INTENSIVE QUENCHING: HEAT TRANSFER AND RESIDUAL STRESS[1]

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Abstract

Intensive quenching is a method that utilizes water or salt solutions which are used to replace more traditional oil and aqueous polymer quench media. In addition, intensive quenching processes may be designed that will produce hardened case structures and superior compressive residual stresses relative to carburizing and may be usedto either replace carburizing or reduce the total carburizing cycles. Intensive quenching methods possess specific heat transfer criteria that are necessary to achieve the desired results which include hardened case depth and very high compressive stresses. This paper will discuss numerical simulation and experimental studies that have been 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.

Key words: Heat treatment; Intensive quenching; Heat transfer; Residual stress

TÊMPERA INTENSIVA: TRANSFERÊNCIA DE CALOR E TENSÕES RESIDUAIS

Resumo

Têmpera intensiva é um método que utilize água ou soluções de sais as quais são usadas para substituir meios mais tradicionais de têmpera, como óleo e soluções de polímeros. Além disso, o processo de resfriamento é projetado de tal maneira produzir camadas endurecidas e de tensões residuais compressivas relativamente superiores às obtidas por cementação, podendo substituir ou mesmo reduzir os ciclos de cementação. Há alguns critérios que devem ser atingidos para que se atinja a transferência de calor necessária a produzir os resultados desejados que incluem camada endurecida de maior profundidade e altas tensões compressivas superficiais. Neste trabalho serão discutidas as simulações numéricas e estudos experimentais que têm sido conduzidos para otimizar determinar as tensões compressivas ótimas usando métodos de têmpera intensiva. Baseados nesses resultados, são fornecidas recomendações para a melhoria do tratamento térmico de componentes de máquinas e equipamentos. Além disso, serão também discutidas a formação das máximas tensões compressivas e as vantagens do uso de aços de temperabilidade controlada.

Palavras -chave: Tratamento térmico; Têmpera intensiva; Transferência de calor; Tensão residual.

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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 hardening, 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 Kobasko and Morhuniuk[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.

DISCUSSION

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. The 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 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 (Figure 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 and[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 Kobasko and Morhuniuk(3), Ganiev, Kobasko, and Frolov(8) and Kobasko.(9)

The results obtained were confirmed experimentally by measuring residual stresses at the surface of quenched parts (specimens) using X-ray analysis.[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 ($Bi \to \infty$), the part surface layer is cooled initially to ambient temperature, while the core temperature remains essentially constant.

During 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.

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 Kobasko(11,13) and Kobasko and Morhuniuk.(12,14)

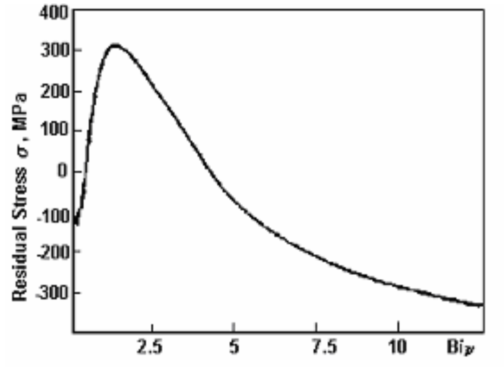

Figure 1. Residual hoop stresses at the surface of a cylindrical specimen versus generalized Biot number.

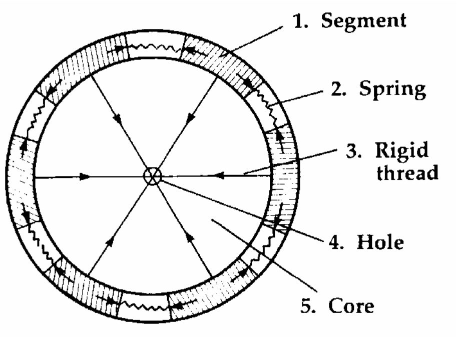

Figure 2. Mechanical model that can be used to explain the formation of hoop stresses at the surface of a cylindrical specimen during intensive quenching.

The reason why intensive quenching results in high compressive stresses can be explained using a simple mechanical model shown in Figure 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.

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 increases in volume.

When the segments expand, 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 volume will then start to increase 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.

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 Figure 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%.

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.

Figure3 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 $Bi = \frac{\alpha}{\lambda} R = idem$. 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 (Figure 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.

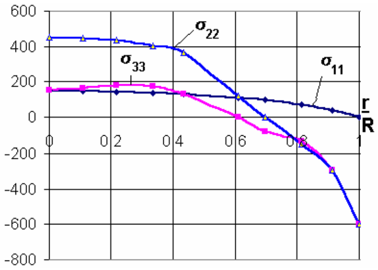

Figure 3. The distribution of stresses on the cross section of cylindrical sample of diameter of 6 mm and 60 mm at the time of reaching maximum compressive stresses on the surface. (ε_1=7; Fo=0.7); 1 – sample of 6-mm-diameter; 2 – sample of 60-mm-diameter.

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.

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.

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 is performed using an 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.

Optimal Depth of Hardening

There are two methods of achieving the optimal depth of the surface hardened layer:

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 $0.8 \le Kn \le 1$ 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]

IQ-quenching steel parts by using intensive jet cooling is described in Ovaku[16] where intensive cooling is applied to superficial hardening of small parts (shafts, axes, pinions, etc.) made of alloy steels. 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 (Figure 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 (Figure 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.

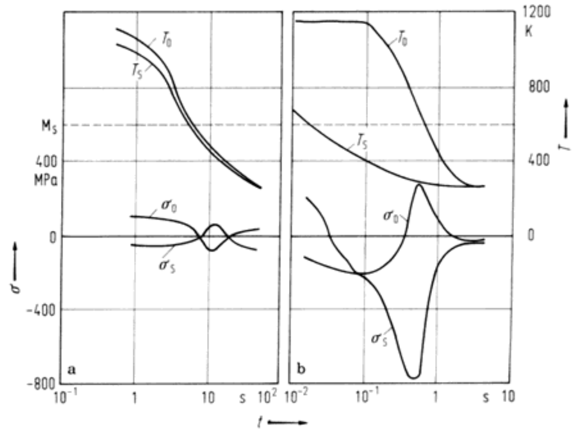

Figure 4. Change of current hoop stresses at the surface (σ_s) and in the center (σ_c) of the cylindrical specimen being cooled under various heat transfer conditions.[12] a) Slow cooling; b) Intensive cooling

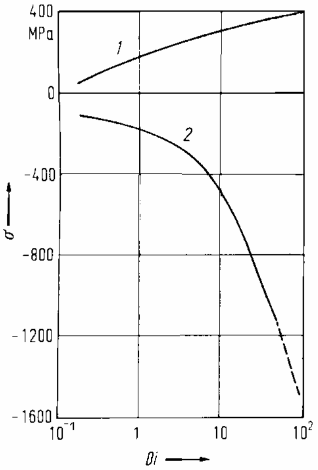

Figure 5. Maximum compressive hoop stresses at the surface (2) and tensile stresses in the center (1) of the cylindrical specimen of 6 mm in diameter versus Biot number

If 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:

$$0.8 \le Kn \le 1$$

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 observations 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.

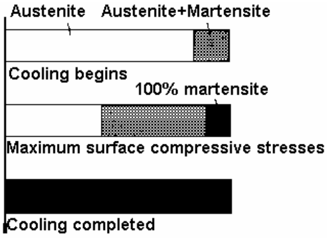

Figure 6. Relative amounts of microstructural phases present at the optimal hard depth in a steel specimen at the beginning and end of intensive quenching, and at the time when the surface compressive stress reaches its maximum value.

CONCLUSIONS

From the study of the kinetics of phase transformations in bodies of complicated configuration the following regularities have been found:

- 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]
- 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.
- 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.[14,22-26] For this purpose TANDEM-ANALYSIS software has been developed.[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.
- 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.
- The practical application of shell hardening for car box rollers and wheels is described.

- 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.
- 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.
- The result of all above-mentioned investigations is that alloy and high-alloy parts can be quenched using just water.
- 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[27,28] and other appropriate programs.

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