MECHANISM OF SURFACE COMPRESSIVE STRESS FORMATION BY INTENSIVE QUENCHING

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ABSTRACT: Numerical simulation and experimental results of investigations conducted to determine the formation of optimal surface compressive stresses using intensive quenching methods. Based on these results, recommendations are provided for the improvement of heat treatment of machine parts and equipment. In addition to the formation of maximum surface compressive stresses, advantages of using controlled-hardenability steels are also discussed.

1. INTRODUCTION

To improve the fatigue strength of many materials such as automotive and truck springs and bearings and the impact strength, such as punches for machine tools, it is important to maximize surface compressive stresses. Currently, this is most commonly accomplished by carburizing and induction heat treating. However, another relatively little-known method to accomplish this has been designated as "intensive quenching" [1,2]. Intensive quenching refers to the rapid cooling of austenitized steel sufficiently fast to obtain maximum surface compressive stresses.

The development of new intensive quenching technology during phase transformation to provide optimal depth of hardness is of great interest. If intensive quenching systems are not properly engineered the large thermal and transformational stresses which may be produced may be sufficient to result in material destruction. For this reason, it is important to determine residual stresses arising from cooling conditions and phase transformations occurring with the steel alloy of interest with respect to CCT or TTT diagrams for the transformation of supercooled austenite. The primary focus of these computations is the formation of the so-called "optimal layer".

It has been known for a long time that simple carbon steel parts could be intensively cooled without cracking. Intensive quenching also provided a greater depth of hardening. Generally, parts constructed through-hardened alloy steels have been quenched in oils or polymer solutions because it was believed that if a part was cooled through to the core, tensile stresses would always be formed at the surface. In 1983, numerical simulations were conducted to examine the use of intensive quenching with parts of complicated configuration [3]. These results showed that in through-hardened parts, it is possible to attain compressive stresses if Biot number is sufficiently high (greater than 18) [3]. It was an unexpected result since it was contrary to the existing general knowledge of that time. At the same time it was established that as as the martensitic transformation moved from the surface to the core, compressive stresses increased to a maximum and then, in the case of through-hardening, the stresses decreased and became tensile. n this basis it was established that there was an optimal

depth of hardeneder, corresponding maximum surface compressive stresses. It was also established that there is a similarity in the distribution of residual stresses.

These factors radically transform the technology of steel heat treatment processes because instead of using oils or polymer solutions it was shown that it is possible to quench alloy steels using water. Because of the principle of similarity it is possible to design IQ process and determine the cooling time using these regularities. In reference [3] it was shown that for unhardened steels compressive stresses are formed at the surface and that the tensile stresses are formed in the core are relatively small in magnitude because the process of intensive cooling is interrupted at the time when the core is austenitic and still viscous. Therefore, if compressive stresses are formed at the surface and tensile stresses in the core, the tensile stresses are relaxed because the material is viscous. Thus, it is possible to significantly intensify the heat transfer during quenching for through-hardened carbon and alloy steels without cracking them. This means that probably in 99% of all cases it is possible, with appropriate quench system design, to replace oil or polymer quenchants to just water. This will result in significant material cost reduction, improvement in part durability, and decreased pollution. This paper will describe these issues in detail.

2. BASIC REGULARITIES OF THE FORMATION OF RESIDUAL STRESSES

Calculation of the thermal and stress-strain states of steel parts was performed using the proprietary code "TANDEM-ANALYSIS" [4,5]. At each time and space step, the calculation results were compared with the CCT or TTT diagrams of the supercooled austenite transformation, and new thermophysical and mechanical characteristics for the next step were selected depending on the structural components. The calculation results are: temperature fields, material phase composition, migration of points in the volume which is calculated, components of stress and strain tensors, intensities of stress and strain, and the field designated as: "safety factor" which indicates the stresses for which the material will be destroyed. These values are presented in the form of tables and isometric lines that permit the observation of the kinetics of transformational phase changes during heating and cooling.

Using this software, the intermediary and residual stresses were determined which are dependent on the cooling intensity for cylindrical specimens constructed from different steel grades. Similar calculations were performed for quenching the parts of complex configuration, such as dies, punches, bearing rings.

The results from these studies showed:

- It was confirmed [3] that with the quench intensity increase, the residual stresses grow at first, then become lower, with the further increase of Biot number subsequently becoming compression stresses (Fig. 1).
- The dependence of residual stresses on the cooling rate of the specimen core at temperature of 300°C is readily represented. It was shown that the maximum probability of quench crack formation and maximum tensile stresses coincided with the cooling rate [2,6-8].
- The absence of quench cracks when quenching alloyed steels under intensive heat transfer can be explained by high compression stresses arising at the surface of the parts being quenched. The mechanism of high compression stress formation in the process of intensive heat transfer is described in Refs. [3,8,9].

The results obtained were confirmed experimentally by measuring residual stresses at the surface of quenched parts (specimens) using X-ray crystallography [10].

The intricate character of residual stress dependence on cooling rate can be explained by "superplasticity" and variation of the phase specific volume at phase changes [11]. Under the conditions of high-forced heat transfer (Bi→∞), the part surface layer is cooled initially to ambient temperature, while the core temperature remains essentially constant.

In the process of cooling, the surface layers should compress. However, this process is hampered by a heated and expanded core. That is why, compression is balanced by the surface layer expansion at the moment of superplasticity. The higher the temperature gradient and the initial part temperature, the greater the surface layer expansion. Upon further cooling, the core is compressed because the surface layer begins to shrink towards the center with corresponding increases in compression stresses. When the core begins to cool, transformation of austenite into martensite occurs. The specific volume of martensite is higher than that of austenite. For this reason, the core swelling occurs that causes the surface layer extension at moderate cooling.
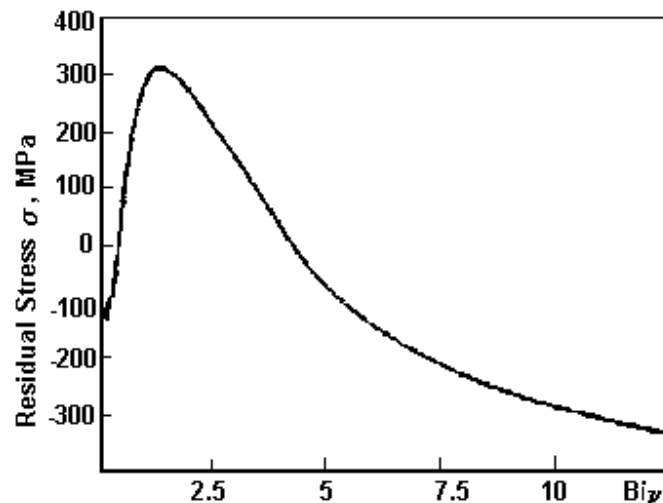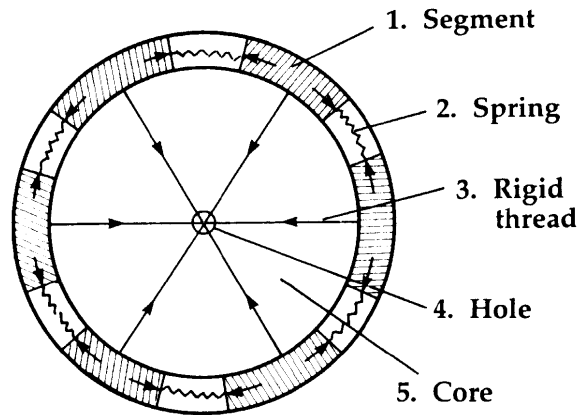

Fig. 1. Residual hoop stresses at the surface of a cylindrical specimen versus generalized Biot number.

At Bi→∞, the surface layer is stretched to a maximum and therefore, despite swelling, it cannot completely occupy an additional volume formed due to the external layer extension. It is just under the conditions of high-forced heat transfer that compression stresses occur in the surface layer. More detailed information about the calculation results can be found in Refs. [11,12,13].

4. MODELING OF RESIDUAL STRESS FORMATION

The reason why intensive quenching results in high compressive stresses can be explained using a simple mechanical model shown in Fig. 2 which consists of a set of segments (1) joined together by springs (2) to form an elastic ring. The segments are placed on a plane surface and connected with rigid threads (3) which pass through a hole (4) in the center of the ring and are attached to the opposite side of the plane

surface. The mechanism of the formation of compressive stresses on the surface of steel parts is very important to the development of new techniques for thermal strengthening of metals, such as intensive quenching.

Fig. 2. Mechanical model that can be used to explain the formation of hoop stresses at the surface of a cylindrical specimen during intensive quenching.

Now consider the processes that occur while quenching a cylindrical steel specimen and how they would affect the behavior of the model. Assume that the specimen is being quenched under conditions of intensive cooling. In this case, the cylinder's surface layer is cooled to a certain depth while the core remains at almost the austenizing temperature and considerably expanded in volume. Let the cooled surface layer correspond to the model's segmented ring.

Because metals contract when cooled, the ring's segments (1) also will contract. The springs (2) will then extend by an amount that corresponds to the increase in tangential tensile stresses. However, when the surface layer is further cooled, austenite transforms to martensite, which has a high specific volume. That is why the cooled layer enlarges or swells.

Now imagine that the segments expand. In this case, resulting compression of the springs corresponds to the appearance of tangential compressive stresses on the surface of the part. With additional time, the temperature of the specimen's core drops, and its diameter decreases. In the model, the core is represented by the smaller blank circle, which is held in tension by the rigid threads.

When the threads are taut, the springs also will compress. The level of hoop compressive stresses will increase until the austenite in the core of the part transforms to martensite. The core will then start to swell, because the specific volume of martensite is greater than that of austenite, which causes the compressive stresses to decrease. In the model, this would be reflected by an enlargement of the blank circle, and a resulting decrease in the springs' compressive power.

5. WHY COMPRESSIVE STRESSES REMAIN IN THE CASE OF THROUGH-HARDENING

During intensive quenching, the temperature of the core almost does not change during the first period of time, and the temperature at the surface instantly drops to the martensite start temperature M_s. At the surface tensile stresses are formed. At the beginning of martensite transformations the phenomenon of superplasticity occurs. Due

to tensile stresses and superplasticity, the surface stress layer obtains the shape of the part, for example, a cylinder, and the surface layer becomes essentially extended. Then, martensite transformations occur, producing a surface layer with increased volume. The core cools to the martensite start temperature and because of greater specific volume of the martensite, the core starts to expand. However, this volume is not sufficient to fill that initial volume formed by the shell. It looks like the formation of the empty space between the core and shell, and the core pulls this surface layer to itself. In Fig. 6, this process can be illustrated by threads pulling the shell to the core resulting in the formation of compressive stresses at the surface.

In the case of conventional slow cooling the difference of temperatures between the surface and core at the time of the martensite start temperature is not large. Therefore, the initial volume of the shell is not large either. In this case, when the core expands, the volume of the core becomes greater than the initial volume of the shell and the core expands the surface layer and it causes fracture. It is similar ice cooling in a bottle, which causes the destruction of the latter. Calculations of the linear elongation factor, show that changes in the surface layer and volume of the core support this fact since the specific volume of martensite is greater than austenite by 4%.

6. SIMILARITY IN THE DISTRIBUTION OF RESIDUAL STRESSES

The intensive quenching mechanism described above was examined by numerical modeling with subsequent experimental validation using a steel part. The numerical calculation of current and residual stresses in accordance with the method described above was performed for cylindrical bodies of different diameters: 6, 40, 50, 60, 80, 150, 200 and 300 mm. Calculations were conducted AISI 1045 steel and for cases when the CCT diagram is 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 intermediate and residual stresses is similar for cylinders of different sizes. This condition is met the following correlation:

$$\theta = F(\overline{Bi}, \overline{Fo}, r/R), \tag{10}$$

where

$$\theta = \frac{T - T_m}{T_0 - T_m}; \qquad Bi = \frac{\overline{\alpha}}{\overline{\lambda}}R = idem; \qquad Fo = \frac{\overline{a}\tau}{R^2} = idem.$$

For this case average values of heat conductivity and thermal diffusivity of the material within the range from T_m to T_0 are used. Despite this, there is a good coincidence of the character of the distribution of current stresses in cylinders of different sizes.

Fig.3 represents the results of 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. For the comparison of current stresses, the first time moment was chosen when compressive stresses on the surface of the cylinder to be quenched achieve their maximum values. For cylinder of 6-mm diameter this time was 0.4 s and for the cylinder

of 60-mm diameter the maximum compressive stresses on the surface are achieved after 40 s provided that $Bi = \dfrac{\alpha}{\lambda} R = idem$. The latter was determined by calculating current and residual stresses for 6-mm-diameter cylinder with α=30000 W/m^{2}K, and for 60-mm-diameter cylinder with α=3000 W/m^{2}K. For both cases Bi=45. Correspondingly, for both cases maximum compressive stresses were reached at Fo=0.24, that is, for 6-mm-diameter cylinder at τ=0.4 s, and for 60-mm-diameter at τ=40 s.

The same values of hoop and tangential values are obtained at the same correlation of r/R (see Fig. 3). Thus, hoop stresses for both cases are zero at r/R=0.65, that is, for 6-mm-diameter cylinder the hoop stresses are zero at r = 1.95 mm, and for 60-mm-diameter cylinder are reached at r = 19.5 mm.
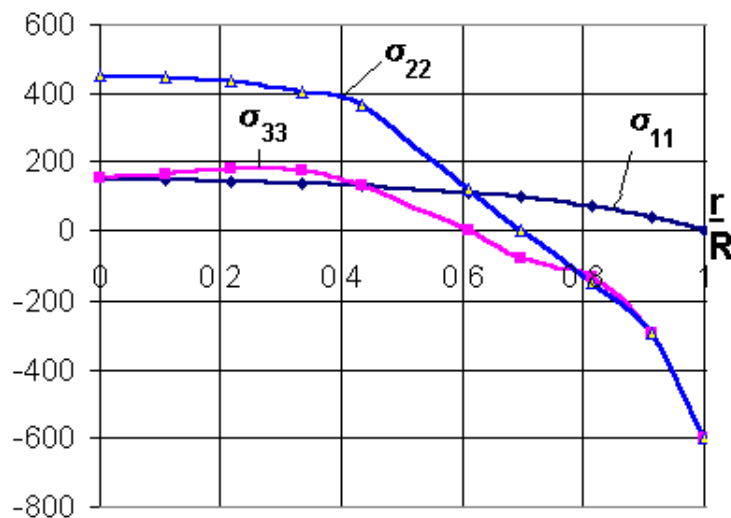
Fig. 3. The distribution of stresses on the cross section of cylindrical sample of diameter of 6 mm and 60 mm at the time of reaching maximum compressive stresses on the surface. (ε_1=7; Fo=0.7); 1 – sample of 6-mm-diameter; 2 – sample of 60-mm-diameter.

More accurate modeling of the hardening process can be fulfilled with the use of water-air cooling, which permits a variation of the heat transfer coefficient by a relationship set in advance. Knowing the cooling conditions, for example, for a turbine rotor, it is possible to select conditions for the rotor and to model the function so that the Bi=f(T) will have have the same value. In this case, there will be similarity in the distribution of residual stresses. In practice, it is advisable to investigate the distribution of residual stresses in large-size power machine parts by models made in accordance with theorems of similarity with regard to necessary conditions of cooling and appropriate CCT diagrams.

7. SOME ADVICE ON HEAT TREATMENT OF MACHINE PARTS

It is of practical interest to investigate the effect of the heat transfer intensification process during the period of time when austenite is being transformed into martensite. Such investigations can be used in two-step quenching, when the transformation of austenite into martensite is delayed during the first step because parts are quenched in

hot oils or liquid medium under pressure, or in high-concentration aqueous salt solutions having high boiling points.

The second step of cooling is made in the area of convective heat transfer, where the transformation of austenite into martensite primarily occurs. The process of the transformation during the convective heat transfer can occur in both cases of great values of Biot number and small cooling rates. During the transformation of austenite into martensite, the cooling process is usually reduced in practice because of the fear that high cooling rates in the martensite range will fracture the material or produce large distortions. The investigations made earlier showed that heat transfer intensification in the martensite transformation range exhibits a favorable effect upon the distribution of residual stresses and also reduces distortion. In particular, the example of two-step cooling of bearing rings made constructed from ShKh15 steel has shown that during the intensive cooling in the martensite range the cone distortion of rings is significantly reduced [14]. The result obtained is practically important not only because the cooling intensification results in increase in cost and time saving but also because in the case of intensive cooling in the martensite range it is possible to achieve high mechanical properties of material, increased strength, and the plastic properties of material are improved [1].

For further validation, the simulation of carburized pin hardening has been performed for a pin constructed of 14KhGSN2MA steel. The carburized pin was first cooled slowly in hot oil (MS-20) to temperature of 220°C, and then after allowing temperature to become uniform throughout the cross section, it was quenched in different media exhibiting different heat transfer coefficients.

The simulation has been conducted for hardening process with different heat transfer coefficients during thesecond stage of cooling. These results showed that while cooling is intensified, compressive stresses in the carburized layer grow and conical distortion of the pin is reduced. In this case, tensile stresses vary insignificantly. Thus, it has been established that cooling intensification in the martensite range exhibits a favorable effect upon the distribution of residual stresses and also reduces the distortion of parts being quenched. This can be used for the development of advanced technology of bearing ring hardening reducing oval distortion of rings and conical distortions while the heat transfer process is intensified. It can be also used for the development of advanced technology of heat treatment for tools and machine parts, in particular, cooling treatment. For example, carburized pins of gas-turbine aviation engine after oil quenching were treated by cooling at 70°C. This treatment is usually made by air cooling in special refrigerators. However, It is advisable in the case of cooling treatment to cool carburized parts as intensively as possible.

9. SHELL HARDENING OF BEARING RINGS (TSH)

The information provided above demonstrates the existence of the optimal depth of hardened layer for bodies of simple shape. It has been emphasized that there is a similarity in the distribution of hardness on the cross section for bodies of simple shape with regard to the size, that is,

$$\frac{\Delta r}{R} = const \, ,$$

where Δr is the depth of the martensite layer (shell), and R is the radius of cylinder or ball (or half width of the plate). It should be noted that the optimal hardened layer

corresponds to the best stress distribution on the surface. In this case, compressive stresses are much higher than when the steel is martensitic throughout the cross section.

Heating at TSH

For TSH, comparatively slow induction heating with isothermal holding at the hardening temperature was used. The required specific high frequency generator power is usually about 0.05 – 0.2 kW per 1 cm^2 of surface area of heated parts. For example, for rings of railway car bearings total heating time is about 3 min including isothermal holding at hardening temperature (820°-850°C) for 50-60 s.

The heating procedure provides nearly uniform heating of rings of complex shape, required degree of carbides dissolution and saturation of austenite by carbon (0.55-0.65%), the fine austenitic grain being the same. (Not worse than No.10, GOST 5639-82. The diameter of grains is an average of 0.01 mm).

Quenching at TSH

Quenching is carried out in special devices by intense water stream or shower from pumps with pressure 1-4 atm. Total water consumption is not large because the closed-circuit water cycle is used (water tank-water pump-quenching device-water tank). A small amount of cold water is added into the tank to prevent water from heating above 50°C.

The design of quenching devices should guarantee velocity of water with respect to the surface of quenched parts in the order of 10-15 m/s. Water inside the devices should be under redundant pressure (1.5 – 3 atm.). Time of intense water quenching should be limited to allow self-tempering of parts at 150-200°C.

10. NEW METHODS OF QUENCHING

There are two methods of reaching the optimal depth of hard layer at the surface.

1. For each specific steel part a special steel grade is selected, which provides the optimal hard layer and maximum compressive stresses at the surface. When the sizes of the part are changed, different steel grades are selected providing meeting the condition $\Delta r/R = const$.

2. Steel part quenching is made so that $0.8 \leq Kn \leq 1$ and the process of intensive cooling is interrupted at the time of reaching maximum compressive stresses at the surface. In this case, the optimal depth of hard layer is reached automatically. This method was protected by inventor's certificate in 1983, which became a patent of Ukraine in 1994 [15].

To confirm the above statements, refer to Ref.[16] where a method of IQ-quenching steel parts by using intensive jet cooling is described. The method of intensive cooling is applied to superficial hardening of small parts (shafts, axes, pinions, etc.) made of alloy steels. A very high intensity of cooling is achieved that yields a 100 percent martensite structure in the outer layer and high residual compression stresses. It should be noted that under the conditions of very intensive cooling the strain decrease is observed. While treating the parts of complex configuration, it is necessary to use

several combined jets to prevent steam jacket formation. A disadvantage of this method is the high cost of the equipment.

The character of changes in the current stress at the surface of the parts being quenched depending on various intensities of cooling will be examined in more detail. Over time, small tensile stresses have occurred upon initial immersion of the surface of the specimen to be quenched, and then during martensite layer formation these stresses transform into the compressive stresses that achieve their maximum at a certain moment of time and then decrease (Fig. 4). The current stresses become residual which can be either tensile or compressive depending on the cooling intensity. The maximum tensile stresses correspond to the maximum compressive stresses in the control layer of the part being quenched (Fig. 5).

The mechanism of the current stress formation is as follows. When the part is completely in the austenite state, there arise tensile stresses that transfer into the compressive ones in the process of the martensite phase formation and due to increase of its specific volume. The larger part of austenite is transformed to martensite and the larger the martensite layer is, the higher the compression stress. The situation goes on until a sufficiently thick martensite crust is formed resembling a rigid vessel that still contains the supercooled austenite in the supercooled phase. The further advance of martensite inside the part causes the effect of water freezing in a glass vessel [11]. Due to the core volume increase at martensite transformations, either decrease of compressive stresses in the surface layers or destruction of the external layer will take place if the phase specific change is large enough and the external layer is insufficiently stretched and strong. Under such conditions, compression stresses in the surface layer change over to stress state that cause destruction in the surface layer.

Reduction of compressive stresses at the further advance of martensite into the part to be quenched is caused by the parting action that is attributed to variation in the phase specific volume in the core.
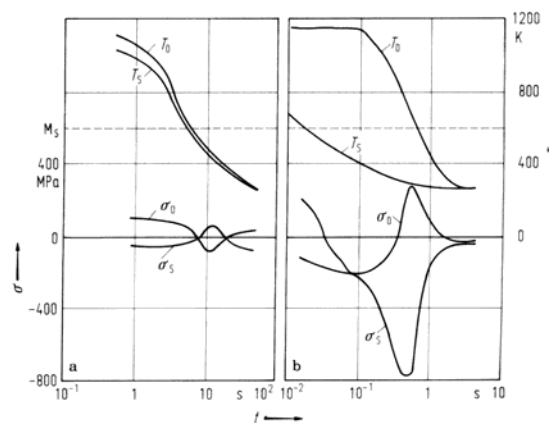
Fig. 4a,b. Change of current hoop stresses at the surface (σ_s) and in the center (σ_c) of the cylindrical specimen being cooled under various heat transfer conditions [12]. a) Slow cooling; b) Intensive cooling
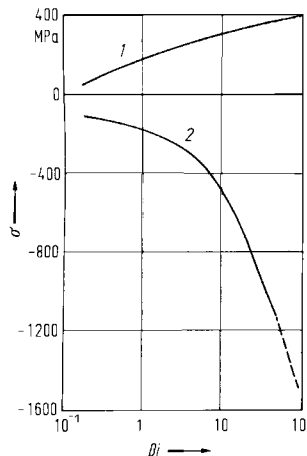
Fig. 5. Maximum compressive hoop stresses at the surface (2) and tensile stresses in the center (1) of the cylindrical specimen of 6 mm in diameter versus Biot number

If the process of intensive cooling is stopped at the moment of achieving the maximum compression stresses, and isothermal holding is realized at the temperature of the martensite start (Ms.) then the martensite phase advance will cease and sufficiently high compression stresses can be fixed. They will slightly decrease due to the isothermal holding at which stress relaxation takes place.

An optimal depth of the quenched layer that depends on part dimensions corresponds to maximum compression stresses.

Using the calculation methods developed and the potentialities of the software package "TANDEM-ANALYSIS" [3, 5] the time of achieving the maximum for bodies of arbitrary axisymmetric form being quenched under various heat transfer conditions can be determined..

The degree of intensive cooling can be characterized by Bi_V number or by Kondratjev number Kn. There is a universal interconnection between these numbers

$$Kn = \Psi \cdot Bi_V = \frac{Bi_V}{\sqrt{Bi_V^2 + 1.437 Bi_V + 1}} \qquad (1)$$

 which is valid for bodies of various configurations.

The author of the well known handbook "Theory of Heat Conduction" A.V. Lykov has called equation (1) an important relation of the theory of regular conditions [17]. Criterion $Kn = \Psi Bi_V$ is the main value determining the heat transfer mechanism of the body. It was named Kondratjev number (criterion) in honor of the outstanding thermal scientist G.M. Kondratjev.

It appeared that the curves $Kn=f(Bi_V)$ for geometrically different bodies (sphere, parallelepiped, cylinder, etc.) were located so close to each other that practically all the family could be replaced by a single averaged curve [17].

The parameter criterion Ψ characterizing the temperature field non-uniformity is equal to the ratio of the body surface excess temperature to the mean excess temperature over the body volume. If the temperature distribution across the body is uniform $(Bi_V \to 0)$ then $\Psi = 1$. As the temperature non-uniformity increases, Ψ decreases. At $\Psi = 0$, the temperature distribution non-uniformity is the highest $(Bi \to \infty,$ while $T \to T_\infty)$

Thus, Kondratjev number characterizes not only the temperature field non-uniformity but also the intensity of interaction between the body surface and the environment. Kondratjev number is the most generalizing and the most universal value, which may serve to describe the cooling conditions under which compression stresses occur at the surface of various bodies. For rather high compression stresses to occur at the surface of the part being quenched it is sufficient to meet the following condition:

$$0.8 \leq Kn \leq 1.$$

On the basis of regularities mentioned above, a new method of quenching was developedso that alloy and high-alloy steel parts are cooled under conditions of high intensive heat transfer $(Kn \geq 0.8)$ up to the moment of reaching maximum compression stresses at the surface with the following isothermal holding under temperature Ms [18]. A year later, similar quenching method was proposed in Japan [19].

In accordance with the method mentioned, alloyed steel parts are quenched in such a way that a very hard surface layer of the given depth and an arbitrarily hard matrix are obtained. An example of such method realization is given below. An alloy steel specimen containing (in %) 0.65-0.85 C; 0.23-0.32 Si; 0.4-0.9 Mn; 2Ni; 0.5-1.5Cr; 0.1-0.2Mo is heated up to 800 — 850°C and spray quenched with water fed under pressure of 0.4—0.6 MPa during 0.2-0.8 s. The specimen is subject further to isothermal heating at 150-250 °C for 10- 50 minutes [19]. It is obvious that the spray quenching under high pressures provides intensive cooling $(Kn > 0.8)$ that is completed when a certain depth of the composition quenched layer is achieved.

For the steel composition cited, the temperature of the martensite start is within the range of 150-200°C. The isothermal holding time at this temperature (about 10-15 minutes) is chosen from CCT diagrams of supercooled austenite dissociation in such a way that to provide this dissociation into intermediate components in the part central layers.

The analysis of the methods described shows that various authors have come independently to an identical conclusion that is a rather pleasant coincidence because it testifies to urgency and authenticity of the technology being studied.

Structural steel transformations during quenching are accounted through dependencies of thermal-physical and mechanical properties of the material on the temperature and time of cooling in accordance with CCT diagram for the transformation of supercooled austenite. The method has been proved by a number of test problems [20]. The error of calculations was ≤3% for temperature and ≤12% for stresses, which provides grounds for using this method for the study of regularities of changes in thermal and stress-strain state of parts to be quenched with regard to cooling conditions and character of structural steel transformations.

The calculation of current and residual stresses for cylindrical sample of 6-mm diameter made out of 45 steel was made for different heat transfer coefficients, so that Bi changed from 0.2 to 100. The temperature of sample heating is 1300 K.
The investigations have shown that as far as the process of cooling is intensified, the residual stresses on the surface of cylindrical sample firstly increase reaching the maximum value at Bi=4, and then when Bi=18, become negative, and as far as Bi grows, they become compressive. At Bi=100 the hoop stresses σ_{33} reach the value of 600 MPa.

The facts observed can be summarized as follows:

- When Bi is small, there is insignificant temperature gradient in the body. As far as austenite is transformed into martensite, due to the large specific volume of martensite, the stresses appearing first on the surface are not large and compressive. However, when the martensite forms at the center of the sample, large forces moving aside appear, which result in the tensile stresses on the surface.

- In the case of intensive cooling (Bi>20) martensite transformations start in thin surface layer of the sample, while the temperature at its other points is high.

- The greater Bi number is, the greater the gradient in the surface layer is, and the further from the axis the layer of freshly formed martensite is. As far as inner layers become cooler, two processes fight against each other: process of shrinking for the account of the temperature reduction and process of expansion of the material for the account of the formation of martensite having big specific volume in comparison with austenite. In the case Bi>20 the process of shrinking prevails in inner points of the sample. Thus, in the cooled sample the surface layer appears to be shrunken, because of shrinkage, the inner layers of the sample try to move initially formed layer of martensite closer to the axis.

- In the case of a small temperature gradient (Bi<<18) the outer layer of freshly formed martensite, in comparison with cold state, is lesser shifted from the axis; for this reason in this case tensile residual stresses will appear for the account of increase in the specific volume of the material during martensite transformations in inner layers. It is obvious that there exist such value of Bi that forces connected with material shrinking compensate each other. In this case on the surface of quenched sample residual stresses are zero (Bi=18-20).

Note that the quenching method [15,21] provides the optimal depth of the hard layer for any alloy steel. The optimum depth of hard layer is that which corresponds to maximum surface compressive stresses.

To obtain very high surface compressive stresses, it is sufficient to meet the condition $0.8 \leq Kn \leq 1$. where Kn is the Kondratjev number. This condition can be satisfied by intensive quenching using water jets or rapidly flowing water. Additional strengthening (superstrengthening) of the surface layer will also result. The high compressive stresses and superstrengthening both help enhance the durability and prolong the service life of machine parts.
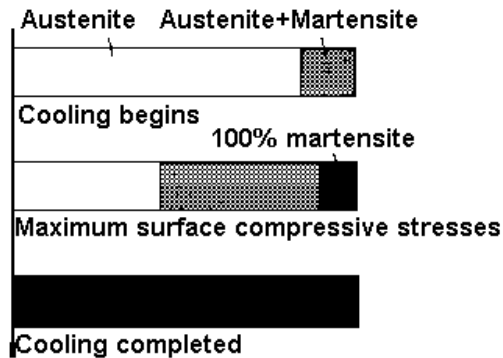
Fig. 6. Relative amounts of microstructural phases present at the optimal hard depth in a steel specimen at the beginning and end of intensive quenching, and at the time when the surface compressive stress reaches its maximum value.

11. DISCUSSION

The results of investigations show that shell hardening is advantageous, since it provides large savings because achieving the optimal depth of hard surface layer can be done with lesser amount of alloying elements which reduces the cost of the steel. For shell hardening, water is used. In the case of the optimal hard layer, optimal compressive stresses are obtained at the surface, the cyclical durability of ready steel products increases, which is shown in Ref.[22].

Although many examples have been published and the existence of the optimal hard layer has been published in 1983 [3], this issue has still not been carefully studied. . This is due to the unavailability of adequate software and databases for these calculations. Experimental methods are particularly disadvantageous due to cost. However the proprietary code TANDEM-ANALYSIS and generalization of large experimental data of many authors does permit more exhaustive examination of the optimal hard layer, which can be widely used in practice for designing of steel intensive quench processes.

Designing of intensive steel quench processes should be performed as follows:
1. Depending on the shape and size of the part, conditions of intensive quenching are selected by calculating the water flow speed or intensity of the shower cooling at the surface of the part to be quenched.
2. The proper steel grade is selected which provides the optimal depth of hard layer and maximum compressive stresses at the surface or the intensive cooling process is interrupted at the time of reaching this optimal depth.
3. On the basis of software TANDEM-ANALYSIS, calculations of parameters of intensive cooling and thermal and stress-strain state are made.
4. Special equipment and devices are designed for the implementation of intensive cooling.

The final steps after designing are as follows:
1. The equipment and devices designed are produced.
2. The quenching conditions and equipment are adjusted in industrial conditions on site to prevent possible failure with the full automation of the whole industrial hardening process. The automation is very important because the work of the line must be stable. Cracks can be formed in the case of failure to meet all the conditions designed.

A steel quenching method where the depth of the quenched surface layer is controlled, which increases the service life, is described in publication [23]. The above-mentioned steels has the following characteristics: low depth of hardened layer, fine grain with arrested growth of austenite grains at high temperatures. Due to limited hardenability, on the surface of parts, residual compressive stresses appear and the fine grain has the effect of high strength of material. In addition to the increase in the service life, there is an opportunity to replace expensive materials with cheaper materials and fire-dangerous quench oils with simple water. Steel quenching where the depth of the hardened surface layer is controlled is performed in intensive water jets. The service life of parts constructed of steels where the depth of the hardened surface layer is regulated increases by some times [23] in comparison with oil quenching.

The weak aspect of this quenching method where the depth of the hardened surface layer is regulated is that steel having the effect of optimal depth of hardened surface layer must be chosen each time for definite shape and dimensions. In the case of the change in the shape or dimensions, it is necessary to change the steel grade to have the effect of high compressive stresses on the surface. As known, the changes in the dimensions of the part and the optimum depth have the following correlation [1]

$$\frac{\Delta\delta}{D} = idem \, ,$$

where *idem* means constant.

When the depth of the hardened layer is greater or less, the compressive stresses are lower. If the layer is thin, in the transition zone high extensive stresses can appear, which results in cracking. In this quenching method there are no criteria allowing to calculate the rate of water flow for each concrete part. High water flow rate is chosen for all kinds of parts which is not always justified and results in unnecessary energy spending and makes the industrial process more complicated.

The high service life of parts where the depth of hardened surface layer is regulated is considered as an advantage of these steel grades, however, for various steel grades the effect of superstrengthening and high residual compressive surface stresses can be reached. In this method the induction heating is mainly used and there is no data regarding oven heating, including such data for carburized parts. The industrial regimes are not optimized. In the method mentioned above, it is advised to use only those steels where the depth of the hardened surface layer is regulated, however, there are some engineering problems related to melting of such steels where the depth of the hardened surface layer is regulated.

There is a steel quenching method [24] dealing with shell hardening, which means uniform quenching of all the surface to the insignificant depth until reaching high hardness on the basis of using intensive jet cooling. In this method the examples of the application of mean-alloy steel 45 are given. The main advantage of this method is the opportunity to increase the service life of steel parts while using usual carbon steels, not using steels where the depth of the hardened surface layer is regulated. This method also has weaknesses the same as in the method above, namely: no consideration is given to conditions optimizing the depth of the hardened surface layer and the following correlation is ignored:

$$\frac{\Delta\delta}{D} = idem \, ,$$

(that is, in the case of the change in dimensions of parts, the depth of the hardened surface layer should be changed correspondingly). This method does not have criteria allowing to calculate the rate of cooling quench flow which would prevent the development of self-regulated thermal process. The technological process is not optimized.

An intensive steel quenching method has been also developed in Japan [19]. In accordance with this method, alloyed steel parts are quenched in such a way that a very hard surface layer of the given depth and an arbitrarily hard matrix are obtained. For given steel grades, according to this method, ranges for hardening regimes are found by experiments to increase the service life of such parts. An example of such method realization is given below. An alloy steel specimen containing (in %) 0.65-0.85 C; 0.23-0.32 Si; 0.4-0.9 Mn; 2 Ni; 0.5-1.5 Cr; 0.1-0.2 Mo is heated up to 800-850°C and spray quenched with water fed under pressure of 0.4-0.6 MPa during 0.2-0.8 s. The specimen is subject further to isothermal heating at 150-250°C during 10-50 minutes [19]. The weakness of the method above is that it considers just high-carbon alloyed steels. The depth of the hard surface layer is not optimal for various dimensions of parts. Because of this steel superstrengthening is not reached. It does not consider conditions of the optimization of the quenchant circulation rate.

The analysis of the existing methods of steel quenching used in various countries (in Russia, USA, Japan and Ukraine) shows that the intensive steel quenching with the formation of hard surface layer of the given depth has greater advantages than for thorough quenching. The common weakness of all these methods is that there is no change in the optimum depth of the hard surface layer in cases of the changes in dimensions of parts and that the quenchant circulation rate is not optimized for the prevention of the development of self-regulated thermal process and reaching material superstrengthening.

The intensive steel quenching method [15] has been chosen as a prototype of this invention, including heating, intensive cooling until the appearance of maximum compressive surface stresses, isothermal heating and tempering. The method is based on the following: intensive cooling is formed in the range of $0.8 \leq Kn \leq 1$, where Kn is the Kondratjev number until reaching maximum compressive surface stresses and then it is isothermally heated at martensite start temperature M_S until the complete transformation of the supercooled austenite of the matrix, then it is tempered.

The basic weakness of this method is that it deals just with alloyed steels. To reach the maximum compressive stresses on the surface the intensive cooling is stopped and due to it the effect of superstrengthening does not show itself in full. There is no concrete method of the calculation of optimal rate of quenchant flow to ensure reaching material superstrengthening.

The proposed quenching method is new since in the part quenched for any steel grades, alloyed and not alloyed, high- mean- and low-carbon the depth of the hard surface layer reached is optimal that the maximum compressive stresses are formed. If the depth of the hard surface layer is greater or less the compressive stresses are lower.

The creation of conditions to reach maximum compressive stresses is reached due to greater effect of additional strengthening (superstrengthening) of material. In the compressed surface layer during the quench process martensite transformations take place. Due to greater specific volume of martensite plates (than for the resulting phases) the plastic deformation of austenite occurs which is located between the martensite plates. The higher compressive surface stresses in the layer being hardened and the higher the cooling rate is in the martensite area, the greater deformations in the austenite which is between martensite plates. In this case martensite plates function like

"microhammers" due to which high density dislocations are reached under high pressure. While cooling is fast, these dislocations are "frozen" in the material.

In such conditions the effect of low-temperature mechanical heat treatment is present. After this treatment the material hardened can have higher mechanical and plastic properties in comparison with usual hardening. Thus the optimal depth of the quenched layer is necessary for not only reaching maximum compressive surface stresses but also for the formation of optimal conditions under which the effect of additional material strengthening (superstrengthening) is present in full. The additional strengthening (superstrengthening) of material and high compressive stresses in the surface layer quenched result in the increase in their service life.

Thus, the application of the proposed steel quenching method allows as follows:

1. To achieve the effect of material superstrengthening and high compressive surface stresses when using arbitrary steel grade.
2. Alloyed and high-alloyed steels can be replaced with simple carbon steels that has the effect that the depth of the hard layer is optimal. In this case the effect of material superstrengthening is greater. Due to it the service life of such parts increases.
3. Expensive and fire-dangerous oils can be replaced by water and water solutions.
4. The labor efficiency increases.
5. The ecological state of the environment is improved.

12. CONCLUSIONS.

As a result of investigating the kinetics of phase transformations in bodies of complicated configuration the following regularities have been found:

1. In the case of through hardening, while Biot number grows, the axial and hoop tensile residual stresses on the surface of a part to be quenched firstly grow reaching the maximum at Bi=4 and then reduced and become negative (compressive) at Bi$\geq$20, which was established for the first time in 1983 [3].
2. The distribution of residual stresses in parts with full and partially controlled hardenability while the heat transfer is highly forced (Bi>20) has different character. In parts of controlled hardenability on the surface high compressive stresses appear, which gradually change to tensile stresses at the center of the part. In the case of thorough hardening while Bi>20 in the surface layer there are high tensile stresses changing to compressive stresses on the surface. With the elapse of the time, parts made out of steel of controlled hardenability have compressive residual stresses on the surface growing all the time, while parts hardened thoroughly have stresses that are compressive and grow until a certain moment of time at which they reach the maximum, then they are reduced.
3. Methods of numerical investigation of the kinetics of phase transformation in bodies of arbitrary shape has been developed. Having CCT diagrams with physical and mechanical properties of structural components for these diagrams one can determine the structure, strength and hardenability of parts having a complicated configuration and forecast the mechanical properties of the material [14,25-29]. For this purpose TANDEM-ANALYSIS software has been developed [4].
4. It has been established that there is optimal depth of hard layer for a part at which compressive stresses on the surface reach the maximum.
5. There is similarity of the distribution of current and residual stresses in bodies having different sizes and the conditions when this similarity is observed are given above.

6. The practical application of shell hardening for car box rollers and wheels is described.
7. For the wide application of these methods, it is necessary to improve further the software and to develop databases of initial data for solving the problem of the calculating the optimal depth of hard layer for various steel grades, which would provide the optimal distribution of compressive stresses at the surface and in the core.
8. The optimal depth of the hard layer can be reached for the account of either proper selection of steel grade or interrupting the cooling at the time of reaching the optimal maximum compressive stresses at the surface.
9. The result of all above-mentioned investigations is that alloy and high-alloy parts can be quenched using just water.
10. It is important to put together our efforts to study discovered regularities more deeply on the basis of software TANDEM-ANALYSIS and highly developed CAE System "HEARTS" and software DANTE [30,31] and other appropriate programs.

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