NEW WAYS OF DESIGNING SUPER STRONG MATERIALS BASED ON USE OF ALLOYED LOW HARDENABILITY STEELS

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Abstract: Currently, metallurgists are trying to improve mechanical properties of steel by increasing alloy elements in it that require slow cooling in oils or high concentration of water polymers solutions. The paper discusses opposite way in increasing service life of machine components by cardinal decrease alloy elements in steel and providing intensive cooling in locally agitated plain water performed by moving sprayers. The proposed new approach is based on two fundamental phenomena which include creation of high surface compressive residual stresses after quenching and obtaining super – strengthened material in surface layers after intensive cooling. These two factors compensate decrease alloy elements in steel. The paper provides methodology of calculation for achieving maximal effect in residual surface compressive stress formation and super- strengthening of material depending on martensite finish temperature of steel. Effectiveness and benefits are considerable due to saving alloy elements, energy and increasing service life of products. A team of Ukrainian leading specialists is organized to design appropriate software for governing and optimizing hardening processes with the aim of achieving above benefits and make environment clean. New steel and technology of hardening is based on UA Patents No. 109577 and No. 114174.

Keywords: compressive residual stress, super-strengthening, alloy elements decrease, service life increase, local cooling, sprayers, new technology, software, environment, benefits.

1. Introduction

In the paper the new technologies of hardening large steel parts are widely discussed [1–6]. The history of intensive quenching starts in 1960 when it was shown that intensively quenched low hardenability steels provide considerably higher service life of machine components as compared with the alloy steel quenched slowly in oil [7–11]. Within the period of time 1960 and nowadays numerous important investigations were fulfilled which showed the great benefits of intensive quenching [12]. By now, there are great achievements in material strengthening, which by now are successfully implemented by some American steel companies. Moreover, IQ processes were applied to relatively small steel components which were quenched in water flow and only a few considered such opportunity for large steel component like big rollers or rotors which cannot be quenched in directed water flow known as "single part quenching" [12]. In this paper, the new patented in Ukraine alloyed low hardenability steel and technology of cooling are discussed. They can be applied to different sizes of machine components and different steels to provide decrease alloy elements and increase service life of machine components after intensive quenching [1, 2].

2. Steels of optimal hardenability

According to UA Patent No. 114174, alloyed low hardenability steel (0.4–1.2 C; ≤0.20Mn; ≤0.20Si; ≤0.50Cr; ≤1.6Ni; ≤0.25Mo; ≤0.20Cu; 0.03–0.10Al; 0.05–0.12Ti; ≤0.40V; ≤0.035S; ≤0.035P) provides optimal hardened martensitic surface layer with the maximal surface compressive residual stresses in it and bainitic or pearlitic microstructure at the core. Optimizing chemical composition of steel is fulfilled using established by author [2] the similarity ratio (1):

$$\frac{DI}{D_{opt}} = 0.35 \pm 0.095, \tag{1}$$

here DI is critical diameter in m; D_{opt} is diameter of steel part to be quenched in m (UA Patent No. 114174 [2]). A procedure of its use is as follows:

– A steel grade with certain chemical composition is chosen.

– The ideal critical size for this steel is determined.

– The ratio DI/D_{opt} for specific steel part is evaluated and alloy elements are reduced two or three times to satisfy the ratio (1) which must be in a range of 0.2–0.5.

– The part is quenched in condition 0.8≤Kn≤1 by locally moving sprayers [2, 6].

– Intensive quenching is interrupted to provide self-tempering [6].

– The part is tempered at the temperature Ms or higher [6].

Eq. (1) is based on similarity stress distribution which was for the first time discussed in the publications [13–18] and used for software development. If a ratio (1) is satisfied, residual hoop stress distribution in steel component is optimal which is shown in **Fig. 1**.

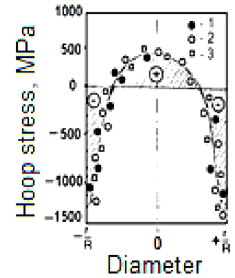


Fig. 1. Residual hoop stress distribution in cylindrical specimens when quenching intensively in water flow or by moving sprayers

3. Super-strengthening effect

To understand the nature of super-strengthening, imagine a superficial layer compressed to the limit (1,200–1,500 MPa) in which there are plates of martensite possessing a greater specific volume than the initial phase structure of supercooled austenite. The period of appearance of such plates is very short and is less than 10^{-6} s. The plates of martensite deform the supercooled austenite that is allocated between them. The higher the cooling rate is within the martensite range, the greater will be the extent to which the austenite is deformed, and the higher is the dislocation density. Consequently, during rapid cooling, there is not enough time for the dislocations to accumulate in the grain boundaries and to form nuclei of future micro cracks; they are frozen in the material. Thus, the superficial layer acts like a blacksmith: under conditions of high stress, the plates of martensite arise explosively, deforming the austenite and creating extremely high dislocation densities, which are frozen during rapid cooling. This process is analogous to low-temperature thermo-mechanical treatment (LTMT) [12].

4. Apparatus for intensive quenching of large steel parts

Apparatus for quenching large steel parts is shown in **Fig. 2**. It consists of two sectioned sprayer which creates round coil when put together [1]. To provide intensive quenching of large steel part, there is no need to agitate a huge amount of water in quench tank. It is enough to provide intensive cooling below sprayer which is moving along the axis of stepped cylinder (roller or rotor) and by this way completely eliminates film boiling and decreases immediately surface temperature of steel part below martensite finish temperature M_F.

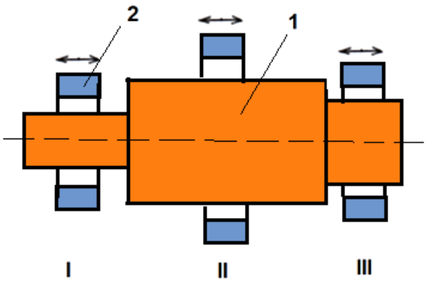


Fig. 2. Apparatus for hardening of large steel parts consisting of two sectioned sprayer moving periodically along the axis in area I, II, and III: 1 is spryer; 2 is rotor [1]

Methodology for evaluating heat transfer coefficients (HTCs) during quenching with sprayers is well known and is widely used in practice [19, 20]. HTC depends on many factors shown in **Fig. 3.**

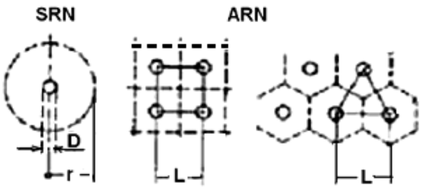


Fig. 3. Positions of round holes in the sprayer used for intensive quenching of large steel part

The average heat and mass transfer coefficients for impinging flow from regular (square or hexagonal) arrays of round nozzles (ARN) may be calculated as described in [7–9] with an accuracy of ±15 %. The generalized dimensionless equation has the following form (2):

$$\bar{N}u = K_1 K_2 Re^{2/3} Pr^{0.42}, \tag{2}$$

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

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

$$f = \frac{(\pi/4)D^2}{A_{sq/hex}}.$$

D is diameter of a nozzle in sprayer; H is a distance from a nozzle (aperture) to the surface to be quenched; and A is the area of the square, hexagon. Dimensionless numbers K_1 and K_2 are connected to the geometry and arrangement of nozzles with respect to the surface to be quenched. The Reynolds number Re is related to the speed of the quenchant at the beginning of the outlet from a nozzle, and the Prandtl number Pr characterizes physical properties of the quenchant. The dimensionless equation of similarity ((2)) is valid within the boundaries of the following values and given parameters [12, 19, 20]:

- $2000 \le Re \le 100000$;
- $0.004 \le f \le 0.04$;
- $2 \le \frac{H}{D} \le 12.$

5. Criteria for direct convection

Direct convection is provided when criterion (6) is satisfied:

$$Bi = \frac{2(\vartheta_o - \vartheta_I)}{\vartheta_I + \vartheta_{uh}}, \tag{3}$$

where

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

$$\vartheta_o = T_0 - T_S;$$

$$\vartheta_{uh} = T_S - T_m;$$

Bi is conventional dimensionless Biot number; T_S is saturation temperature; T_m is bath temperature; $\beta = 3.41$; λ is thermal conductivity in W/mK; R is radius in m.

Calculated HTC from (3) is substituted into Nusselt of (2) that allows evaluating Reynolds number Re which in its turn allows calculating flow velocity of spray or pressure in sprayer to provide direct convection.

Criterion (6) is used when nucleate boiling process should be eliminated. For water, it occurs approximately at 100 °C. However, finish temperature of martensitic transformations for many steels is below 100 °C. In this case, universal correlation (4) is used [12]:

$$\frac{\bar{T}_{sf} - T_m}{\bar{T}_V - T_m} = \frac{1}{\sqrt{Bi_V^2 + 1.437 Bi_V + 1}}, \tag{4}$$

where $\bar{T}_{sf}$ is average surface temperature; $\bar{T}_V$ is average volume temperature, T_m is bath temperature, Bi_V is generalized Biot number.

Example: Calculate HTCs to provide direct convection for cylindrical specimen 50 mm in diameter which should be quenched from 860 °C in water spray at 20 °C. Calculation can be done using equations (6) or (8).

According to (7),

$$Bi = \frac{2(760^\circ C - 20.3^\circ C)}{20.3^\circ C + 80^\circ C} = 14.3,$$

where

$$\vartheta_I = \left[\frac{2 \times 23(760^\circ C - \vartheta_I)}{0.025}\right]^{0.3} = 20.3.$$

According to (9),

$$\frac{\bar{T}_{sf} - T_m}{\bar{T}_V - T_m} = \frac{100^\circ C - 20^\circ C}{480^\circ C - 20^\circ C} = 0.174;$$

$$Bi_V = 5;$$

$$Bi = 14.45$$

that practically is the same. It means that universal correlation can be used to predict direct convection for complicated configurations using (2) and (8). (2) is used to calculate absence of transient nucleate boiling process.

6. Discussion

To perform correctly intensive quenching processes and receive maximal benefits from their practical use, one should pay special attention to martensite start temperature M_S and martensite finish temperature M_F. As seen from **Fig. 4**, coinciding martensite start temperature with self-regulated thermal process delays martensite transformation during transient nucleate boiling process. If at the end nucleate boiling cooling will be interrupted and steel part put immediately for tempering, no martensite transformation at all. It will take place austempering process in cold liquid. This example shows that designer of new technologies must operate with M_S and M_F values. **Table 1** provides these values depending on content of carbon in steel.

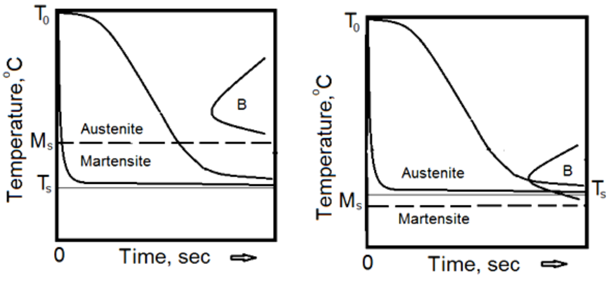
Table 1

Martensite start temperature and martensite finish temperature vs content of carbon in steel

Carbon, %wt	0.2	0.4	0.6	0.8	1.00	1.20	1.4	1.6
M_S, °C	450	350	300	250	210	180	140	100
M_F, °C	380	110	Below 0	Below 0	–100	–105	–110	–115

High carbon steels should be cooled intensively within the convection area to reduce surface temperature of hardened product to bath temperature within a short time because martensite finish temperature is low (**Table 1** and **Fig. 4**).

If intensive quenching process is correctly designed, service life of steel components considerably increases [12, 18].



a *b*

Fig. 4. Relationship: *a* – martensite start temperature; *b* – self-regulated thermal process: T_S is saturation temperature; M_S is martensite start temperature; B is Bainite

7. Conclusions

1. A method for optimizing chemical composition of steels to reduce radically their alloy elements and increase service life of machine components after intensive quenching is developed.

2. A method and apparatus for intensive quenching of large steel products is proposed which simplifies significantly its performance and reduces cost.

3. A new criterion for calculating and creating condition for direct convection is discussed and methodology of calculation is provided.

4. Based on developments, appropriate software for optimizing chemical composition of steel and governing technological process is being elaborated.

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