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Two-Stage Quenching Method with the Use of Oils at Optimal Temperature

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Abstract:- Two-step quenching method with the use of hot oils is suggested. At the first stage, cooling in hot oil, the transformation of austenite into martensite is suspended. At the second stage intensive cooling within the martensite range and simultaneously washing steel parts are performed. On the basis of the study of heat transfer processes, the full automation and optimization of steel heat treatment processes have been suggested. The optimization is based on the determination of extreme values of critical heat flux densities. This advanced technology improves the quality of products and saves the ecology for the account of lesser oil exhaust emission in atmosphere and shorter time of heat transfer processes.

Key words::- Two-step quenching, Critical heat flux densities, Heat transfer coefficients, Automation, Quality improvement, Ecology

1 Introduction

As is known, parts of complex geometry made out of alloy and high-alloy steels, as a rule, are quenched in mineral oils. As the intensity in oils is not big, the increase in the hardenability is reached for the account of adding alloys. Besides, slow and uniform cooling within the martensite range reduces the distortion and eliminates the possibility of quench crack formation. However, regarding thermal and physical processes, not all potentialities of mineral oils have been fully discovered. The authors of this paper optimize the quench cooling processes on the basis of determining extreme (maximum) heat flux densities and heat transfer coefficients obtained through solving inverse heat transfer problems.

This approach brings forth the results as follows:

- More uniform intensive cooling of parts, which results in the increase of hardenability and reduction of distortion.
- The opportunities of two-stage quenching are extended through the use of hot oils.
- The service life of parts increases.
- CO_2 emission to atmosphere is reduced.
- The labor productivity increases for the account of reducing the time of heat treatment process.

2 Extreme values of critical heat flux densities

For every kind of oil there is extreme value of critical heat flux densities, which is due to the oppositely influencing factors: viscosity and underheating. When the temperature drops, underheating increases and at the same time oil viscosity drastically increases, which causes the formation of vapor films and non-uniform cooling. With the increase of the oil temperature, the viscosity of oil decreases, which results in more intensive and uniform cooling of parts. However, the further increase in temperature of oil results in the reduction of underheating ($T_s - T_m$.), and therefore, the appearance of vapor films, and again, non-uniform cooling. Therefore, there exists the optimal temperature of oil at which the most intensive and uniform cooling of steel parts is reached. The optimal temperature of various oil grades can be determined from Fig. 1 by maximum of q_{cr1} [1].

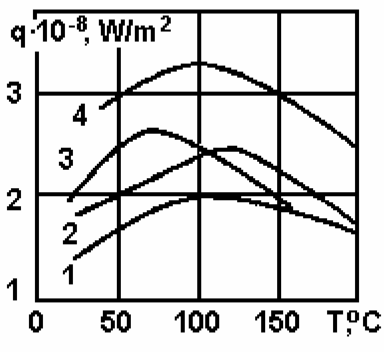


Fig. 1 The first critical heat flux density vs. oil temperature: 1 – MZS-120; 2 – MS-20; 3 – Effectol B; 4 – MZM-16

Besides the oil temperature, it is also necessary to optimize the circulation of the oil, which, of course, has effect upon the critical heat flux densities.

3 Heat transfer coefficients obtained on the basis of solving inverse heat transfer problems

N.A.Tikhonov created a new direction in methods of regularizing algorithms, which allowed to solve inverse problems that could not be solved by any other method. The first works were devoted to problems that are solvable analytically. For many problems theorems of existence and uniqueness of the solution were proved, algorithms of search for the regularization parameter α were suggested [2 - 5].

For the practical problems related to heating and cooling of steel, it is of interest to consider regularizing numerical algorithms for heat conduction problems in nonlinear statement. For this kind of problems the method of regularization is reduced to the introduction of a regularizing term into the error functional, which is to be minimized:

$$F_\alpha[u] = \|Au - f\|_m^2 + \alpha\|u\|_C^2,$$

where u is a vector of required parameters, F is an error functional to be minimized, f is a vector of experimental data, A is a matrix of transition from required parameters to estimated values at appropriate points of temperature measurement, $\|\cdot\|_m$ is norm in space R^m, $\|\cdot\|_C$ is a norm which is defined as follows: $\|u\| = (Cu, u)^{1/2}$, where C is a positively determined matrix. For example, it is possible to assume C=E, where E is a unit matrix.

Tikhonov's method was used in the determination of heat transfer coefficients during steel quenching in cold and hot oils [6]. Fig. 2 presents the dependence of heat transfer coefficient on surface temperature for steel quenching in mineral oil MZM – 16.

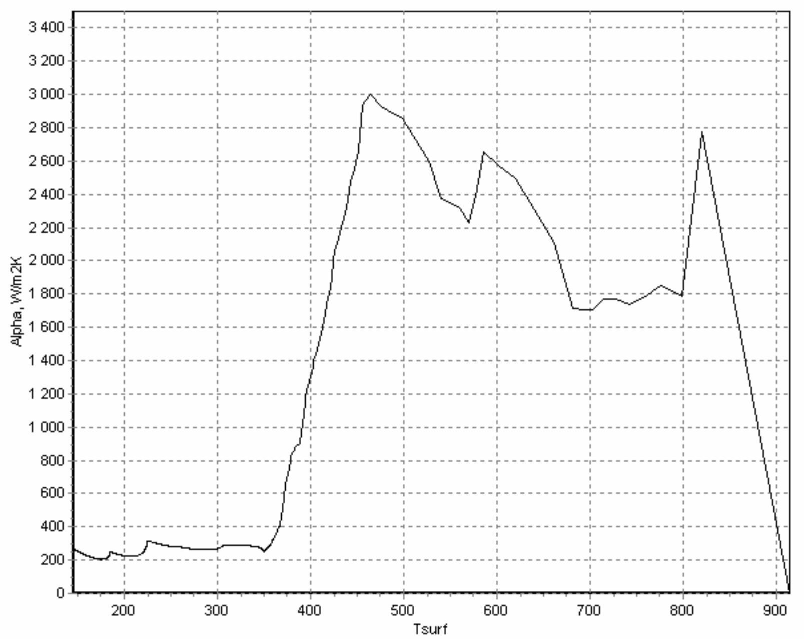


Fig. 2 Heat transfer coefficient vs. surface temperature

As Fig.2 shows, during oil boiling the mean heat transfer coefficient is within the range of 1800 -2000 W/m^2K. Upon the end of boiling, heat transfer coefficient decreases to about 300 W/m^2K and in the further it changes very little. The mean values of heat transfer coefficients for various oil grades are presented in Table 1.

It should be noted that heat transfer coefficients depend on the shape and size of parts being quenched, therefore, it is necessary to have the generalization of this function.

Table 1 Mean heat transfer coefficients during quenching steel parts in mineral oils, W/m^2K

Oil grade	Mean heat transfer coefficient for temperatures above 300°C, W/m^2K	The same below 300°C
I - 20	1000	300
MS - 20	1500	320
MZM - 16	1800	300
MZM -120	950	-
I -50	900	-

4 Conveyer line for the implementation of two-stage quenching with the use of hot oils

The time of heating and cooling for bodies of any geometry and speeds of conveyor movement are determined on the basis of dimensionless equation [7]:

$$Fo_v\ Kn = \left[\frac{k\,Bi_v}{2.095 + 3.867\,Bi_v} + \ln\theta \right] \quad (1)$$

Here t and τ are time of heating and cooling of the steel parts;

Bi_v is generalized Biot number;

K is Kondratjev form factor;

Kn is Kondratjev number;

T_o is initial temperature before cooling;

T_c is quenchant temperature.

K depends on shape and size of steel part. Kn depends on cooling capacity of quenchant.

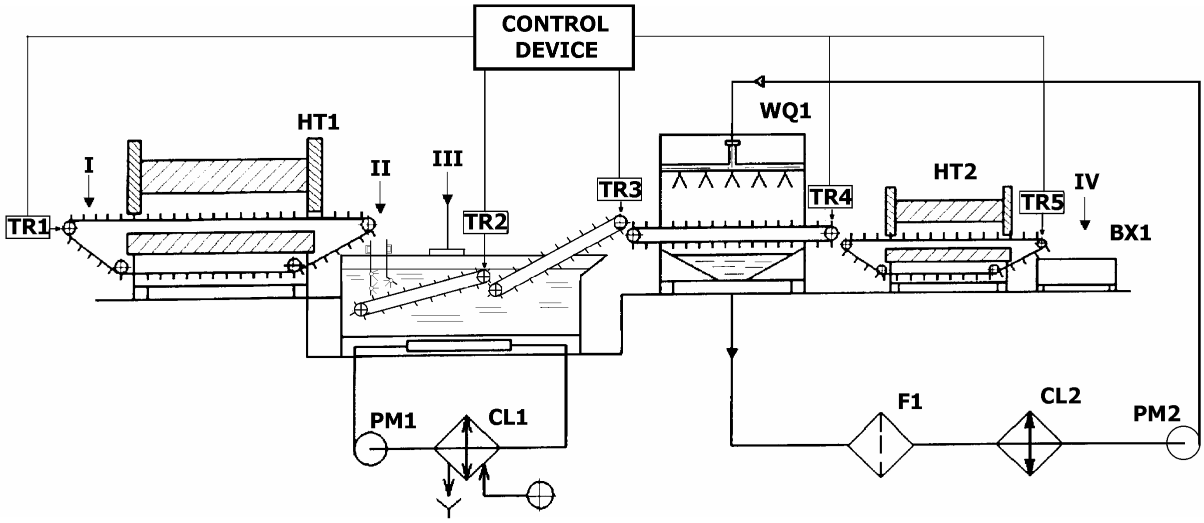


Fig. 3 Industrial installation for the implementation of IQ-2 technology [4]
I – loading steel parts to conveyor for their heating in heater 1; II – chute with intensive cooling devices; III – loading of quenchant to quenching tank with two conveyors; IV – unloading of steel parts from heater 2; TR1, TR2, TR3, TR4, TR5 – speed control units for conveyors 1, 2, 3, 4 and 5 operated by the control device; HT1, HT2 – heaters 1 and 2; WQ1 – washing and quenching device; PM1, PM2 – pumps 1 and 2; CL1, CL2 – coolers 1 and 2; F1 – filter; BX1 – container for quenched parts

Table 2 Martensite start temperature and temperature at which 25% martensite is formed, for various steel grades, °C

Steel grade AISI/ GOST	Austenitizing temperature, °C	Carbon content in steel, %	M_S, °C	25% martensite temperature
T1/R18	1300	0.72	190	150
E52100/ ShKh15	860	1.04	245	190
A485(2)/ ShKh15SG	850	0.99	200	120
L2/ 9Kh2	980	0.97	150	90
4320/ Carburized 20KhNM	850	1.18	140	120
W1/ U8	800	0.81	235	150
W1/ U10	780	1.1	200	130

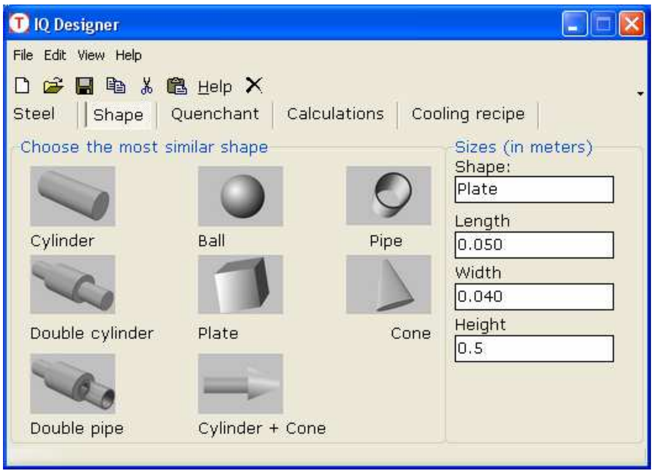
The process can be fully automated on the basis of known equation [8]:

$$W = \frac{L}{\tau} = \frac{aLKn}{(\Omega + b\ln\theta)K} \quad (2)$$

The above-mentioned conveyor line is universal in the sense that it allows to apply various quenchants: aqueous salt solutions of optimal concentration, aqueous polymer solutions exhibiting inverse solubility and forming the optimal depth of polymer film, hot oils at optimal temperature, and so on.

Hot oils have one important advantage that lies in their high boiling point (see Table 1). It follows that hot oil at optimal temperature not only speed up cooling process in comparison with cold oils, but also delays the transformation of austenite into martensite, since in the majority of cases, the optimal temperature of oil is greater than or equal to martensite start temperature. The martensite start temperature for some steels is presented in Table 2. When the transformation of austenite into martensite is delayed at the first stage, and a part is intensively cooled in the martensite range at the second stage (where washing and intensive cooling coincide), it is possible to significantly increase the strength properties of material.

At each step the time and speed of conveyor is calculated by the program, which includes the database of Kondratjev form coefficients, heat transfer coefficients and quenchant properties. The window of choosing the part's shape and sizes is presented below:



Heat transfer coefficients for sprayer cooling can be determined by known formula [9, 10] as follows:

$$\overline{Nu} = K_1 \cdot K_2 \cdot \mathrm{Re}^{\frac{2}{3}} \cdot \mathrm{Pr}^{0.42}, \qquad (3)$$

where

$$K_1 = \left[1 + \left(\frac{H/D}{0.6}\sqrt{f}\right)^6\right]^{-0.05};$$

$$K_2 = \frac{\sqrt{f}(1 - 2.2\sqrt{f})}{1 + 0.2(H/D - 6)\sqrt{f}};$$

$$f = \frac{\left(\pi/4\right)D^2}{A_{square(hexagon)}};$$

D is a diameter of a nozzle in sprayer ;
H is a distance from a nozzle (aperture) to a surface to be quenched;
A is the area of the square, hexagon.

Dimensionless numbers K_1 also K_2 are connected with geometry and arrangement of nozzles with respect to the surface to be quenched. Reynolds number Re is connected with the speed of the quenchant in the beginning of the outlet from a nozzle, and the number Pr characterizes physical properties of the quenchant. The dimensionless equation of similarity (6) is fair within the boundaries of the following values and given parameters:

$$2000 \le \mathrm{Re} \le 100000;$$

$$0.004 \le f \le 0.04;$$

$$2 \le \frac{H}{D} \le 12.$$

5 Discussion

The authors are adherents of intensive steel quenching methods. In the near future, in the majority of cases, alloy and high-alloy steels will be replaced with plain carbon steels of low hardenability. Oils and high-concentration polymer quenchants substituting them will be replaced with plain water, that is, intensive water streams or jets. It became possible due to the discovered property of material superstrengthening and formation of high compressive stresses at the surface of parts quenched [8].

Since the implementation of intensive quenching methods in production is delayed because of the lack of appropriate equipment and sufficient availability of low-hardenability steels, the authors consider it their duty to start the optimization of usual processes of alloy-steel quenching in usual oils. As it is mentioned above, the optimization solves, to some extent, ecological problems and increases the service life of steel parts due to intensive cooling within the martensite range, when at the same time the parts are washed.

It should be noted that washing steel parts becomes essentially easier due to lesser viscosity of hot oils, which considerably reduces the amount of oil carried out together with the part when it is taken out of the quenchant. When quenching is performed in cold oil, such amount of oil carried out significantly increases, and washing becomes more complicated.

Therefore, the optimal temperature of oil not only improves the quality of parts, reduces the CO_2 emission to the atmosphere, but also saves quench oils due to the lesser amount carried out of the quench tank during unloading parts.

In our opinion, if there is the faintest chance to solve ecological problems and improve the quality of products at the same time, it must be done immediately. Finally, by such efforts of many people, the environment cleansing will occur and the quality of products will grow up.

6 Conclusions

1. The optimized two-stage quenching process with the use of hot oils possessing the maximum value of the first critical heat flux density is proposed.
2. At the first stage, parts are cooled to the temperature of hot oil with the delay of martensite transformations. At the second stage the parts are both washed and intensively cooled within the martensite range.
3. The maximum value of the first critical heat flux density reduces the distortion, increases hardenability and reduces CO_2 emission to atmosphere, provides more uniform cooling.
4. The optimization of cooling processes on the basis of determining optimal critical heat flux densities essentially improves the quality of parts at the minimum cost and without radical changes in the production lines.
5. It is important to start the study of the effect of all possible additions to oils upon the absolute value of critical heat flux densities.
6. The Software has been developed, which is based on generalized criterion functions, for the control of industrial heat treatment processes.
7. The new conditions of material heat treatment are exacted and perfected on the basis of computer simulation of all heat treatment processes taking place in practice.

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