# Intensive Quenching of Limited - Hardenability Steels Saves Energy and Increases Service Life of Products

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*Abstract:* - Low and limited hardenability steels and their new technology of heat treating in the paper are discussed. It has been shown that standard materials can be used as steels of limited hardenability. In this case there is no need to develop and produce new steel grades. It has been developed a method for the selection of optimal chemical composition of steel on the bases of the correlation DI/D. This allows providing the optimal distributions of residual stresses in the part, which is based on the similarity theory. The steel quenching process for limited-hardenability steels is performed on the basis of new patents. The wide use of limited-hardenability steels in the production may be reached if the appropriate industrial equipment is designed. New patented technologies related to the limited-hardenability steels save the energy resources, increase the service life of steel parts, and increase the labor productivity. For the production of small gears, one can use carburized steels reducing the carburizing time by 30 – 40% at IQ process.

*Key-Words*- Limited hardenability, Optimized composition, Service life, Saving energy, Ecology.

## 1 Introduction

Low and limited hardenability (LH) steels are plain carbon steels characterized by a low content of alloying elements (Cr, Ni, Mo, W, V, etc.). The use of LH steels with an intensive quenching (IQ) method allows full elimination of the carburization process for a variety of steel parts, such as, gear and bearing products, tools, wear parts for different applications. It is based on steel superstrengthening phenomenon and creation of high residual compressive stresses at the surface of intensively quenched steel parts [1, 2]. Both these factors allow to replace expensive alloy steels with plain carbon steels. The unique characteristic of limited hardenability steels is that these alloys only harden to a shallow depth when heated through and quenched. The main idea of this paper consists in creation of the optimal depth of shell which provides optimal stress distribution in quenched steel parts. Since the LH steel core does not harden significantly, the ductility of the core is also maintained. The grain sizes of LH steels are above ASTM 8. Several patents on LH steels have been issued in Russia. A number of technical papers on using the LH steels for gears and bearing products were published in Russia and Ukraine. Elimination of carburizing saves energy and prevents the emissions of tons of gases. Furthermore, the high level of compressive surface residual stresses can eliminate the need for secondary shot peening or surface induction operations. The transition from the hardened case to the ductile core is more gradual that reduces probability of crack formation in the intermediary zone. At present time quench oils and alloying elements are becoming more and more expensive. With the rise in both energy costs and the cost of alloying elements, LH steels, intensively quenched in water, can be widely used for manufacturing gears, bearings, shafts, etc. The paper shows that IQ process optimization for LH steels can be designed on the basis of new patents [3, 4].

## 2 Similarities in the Distribution of Residual Stresses

The intensive quenching process was examined by numerical modeling on the basis of FEM method with subsequent experimental validation. The numerical calculation of current and residual stresses in accordance with the method was performed for cylinder-shaped bodies of different diameters: 6, 40, 50, 60, 80, 150, 200 and 300 mm. Calculations were conducted for AISI 1040 and 1045 steels and for cases when the CCT diagram was shifted to the right by 20 s, 100 s and 1000 s. This permitted subsequent simulations for alloy steels where martensite formation is observed on all cross sections of parts to be quenched. The results of these studies showed that in the case of fulfillment of certain conditions, the distribution of current and residual stresses is similar for cylinders of different sizes. For this condition the following correlation is true [5]:

$$\frac{\Delta r}{R} = idem \quad (1)$$

where $\Delta r$ is the optimal depth of hard layer which is shown in the Fig. 1 on the second tape.

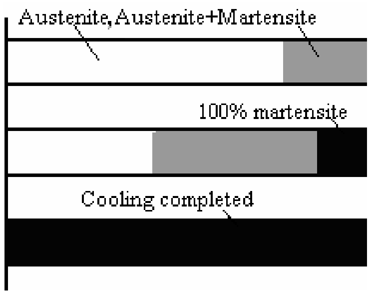


**Fig.1** Relative amounts of microstructural phases present in a steel specimen at the beginning and end of intensive quenching, and at the time when the surface compressive stress reaches its maximum value (see the second tape).

The optimal stress distribution which corresponds to optimal quenched layer is shown on the Fig. 2.

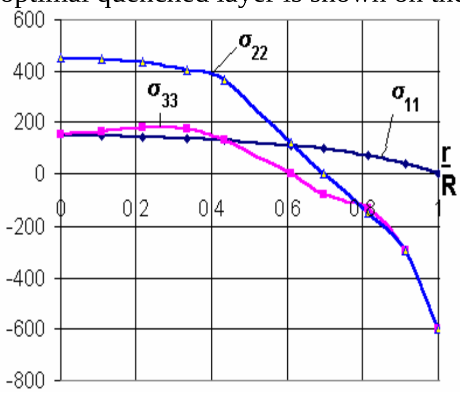


**Fig. 2** The distribution of stresses on the cross section of cylindrical samples of diameter of 6 mm and 60 mm at the time of reaching maximum compressive stresses on the surface. (Bi = 7; Fo = 0.7); 1 – sample of 6-mm-diameter; 2 – sample of 60-mm-diameter.

Computations conducted for a cylinder of 6-mm diameter and 60-mm diameter. In both cases, the martensite was formed throughout the cross-section of the cylinder, which was fulfilled through the shift of the CCT diagram by 100 s.

The tensile stresses at the core of cylinder and compressive stresses at the surface at the moment of reaching optimal quenched layer depending on Biot number *Bi* is shown on the Fig. 3.

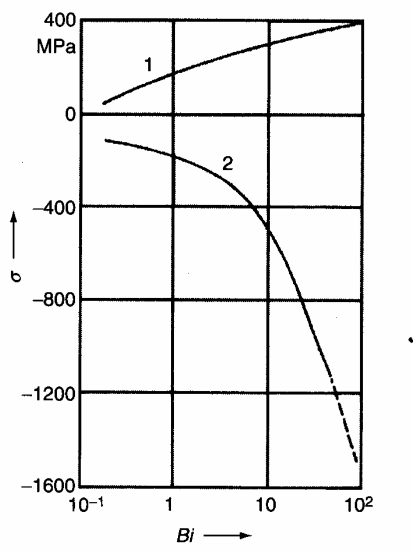


**Fig. 3** Tensile hoop stresses at the core (1) and maximum compressive hoop stresses at the surface (2) for cylinders depending on Biot number *Bi*.

As it was discussed [2, 5, 6], the optimal residual stress distribution in the quenched steel part occurs when the following condition is met:

$$\frac{DI}{D_{opt}} = const. \qquad (2)$$

Here *DI* is the ideal critical diameter or size; *Dopt* is size of the steel part with the optimal stress distribution. Ideal critical diameter is calculated by next equation [6]:

$$DI = \left( \frac{\bar{a} b \tau_M}{\Omega + \ln \theta} \right)^{0.5} \qquad (3)$$

Here $a$ is average thermal diffusivity ($m^2$/s); $\tau_M$ is limit time of the core cooling from the austenitizing temperature to martensite start temperature, providing the formation of 99% or 50% martensite; b is constant depending on the shape of steel part.

The same regularities in stress distribution are true for the LH steel if shell (hardened) layer is optimal.

The ideal cylindrical critical diameter *DI* can be estimated from an equation which has a form [7]:

$$DI = 25.4\ DI_{base} \cdot f_{Mn} \cdot f_{Si} \cdot f_{Cr} \cdot f_{Mo} \cdot f_{V} \cdot f_{Cu\ ...} (mm), \qquad (4)$$

where $f_x$ is the multiplicative factor for the particular alloying element.
Transition to another form of steel parts can be done using equation (3).
The base *DI* and one set of alloy factors are presented in Table 1 . The alloy factors were developed based on data from medium-carbon steels of medium hardenability. The procedure for calculating the hardenability of a steel from the composition includes the following steps:

- Determine the ASTM grain size.
- Determine the chemical composition.
- Determine base *DI* from carbon content and grain size;.
- Determine alloy factors $f_x$;
- Multiply the factors according to Eq.(4)..

**Table 1** Tabulated hardenability factors of steels as a function of carbon content, carbon grain size, and selected alloying elements

| Carbon, % | Base ideal diameter, $DI_{base}$, at following carbon grain size | | | Alloying factor, $f_x$, where element, X, is | | | | |
|---|---|---|---|---|---|---|---|---|
| | No.6 | No.7 | No.8 | Mn | Si | Ni | Cr | Mo |
| 0.05 | 0.08 | 0.075 | 0.070 | 1.17 | 1.04 | 1.018 | 1.108 | 1.15 |
| 0.10 | 0.12 | 0.107 | 0.099 | 1.33 | 1.07 | 1.036 | 1.216 | 1.30 |
| 0.15 | 0.14 | 0.132 | 0.121 | 1.50 | 1.11 | 1.055 | 1.324 | 1.45 |
| 0.20 | 0.16 | 0.151 | 0.140 | 1.67 | 1.14 | 1.073 | 1.432 | 1.60 |
| 0.25 | 0.18 | 0.168 | 0.156 | 1.833 | 1.175 | 1.091 | 1.540 | 1.75 |
| 0.30 | 0.20 | 0.185 | 0.170 | 2.000 | 1.210 | 1.109 | 1.648 | 1.90 |
| 0.35 | 0.22 | 0.200 | 0.184 | 2.167 | 1.245 | 1.128 | 1.756 | 2.05 |
| 0.40 | 0.23 | 0.213 | 0.198 | 2.333 | 1.280 | 1.146 | 1.864 | 2.20 |
| 0.45 | 0.24 | 0.226 | 0.209 | 2.500 | 1.315 | 1.164 | 1.972 | 2.35 |
| 0.50 | 0.26 | 0.238 | 0.220 | 2.667 | 1.350 | 1.182 | 2.080 | 2.50 |
| 0.55 | 0.27 | 0.251 | 0.231 | 2.833 | 1.385 | 1.201 | 2.188 | 2.65 |
| 0.60 | 0.28 | 0.262 | 0.241 | 3.000 | 1.420 | 1.219 | 2.296 | 2.80 |
| 0.65 | 0.29 | 0.273 | 0.251 | 3.167 | 1.455 | 1.237 | 2.404 | 2.95 |
| 0.70 | 0.31 | 0.283 | 0.260 | 3.333 | 1.490 | 1.255 | 2.512 | 3.10 |
| 0.75 | 0.32 | 0.293 | 0.270 | 3.500 | 1.525 | 1.273 | 2.620 | 3.25 |
| 0.80 | 0.33 | 0.303 | 0.278 | 3.667 | 1.560 | 1.291 | 2.728 | 3.40 |
| 0.85 | 0.34 | 0.312 | 0.287 | 3.833 | 1.595 | 1.309 | 2.836 | 3.55 |
| 0.90 | 0.35 | 0.321 | 0.296 | 4.000 | 1.630 | 1.321 | 2.944 | 3.70 |
| 0.95 | … | … | … | 4.167 | 1.665 | 1.345 | 3.052 | … |
| 1.00 | … | … | … | 4.333 | 1.700 | 1.364 | 3.160 | … |

**Table 2** Chemical composition of AISI 4340 and 1040 steels

| Steel | C | Mn | Si | Ni | Cr | Mo |
|---|---|---|---|---|---|---|
| 4340 | 0.38-0.43 | 0.60-0.80 | 0.20-0.35 | 1.65-2.0 | 0.70-0.80 | 0.20-0.30 |
| 1040 | 0.37-0.44 | 0.60-0.90 | < 0.15 | - | - | - |

In the Table 2 the chemical composition for both steels is presented.

According to equation (4) and Table 1 the ratio $DI/D = 0.3$ if thickness of half axles is 62 mm that provides optimal stress distribution in the steel part.

# 3 Intensive Quenching of LH Steels

To have the best results the steel parts should be quenched in the conditions:

$$Bi = \frac{2(\vartheta_0 - \vartheta_I)}{\vartheta_I + \vartheta_{uh}}, \qquad (5)$$

where

$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3}$. For water at 20°C: $\beta$=7.36. $\vartheta_0 = T_0 - T_s$; $T_o$ *is* initial temperature of steel part at the moment of immersion into quenchant, for example $T_o$ = 870°C; $T_s$ *is* saturation (boiling) temperature; $T_m$ is medium temperature; $T_m$

= 20°C; $\vartheta_{uh} = T_s - T_m = 100^0 C - 20^0 C = 80^0 C$, $\lambda$ is thermal conductivity; $\lambda$ = 22 W/mK. *R* is radius. In the left and right side of the equation (5) $\vartheta_I$ is the same symbol. It can be evaluated step by step calculation.

In the Fig. 3 results of fatigue testing of truck half-axles are presented. The half-axles of diameter 62 mm were made of AISI 4340 and 1040 steels. The half-axles made of plain carbon steels were intensively quenched providing optimal residual stress distribution in the steel part. The half-axles made of alloy steel 4340 were quenched in oil. Instead of plain carbon steel, the half-axles which were intensively quenched were stronger (see Table 3).

**Table 3** Fatigue tests of KrAZ truck half-axles

| Quenching method | Steel grade | Number of cycles to fracture | Note |
|---|---|---|---|
| Oil | AISI/SAE 4340 | $(3.8\text{-}4.6)10^5$ | Half-axles were destroyed |
| Intensive water spray cooling | AISI/SAE 1045 AISI/SAE 1040 | $(3.0\text{-}3.5)10^6$ | No fractures observed |

As is seen from the tables, the truck half-axles made of 1040 and 1045 steels and intensively quenched to the optimal depth at the surface layer, have much longer service life than the half-axles made of 4340 steel but quenched in oil. In addition to the increase in the service life, the alloying elements are also saved. Thus, per one ton of steel, the saved is 16-20 kg of nickel, 7-8 kg of chromium and 2-3 kg of molybdenum. Besides, this technology is ecologically clean, saves the expensive oil and increases the labor productivity. The increase in the service life of half-axles is due to the high compressive stresses at the surface and additional strengthening (superstrengthening) of material. The intensive quenching can be fulfilled by using water flow cooling or spray cooling. Some information about both methods is discussed below.

### 3.1 Water Flow Cooling

Similarity of the processes of heat transfer at the forced convection in directed water flow is described by equations of similarity as follows:

$$Nu = f(\mathrm{Re}, \mathrm{Pr}).$$

$\mathrm{Re} = \frac{wD}{\nu}$ is criterion of Reynolds; $\mathrm{Pr} = \frac{\nu}{a}$ is criterion of Prandtle.

The similarity of directed streams of a liquid in ring channels of any cross-section shape has the form [8]:

$$\overline{N}u = 0.021\,\mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.43} (\mathrm{Pr}_m / \mathrm{Pr}_{sf})^{0.25} \cdot \varepsilon_e \qquad (6)$$

Here the determining temperature is the average temperature of a quenchant far from a surface to be quenched, and the determining size is equivalent diameter $d_{eq}$, equal to fourfold areas of the cross-section of the ring channel, divided by its full wetted perimeter disregarding which part of this perimeter participates in heat transfer: $d_{eq} = \frac{4S}{u}$,

where $S$ is the area of cross-section of the channel;

$u$ is the full perimeter of the channel;

$\mathrm{Pr}_m$ is Prandtle number for a quenchant far from the surface;

$\mathrm{Pr}_{sf}$ is Prandtle number for a quenchant near a surface to be quenched.

For pipes of round section the equivalent diameter $d_{eq}$ is equal to geometrical diameter *D*.

### 3.2 Spray Cooling

Similarity of the processes of heat transfer at spray cooling is described by equations [9, 10]:

$$\overline{N}u = K_1 \cdot K_2 \cdot \mathrm{Re}^{\frac{2}{3}} \cdot \mathrm{Pr}^{0.42}, \qquad (7)$$

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 $\mathrm{Re}$ is connected with the speed of the quenchant in the beginning of the outlet from a nozzle, and the number $\mathrm{Pr}$ characterizes physical properties of the quenchant. The dimensionless equation of similarity (6) is fair within the boundaries of the following values and given parameters:

$$2000 \le \mathrm{Re} \le 100000; \quad 0.004 \le f \le 0.04;$$

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

Author [8, 9] considers dimensionless equation (7) for nozzles of different configuration which are shown on the Fig. 4.

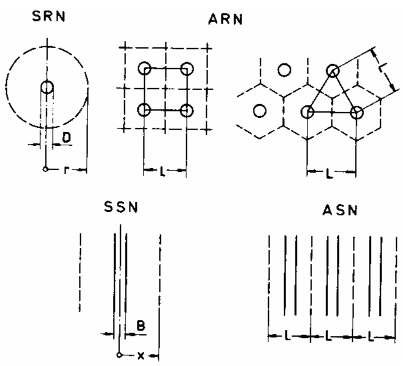


**Fig. 4** Possible configuration of nozzles

From the equations (5), (6) and (7) it is possible to evaluate water flow to eliminate non – stationary nucleate boiling (self-regulated thermal process). Such condition provides additional strengthening of the material. Some practical use of LH steels in the industry is shown in the Table 4.

Table 4 presents the results of experiments as for the use of LH steels for such parts as gears, bearing rings and truck leaf springs. The advantage of LH steel usage is that even in bodies of complex shape a uniform shell is formed, which creates high compressive stresses at the whole surface. As a result of such distribution and soft core, the quench crack formation does not take place in bodies of the complex shape. The saving of energy resources is due to the elimination of carburization, which is a highly power-consumable process. Usually carburized parts are quenched in oils. The transfer to LH steels allows to replace oils with plain water, which means that it is ecologically clean ecology. So, in addition to increase in the service life this technology is ecologically clean, saves energy resources and allows to reduce the weight of the finished parts.

**Table 4** Production Applications of Intensive-Quenched Limited- Hardenability Steels [2].

| Application | Former Steel and Process | New Steel and Process | Advantages |
|---|---|---|---|
| Gears, modulus m = 5 – 8 mm | 18KhGT | 58 (55PP) | No carburizing, steel and part cost decrease, durability increases |
| Large modulus gears, m = 10–14 mm | 12KhN3A | ShKh4 | No carburizing, durability increases 2 times, steel cost decreases 1.5 times |
| Truck leaf springs | 60S2KhG | 45S | Weight decreases 15 – 20%, durability increases 3 times |
| Bearing rings thicker than 12 mm | ShKh15SG and 20Kh2N4A | ShKh4 | No sudden brittle fracture in service, durability increases 2 times, high production rate |

## 4 Conclusions

1. It has been shown that standard materials can be used as steels of limited hardenability. In this case there is no need to develop and produce new steel grades.
2. The author has developed a method for the selection of optimal chemical steel composition on the base of the DI/D correlation with the optimal distributions of residual stresses in the part, which is based on the similarity theory.
3. The steel quenching process for limited-hardenability steels is performed on the basis of new patents.
4. The wide use of limited-hardenability steels in the production may be reached if the

appropriate industrial equipment is designed.

*5.* New patented technologies related to the limited-hardenability steels save the energy resources, increase the service life of steel parts, and increase the labor productivity.

*6.* For the production of small gears, one can use carburized steels reducing the carburizing time by 30 – 40% at IQ process.

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