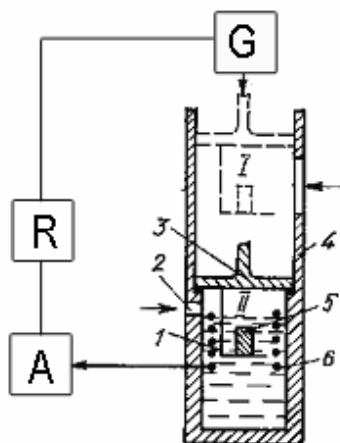
Fig. 5 Basic scheme of the automated process of steel quenching in water and aqueous solutions under pressure: 1 - a tray; 2 - an aperture for pumping in the compressed air; 3 - mobile platform (cover); 4 - case of the quench tank; 5 - a part to be quenched; 6 - the solenoid for fixing the initial time of transformation of austenite into martensite; A - the amplifier of a signal of the martensite start; R - the relay of current; G - the driving mechanism; I - a starting position; II - a work position during quenching.

The steel part 5 is cooled in tank until finishing nucleate boiling. At the end of nucleate boiling the temperature at the surface starts to go down to the temperature of quenchant. The formation of ferromagnetic phase, martensite, begins which is fixed by solenoid 6. The signal from the solenoid is amplified and moves to the relay, and upon the actuation of it, the driving mechanism moves the platform to top starting position I. The part 5 is unloaded from the tray and delivered for tempering, and its place is occupied by the next part, and this cycle is repeated again [1]. The described way of cooling can be used at continuous automated industrial lines.

5 Discussion

The described quenching method [1] expands the potentialities of a low-temperature thermomechanical treatment. Part 5 at the end of nucleate boiling consists mainly of the supercooled austenite. The temperature in the core of the part at this time reaches values related to the area of relative stability of the supercooled austenite. Therefore, after nucleate boiling the part can be subjected to the plastic deformation, i.e., low-temperature thermomechanical treatment. In the case of the use of the latter, the mechanical and plastic properties of material become better.

In practice it is widely used to apply heat treatment of tools with isothermal quenching in melts of salts and alkalis. The developed quenching method allows to replace melts of salts and alkalis with water and aqueous solutions having high temperature of boiling of a boundary liquid layer, i.e. $M_S \approx T_S$ (see Tables 1 and 2). The method of quenching considerably reduces the cost and simplifies industrial heat treatment process and makes it environmentally friendly.

The installation presented in Fig. 5 can be adapted for quenching parts in water under pressure in the clamped condition. Such process becomes rather efficient if we deal with steels with high content of carbon, which martensite start temperature M_s is around 200°C and lower. In this case it is easy to detain for some time martensite transformations during the period of the action of maximal stresses.

As is known, during phase transformations superplasticity of material is observed. In conditions of superplasticity the resistance to deformation is less

by two or three orders than in usual conditions of deformation. It opens new opportunities of punching, allows to minimize deformability and minimize distortion of parts and correct defects even after machining.[21-24].

Quenching in stamps under pressure allows to apply usual water instead of oils, as pressure raises the water saturation temperature and, due to it, detains the martensite transformation during self-regulated thermal process. When the temperature of the core achieves martensite start temperature M_s, superplasticity occurs in material and during this period, under small forces, the shape of the part is corrected, i.e., the part receives the required shape set by stamp.

6 Summary

- Steel quenching in water and aqueous solutions under superfluous pressure eliminates film boiling and detains transformation of austenite into martensite at nucleate boiling. It expands potentialities of low-temperature thermomechanical treatment, allows to perform quenching of tools made of alloy and high-alloy steel grades in plain water.
- Melts of salts and the alkalis used for isothermal quenching may be replaced with water and water solutions under pressure which reduces the cost and simplifies the industrial heat treatment process. It makes the process as green and environmentally friendly technology.

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