THERMAL STRESSES IN HARDENED STEEL OBJECTS OF CYLINDRICAL SHAPE WITH AN AXIAL HOLE

V. E. Loshkarev

UDC 539.3:669.15

On the basis of the numerical solution of the unconnected problem of thermoplasticity, the article investigates the effect of the characteristics of external heat exchange and of geometric parameters on the state of thermal stress of hardened products.

The object of hardening is to obtain the required structure and mechanical properties of steel at a permissible level of internal stresses. In some cases the problem of a specified distribution of residual stresses may be posed, such that the operational reliability of the product is enhanced. It is expedient to work out rational hardening regimes for key components on the basis of an analysis of the thermal state, the structural state, and state of stress of the metal.

Many large components in power and heavy engineering (shafts, rotors, rolling-mill rolls, etc.) have the shape of cylinders with an axial hole. The methods of hardening them differ both in the cooling medium used and in the nature of the motion of the media in the axial channel and at the outer surface. In particular, hardening methods with forced cooling of the axial channel of the component (e.g., [1]) are used. Elaboration of rational methods of hardening large cylindrical components with an axial hole is seriously hindered by the lack of sufficiently clear notions concerning the regularities of formation of thermal stresses.

When the state of thermal stress of hardened components is mathematically modeled, it is necessary to take into account the substantial change of the thermophysical and mechanical characteristics of steel depending on the temperature and on the structural state, and also the development of considerable inelastic deformations. The unconnected problem of thermoplasticity for a hardened hollow cylindrical object of infinite length, on the assumption of axial symmetry of heat transfer from the surface and the absence of external loads includes the equation of heat conduction with the corresponding condition of single-valuedness:

$$C_V(T,S)\frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left[\lambda(T,\ S)\ r\ \frac{\partial T}{\partial r}\right] + L_V\frac{\partial v}{\partial \tau}\ , \tag{1}$$

$$T|_{\tau=0} = T_0(r), \tag{2}$$

$$\lambda(T,\ S)\frac{\partial T}{\partial r}\Big|_{r=R_1} = \alpha_1(T_{s1})(T_{s1} - T_{m1}), \tag{3}$$

$$-\lambda(T,\ S)\frac{\partial T}{\partial r}\Big|_{r=R_2} = \alpha_2(T_{s2})(T_{s2} - T_{m2}), \tag{4}$$

where

$$\alpha_1(T) = \varphi_i(T),\ \tau_i \leqslant \tau < \tau_{i+1}, \tag{5}$$

$$\alpha_2(T) = \psi_j(T),\ \tau_j \leqslant \tau < \tau_{j+1}, \tag{6}$$

and also the equation of equilibrium

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0, \tag{7}$$

the conditions of the absence of loads on the lateral surfaces, and equality to zero of the resultant of the axial stresses in the cross section:

All-Union Research and Project Institute Teploproekt, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 46, No. 3, pp. 491-498, March, 1984. Original article submitted September 29, 1982.

$$\sigma_r \big|_{r=R_1} = \sigma_r \big|_{r=R_2} = 0, \tag{8}$$

$$\int_{R_1}^{R_2} \sigma_z r dr = 0, \tag{9}$$

the correlation of the principal strains with radial displacement

$$e_\theta = \frac{u_r}{r}, \quad e_r = \frac{du_r}{dr} \tag{10}$$

(axial strain e_z depends solely on time).

To obtain a closed system of equations, the relations between stresses and strains suggested by Lomakin [2] were used. These relations are based on the theory of small elastoplastic deformations, they take into account the repeated changes in direction of the deformation of each element of the bulk of the material and other features characteristic of the real process of hardening of steel. In contrast to [2], in the present investigation the compressibility and increased strength of steel were also taken into account. In that case the ratios of stresses and strains have the form

$$\bar{e} = \frac{\bar{\sigma}}{3K(T,S)} + e_f(T, S), \tag{11}$$

$$\sigma_x - \bar{\sigma} = \frac{2}{3}\frac{\sigma_i}{\varepsilon_i^n}[(e_x - \bar{e}) - e_{px}^n], \ x = z, \theta, r, \tag{12}$$

$$\sigma_i = \begin{cases} 3G(T, S)\varepsilon_i^n, & \varepsilon_i^n < \dfrac{\sigma_y(T, S, e_{pi})}{3G(T, S)}, \\ \sigma_y(T, S, e_{pi}), & \varepsilon_i^n \geqslant \dfrac{\sigma_y(T, S, e_{pi})}{3G(T, S)}. \end{cases} \tag{13}$$

When steel is cooled, its initial high-temperature structure (austenite) disintegrates, and various structural components form. The structural transformations of steel were predicted with the aid of the so-called thermokinetic diagram of disintegration of supercooled austenite, taking into account the cooling rate of a certain point of the component [3]. It was envisaged that the structural transformation of the steel may be suspended when the intensity of external heat exchange during the hardening process is abruptly reduced. It was assumed that the physicomechanical properties of austenite and of its disintegration products are different, and that they depend solely on the temperature. The rule of additivity was used for determining the effective properties of steel at the time of structural transformations.

The problem of thermoplasticity (1)-(13) was solved numerically with the aid of a suitably developed FORTRAN program STRESS whose algorithm was briefly described in [4]. A comparison of the experimental and calculated graphs of axial, tangential, and radial residual stresses in a water-hardened steel specimen having the shape of a cylinder with an axial hole confirmed the reliability of calculation method used.

Let us briefly discuss the data on the nature of the distribution of internal stresses in hardened objects having the shape of hollow cylinders. According to the traditional notion [5], with approximately equal cooling conditions of the outer surface of the object and of the surface of the axial hole, compressive residual stresses arise in both surfaces. Conversely, in case the cooling intensity of the axial hole is relatively low, tensile residual stresses result on its surface. A consequence of this notion is that intensive cooling of the axial hole of objects seems advisable to reduce the danger of hardening cracks forming. The correctness of such a notion for purely thermal stresses, with no structural transformations in the metal occurring, is undoubted, and it is in particular confirmed by the calculation carried out by the present author.

In fact, when there are no structural transformations, the specific volume of the metal in the layers adjacent to the cooled surfaces decreases, and in consequence, temporary tensile stresses arise at the initial period of cooling, and irreversible plastic deformations occur, leading eventually to compressive residual stresses near the surface of the object.

Generally speaking, cases are known when in steel parts after hardening compressive residual stresses arose on the surface and tensile ones in the bulk. However, on the whole the

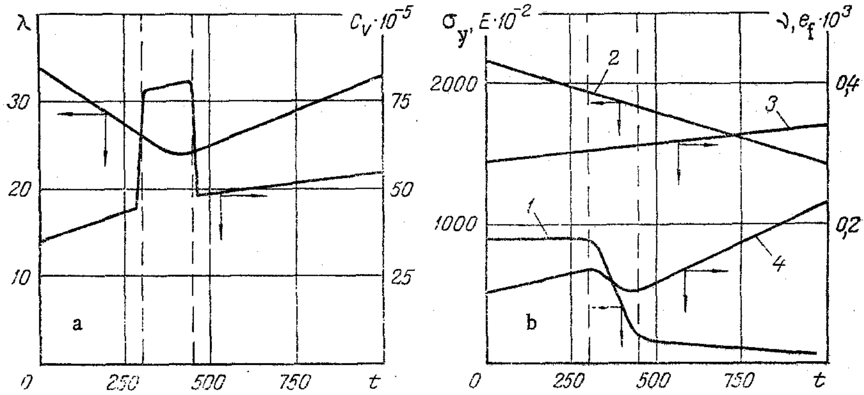

Fig. 1. Values of the thermophysical (a) and mechanical (b) properties of steel: 1) σ_y; 2) E; 3) ν; 4) e_f (b); t, °C; λ, W/m·°K; C_V, J/m³·°K; σ_y, MPa; E, MPa.

above scheme is insufficient for describing the formation of hardening stresses which are substantially affected by structural transformations of the steel [6].

The results of theoretical investigations, carried out by taking the changes of physicomechanical characteristics of steel in structural transformations into account, indicate that dangerous tensile residual stresses arise at the surface of axial channels of rotors when they are cooled with sufficient intensity [7, 8]. These results are qualitatively confirmed by known cases of hardening cracks forming in the axial channels of rotors [8]. Thus, it is obvious that the traditional notions concerning the formation of internal stresses in hardened cylindrical objects with axial hole are unsatisfactory. However, an open question in still the effect of various factors on the level and the nature of the distribution of these stresses.

The internal stresses were investigated theoretically as concerns bulk hardening of objects to obtain a bainitic structure. This case is characteristic of the heat treatment of large products in the construction of power engineering (in particular shafts and rotors of chrome—nickel—molybdenum—vanadium steels). It should be pointed out that the structural transformations entail considerable changes of the specific volume, the yield strength, and other characteristics of steel. Therefore the formation of internal stresses depends to a large extent on the temperature range and the type of transformations, and also on the region where the transformations occur: whether over the entire cross section or only in the surface layer of the object. In the calculations it was assumed that in the entire cross section of the objects there occurs bainitic transformation of the steel in the temperature range 450–300°C.

The values of the physicomechanical properties of steel used in the calculations are shown in Fig. 1a, b. The dashed lines indicate the temperature range within which bainitic transformation of steel occurs. In the case under examination the boundaries of the temperature range of structural transformation do not depend on the cooling rate. The physicomechanical properties of steel may therefore be represented as a function of the temperature alone.

Calculations for studying the influence of the heat exchange intensity on the internal stresses were carried out for a cylinder with outer diameter 1 m and inner diameter 0.2 m. We examined cooling of an object from 850°C, the medium having a temperature of 50°C. At first the heat-transfer coefficient α was varied for different variants of the calculation and heat exchange surfaces, but it was considered independent of the surface temperature.

Figure 2a shows the distributions of the tangential residual stresses over the radius of the cylinder at different cooling intensities, where the conditions of heat exchange on the outer surface and on the surface of the axial hole are the same: $\alpha_1 = \alpha_2$. Especially for the tangential components the tensile stresses attain their largest value. By the nature of their distribution and magnitude, the largest temporary stresses in the case under examination are close to the residual stresses. Therefore, to simplify explanations, we will deal henceforth chiefly with residual stresses.

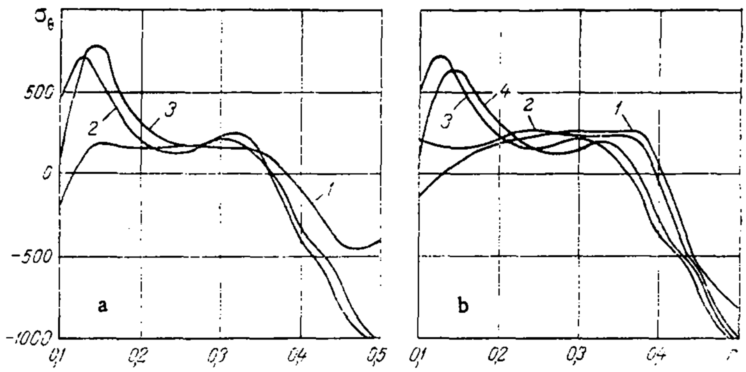

Fig. 2. Distribution of the tangential residual stresses in an object with equal (a) and different (b) conditions of cooling the outer surface and the axial hole: 1) α = 100 $W/m^2 \cdot {}^\circ K$; 2) 1000; 3) 10,000 (a); α_2 = 1000 $W/m^2 \cdot {}^\circ K$; 1) $\alpha_1 \neq 0$; 2) 100; 3) 1000; 4) 10,000 (b). σ_θ, MPa; r, m.

After hardening, compressive stresses act on the outer surface of objects. The residual stresses on the surface of the axial hole are compressive only in case of nonintensive cooling (α = 100 $W/m^2 \cdot {}^\circ K$), and tensile when cooling is more intensive. We want to point out that in the latter case the maximal tensile stresses are attained in the direct vicinity of the surface of the hole. There is no doubt that such a stress distribution is dangerous.

Figure 2b shows the distributions of tangential residual stresses in a hardened object when the heat transfer coefficient (α_2) on the outer surface is equal to 1000 $W/m^2 \cdot {}^\circ K$, and when it assumes different constant values on the surface of the hole (α_1). Worthy of attention is the fact that by reducing the intensity of cooling of the axial hole (curves 1 and 2) it is possible to attain a substantial reduction of the level of the dangerous tensile stresses compared with the variant envisaging equal cooling intensity on the surface of the hole and on the outer surface of the object (curve 3). However, the level of the residual tensile stresses can also be somewhat reduced by increasing the cooling intensity of the hole in comparison with the cooling intensity of the outer surface (curve 4).

Of considerable interest to heat-treatment practice are the methods of quenching where the thermal state and the state of stress of the objects are controlled by changing the instant of supplying the cooling medium to part of the surface.

Let us examine two similar methods of hardening hollow cylindrical objects. After heating, the object is immersed in the quenching liquid, and the liquid is fed to the axial hole with some delay, or else it is fed immediately, but then its supply is interrupted. We will call the first method hardening with delay, and the second method hardening with interrupted cooling of the axial hole.

Figure 3 shows the dependences of the maximal temporary and residual stresses on the length of the delay of cooling the hole with quenching in water. In addition, the graph shows the lowest mean cooling rates in the section in the temperature range of structural transformations of steel. We used the relative duration of the delay $\bar{\tau}$ (ratio of the real duration to the cooling time of the object to the level of 200°C without feeding liquid to the axial hole). The calculations were carried out by taking the dependence of the heat-transfer coefficient on the surface temperature into account. It is interesting that when the delay of cooling the hole is short, the stress level is higher than when, in hardening, the outer surface of the object and the hole are cooled simultaneously. This is due to the unfavorable superposition of deformations caused by the nonuniform distribution of temperature and of structural composition in the cross section of the object. Thus, hardening with delayed cooling of the hole requires strict supervision because the danger of failure of the object may increase. In addition, when the level of internal stresses is reduced by delaying the cooling of the axial hole, the cooling rate is substantially reduced within the range of transformations of steel (see curve 3 in Fig. 3), and all the more so before this range is reached. That may have the consequence that the mechanical properties of the steel are not sufficiently good. We note that when a vapor plug forms spontaneously in the hole, a situation arises that is similar to hardening with delayed cooling of the axial hole.

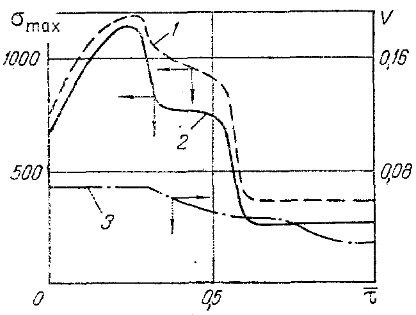

Fig. 3.

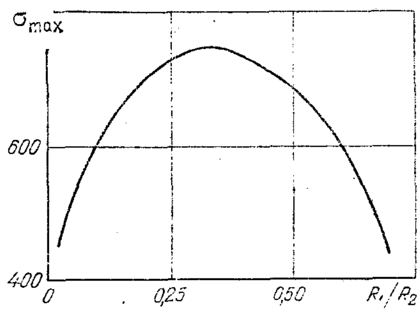

Fig. 4.

Fig. 3. Dependence of the maximal temporary (1) and residual (2) stresses and of the minimal cooling rate in the cross section of the object in the range of structural transformations of steel (3) on the relative duration of the delay of cooling the axial hole. σ_{max}, MPa; V, °K/sec.

Fig. 4. Dependence of the maximal residual stresses after hardening in water on the ratio of the inner and outer radii of the object.

According to the results of calculations, hardening with interrupted cooling of the axial hole is inefficient because a substantial reduction of the internal stresses is attained with low cooling rates in the cross section of the object.

The obtained data show that there are extensive possibilities of controlling the state of stress of cylindrical objects with an axial hole by changing the conditions of heat exchange on the cooled surfaces. However, it must be borne in mind that a lowering of the level of dangerous tensile stresses is attained, as a rule, by using a lower cooling rate. This makes it somewhat difficult to work out hardening methods ensuring that good mechanical properties of the steel are obtained.

Very important is the question of the effect of the dimensions of the object (outer and inner diameter) on its state of stress. It is expedient not to examine this effect in isolation, but together with the effect of the heat exchange characteristics. A convenient parameter is the test $Bi = \alpha R/\lambda$. However, even with fixed chemical composition of the steel, type and temperature range of the structural transformations, the use of the Bi test is only approximate because the values of α and λ change considerably during the cooling process.

A previous theoretical analysis of the state of stress of solid cylindrical objects showed that when $Bi > 5$, an increase of the size of the object and of the cooling intensity has only a weak effect on the maximum level of the internal stresses. Comparative calculations of the state of stress of cylinders with outer diameters 1 and 0.2 m and inner diameters 0.2 and 0.04 m, respectively, show that the above conclusion also applies to hollow cylindrical objects. Thus, when the cooling intensity is sufficiently great, a proportional change of the outer and inner diameters of the object has only a slight effect on the state of stress. However, the ratio of the diameters has a substantial effect on the state of stress of hollow cylindrical objects even with intensive cooling.

A series of calculations was carried out for cooling cylindrical objects with 1 m outer diameter and different diameters of the axial hole in water. The dependence of the largest tensile residual stresses on the ratio of the inner and outer diameters is presented in Fig. 4. This dependence has a maximum when R_1/R_2 is approximately 0.3. Conditionally the most dangerous range of changes may be said to be $R_1/R_2 = 0.2$–0.5.

In conclusion it must be pointed out that the presented data characterize the effect of the cooling method (conditions of external heat exchange) and of the dimensions of an object of cylindrical shape with an axial channel on the internal stresses in steel when it is hardened to bainitic structure. However, the level of the stresses, and to a certain extent also the nature of their distribution, depend on a number of characteristics of the steels concerned. The influence of these characteristics requires a separate investigation, and it was not discussed above. In particular, calculations by the present author showed that when the temperature range of structural transformations is halved, the residual stresses increase by approximately one-half compared with the case examined above. The stresses also increase substantially when the structural transformations have a large volumetric effect. Thus, in some cases the internal (temporary and residual) stresses may considerably exceed the values shown in the graphs, and then they are an even greater danger to the integrity of steel parts.

NOTATION

C_V, volumetric heat capacity, $J/m^3 \cdot {}^\circ K$; T, temperature, °K; S, variable characterizing the structural state of steel; τ, time, sec; r, coordinate, m; λ, thermal conductivity, $W/m \cdot {}^\circ K$; L_V, volumetric thermal effect of structural transformations of steel, J/m^3; v, volume fraction of products of transformation; α, heat-transfer coefficient, $W/m^2 \cdot {}^\circ K$; T_S, surface temperature, °K; T_m, temperature of the medium, °K; R, radius, m; τ_i, τ_j, instants of change of the cooling media in the axial hole and on the outer surface, respectively, sec; V, cooling rate, °K/sec; σ_z, σ_r, σ_θ, principal stress components, MPa; e_z, e_r, e_θ, principal strain components; u_r, radial displacement, m; $\bar{\sigma}$, mean stress, MPa; $\bar{e}$, mean strain; e_f, free strain; $K = E/3(1 - \nu)$, bulk modulus of elasticity, MPa; $G = E/2(1 + \nu)$, shear modulus, MPa; E, modulus of elasticity, MPa; ν, Poisson ratio; σ_i, stress intensity, MPa; ε_i^n, intensity of the tensor, being the difference between the full strain tensor at the current instant and the plastic strain tensor at the instant of the last (n-th) unloading of the given element of the volume; e_p^n, plastic strain at the instant of the last unloading of the given element of the volume; σ_y, yield strength, MPa; e_{pi}, plastic strain intensity. Subscripts 1 and 2 relate to the axial hole and the outer surface, respectively.

LITERATURE CITED

1. P. V. Sklyuev and B. D. Petrov, "Method of hardening cold-rolled rolls," Inventor's Certificate No. 153925, Byull. Izobret., No. 8 (1963).
2. V. A. Lomakin, "Theoretical determination of residual stresses in the heat treatment of metals," Probl. Prochn. Mashinostr., No. 2, 72-83 (1959).
3. V. E. Loshkarev, G. G. Nemzer, and Yu. A. Samoilovich, "Determination of the thermophysical characteristics of steel from the solution of the inverse heat-conduction problem," Promyshlen. Teplotekh., 2, No. 3, 22-28 (1980).
4. Yu. A. Samoilovich and V. E. Loshkarev, "Investigation of the stress state of hardened products," in: Design and Construction of Thermal Plants, Transactions of the All-Union Research and Project Institute of Thermal Plants (VNIPITeploproekt), Issue 54, Moscow (1981), pp. 15-26.
5. H. Wolf and W. Bohm, "Entstehung, Messung und Beurteilung von Eigenspannungen in schweren Schmiedestucken fur Turbinen und Generatoren," Arch. Eisenhuttenwes., 42, No. 7, 509-513 (1971).
6. H. Bühler and A. Rose, "Darstellung des Entstehens von Eigenspannungen in Werkstücken aus Stahl in ihren Umwandlungsschaubildern," Arch. Eisenhuettenwes., 40, No. 5, 411-423 (1969).
7. I. A. Borisov, "Heat treatment of key components in the construction of power machinery," Metalloved. Term. Obrab. Met., No. 9, 2-6 (1979).
8. V. E. Loshkarev and P. M. Libman, "Investigation of stresses in hardened cylindrical products with an axial hole," in: Technology, Organization of Production and Management, No. 5-82-03, NIIÉINFORMÉNERGOMASh, Moscow (1982), pp. 12-15.