# TECHNOLOGICAL STRENGTH AND NONDESTRUCTIVE METHODS OF TESTING DURING HEAT TREATMENT

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## Technological Strength

The operating characteristics of steel are determined by the combination of physicomechanical properties and structure resulting from heat treatment. Operation at low temperatures carries the danger of brittle fracture. At elevated temperatures, where the time factor is basic to the resistance of the material, the steel is affected most by changes in structure and defects in elastic, temperature, and concentration fields. Softening of the material and the formation of fracture centers are associated with dislocation reactions, the interaction of dislocations with defects, coalescence of inclusions and vacancies in pores, and other processes. Fracture centers are nucleated and grouped around structural defects that occur during solidification of metals and alloys, manufacturing of machine parts, and heat treatment, especially hardening treatments. Heat-treatment conditions must be selected in view of the characteristic structural defects inherited by the material after the primary metallurgical and other treatments. The heat treatment must weaken and not strengthen these defects. The inheritance of defects is not always taken into account, and thus the use of individual technological processes, especially some types of thermomechanical treatment, does not always give positive results.

For critical machine parts not only numerical values of the mechanical characteristics in standard tests are of importance, which may be identical after various heat treatments of the same steels, but also the structure of the material, which must ensure the least damage and thus high resistance of the section and the surface under operating conditions. The structure ensuring the necessary operating characteristics in combination with given mechanical properties is formed in the process of manufacture and heat treatment. The technological process of manufacturing parts from a given material must be selected so as to avoid defects that are dangerous under given operating conditions. Of particular interest in this connection is the "technological strength," taking into account both the numerical value of the mechanical property and the characteristics of the structure – for example, structural defects inherent in the material after the treatment, especially heat treatment – ensuring this property. A properly selected technological strength ensures high structural strength of machines and equipment.

Let us consider several examples associated with the technology of heat treatment and chemicothermal treatment.

Diffusional chromizing of steel 08kp in vacuum at 1450°C for 30 h produces a coating of considerable depth (~3.5 mm) with a high concentration of chromium on the surface (32%). A high dislocation density, revealed by etch pits, is observed in the diffusion zone. Dislocations are formed under the influence of stresses similar to thermal stresses occurring in the flow of the diffusing substance as a consequence of the difference in the atomic sizes and compressibility of the diffusing atoms and the atoms of the base metal. The dislocation density at the surface of the part is small, since dislocation loops generated from sources in the direction of the the surface reach the surface, forming porosities in the surface zone. These porosities are points of crack nucleation during loading in the process of operation and pitting under the influence of gas flows. The porosities can be eliminated by even small plastic deformations (~15%). This creates a more even distribution of strength in the diffusion coating as the result of the more intensive work hardening of the layer less alloyed with the diffusing substance. The technological strength is increased by a combination of diffusion chromizing in vacuum and plastic deformation of the diffusion coating. To create a complex scale-resistant diffusion coating it is necessary to take into account the diffusional exchange with the alloy that occurs during high-temperature

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operation of the part. Preferential diffusion of the atoms of the substance from the coating, with high mobility, into the base metal lowers the concentration of vacancies in the sublayer; this prevents the development of damage during creep and crack growth – the zone of diffusion of the substance protecting the part. Thus, along with the alloying elements ensuring high scale resistance the coating must contain a substance whose atoms diffuse rapidly into the base metal, eliminating the supersaturation with vacancies that occurs due to the development of diffusion and plastic deformation. The coating also protects the base metal against gases and damage inducing nucleation and development of cracks in the elastic field. If the coating does not contain rapidly diffusing atoms, then porosities and cracks form in the material in contact with the coating because of the diffusional exchange at high temperatures with the base metal, in which the substance diffuses more rapidly than in the coating. Such coatings may even stimulate premature failure, lowering the technological strength of the part operating at high temperatures.

The technique of applying diffusion coatings and the technique of soldering and facing must ensure favorable dislocation arrays in the diffusion zone, consisting of subboundaries with a normal orientation with respect to the outer surface [1]. The substructural boundaries are places of active precipitation of intermetallic compounds, the components of which decorate dislocations. When separate dislocation loops and subboundaries are localized at the surface of the diffusion zone, forming dense clusters of intermetallic compounds, the material becomes brittle and the strength decreases; with even distribution in a well-developed favorable substructure in the diffusion zone the strength even increases.

The favorable arrangement of substructural boundaries oriented normal to the surface and fairly extensive can be created by a combination of preliminary plastic deformation of the surface layers of the material and temperature–time conditions.

By utilizing favorable dislocation arrays one can obtain considerable additional strengthening by diffusion coating – as much as 25%. For example, the resistance of boride coatings increases due to strengthening of the sublayer. A high dislocation density can be obtained even in the zone of coarse-grained ferrite.

Heating of steel in protective atmospheres containing hydrogen leads to hydrogen embrittlement during heat treatment. For example, when steel 25KhGT is heated in an atmosphere containing 40% hydrogen after austenitizing and rapid cooling (quenching + tempering) the notch toughness drops from 21 to 15 kgf-m / $cm^2$ and the reduction in section from 17 to 9%. Heating in a hydrogen-free atmosphere (nitrogen) increases the notch toughness as compared with heating in an atmosphere containing 20% hydrogen. Raising the hydrogen concentration to 40% lowers the notch toughness still more. Exceeding a concentration of 30% $H_2$ in the atmosphere is dangerous. Numerous statistical data for standard structural and low- and medium-alloy steels indicate that changing from the widely used endothermal atmospheres containing 40% $H_2$ to exothermal gas PSO-45, which contains 20% $H_2$ and has equal protective properties, reduces hydrogen embrittlement. It produces a systematic improvement in the mechanical properties (especially the ductility and notch toughness) by an average of 15%. Exothermal gas generators are now being developed.

The examples given indicate that the operational reliability of alloys depends simultaneously on the strength characteristics and defects resulting from the characteristics of the manufacturing and heat-treatment processes, i.e., their technological strength.

## Nondestructive Testing

In connection with the problems of the technological and structural strength, it is necessary to develop methods of analyzing the damage that occurs during heat treatment and subsequent operation of heat-treated machine parts.

Several methods of nondestructive testing, such as magnetic and ultrasonic defectoscopy, are used in analyzing parts before heat treatment in furnaces. Let us consider here the possibility of analyzing the physicomechanical characteristics sensitive to disruptions of continuity and stress concentrators: internal friction, the modulus of elasticity, density, exoelectronic and acoustic emission. Repeating the tests after heat treatment, one can determine the presence of inadmissible discontinuities in the structure and scrap these parts. Studies of changes in these characteristics in the process of operation of finished parts in relation to deformation, time, temperature, and stress make it possible to plot the development of damage and determine the type and size of defects. It is often of interest to conduct similar studies on samples of the material where the loading conditions match the operating conditions of the part.

Internal Friction. Damping of vibrations in parts of complex shape is measured in special testing machines under resonance conditions. These machines simultaneously record the rate of propagation of sound waves, which makes it possible to calculate the modulus of elasticity. The internal friction can be determined much more precisely by an apparatus of different design, described in [1].

In analyzing internal friction curves one must take into account that the discontinuity of the material that occurs during heat treatment (various pores and cracks) gives characteristic changes of the internal friction. The decrement resulting from absorption of energy associated with the periodic increase and decrease of the surface area of the discontinuity in the variable elastic field, without accounting for the stress concentration, is

$$\delta = \frac{\xi \bar{r}(1-\mu) n \gamma}{E \varepsilon_0} e^{bE\varepsilon_0}, \tag{1}$$

where $\xi$ is a coefficient; $\bar{r}$ and n are the average radius and number of pores; $\varepsilon_0$ is the amplitude value of deformation; $\mu$ is Poisson's ratio; $\gamma$ is the surface tension; b is the relative change of plastic deformation per unit stress.

The indication of damage due to the discontinuity is the amplitude dependence of the decrement, close to exponential.

Modulus of Elasticity. The modulus is a measure of the binding force in the solid solution. Exact measurements are made by the dynamic method with use of bending and longitudinal vibrations. If the binding force does not change, then the modulus varies with the discontinuity of the material and the volume, i.e., the number of broken bonds is determined.

The modulus of elasticity

$$E = \frac{M \rho^{1/2}}{4742} \theta^3, \tag{2}$$

where $\theta$ is the characteristic temperature; M is the molecular weight; $\rho$ is density.

Consequently, $E \sim \theta$ and defects affecting $\theta$ also affect E. Increasing the concentration of vacancies leads to a reduction of $\theta$ and E. The modulus of elasticity decreases considerably more with increasing number and size of the discontinuities. Calculations made in collaboration with G. F. Lepin showed that

$$E = E_t e^{-V_p/V}, \tag{3}$$

where $E_t$ is the true modulus of elasticity of the undamaged material; $V_p$ is the volume encompassed by the effect of discontinuities; V is the volume of the sample.

If it is assumed that cracks or other discontinuities are evenly distributed through the bulk of the material, then $V_p/V = F_p/F$, where $F_p$ is the average area of the cross section encompassed by the effect of cracks and other discontinuities. Then we have

$$E = E_t e^{-F_p/F}. \tag{4}$$

The results obtained indicate that by measuring the modulus of elasticity one can determine the volume percentage of the material affected by discontinuities. However, with an identical total volume of discontinuities the size of the discontinuities has a decisive effect on the modulus of elasticity.

If previously evenly distributed vacancies with concentration C coalesce in a very thin discontinuity oriented normal to the tensile stress and having an average dimension d in this direction, then

$$E_{Cr} = E_t e^{-Cda^2}, \tag{5}$$

where $a$ is the lattice constant.

Substituting in formula (1) the value of E determined from (3) or (4), one can find a common approach to determine the damage by the two methods described.

Density. The density of the material

$$\rho = \frac{m}{V - V_{Cr}}, \tag{6}$$

where m and V are the mass and volume of the sample; $V_{Cr}$ is the volume of the discontinuity. Since $V_{Cr} \ll V$, then

$$\rho = \rho_0 \left(1 - \frac{V_{Cr}}{V}\right), \tag{7}$$

where $\rho_0$ is the density of the original material.

It is interesting to compare measurements of the density with measurements of the modulus of elasticity, since the first method makes it possible to determine the volume of the material unloaded by discontinuities $V_p$ and the second the volume of the discontinuities themselves. These two values make it possible to determine the extent of damage after heat treatment and after operation. These studies indicate that the dimensions of discontinuities measured metallographically are in good agreement with those determined by measuring the density and the modulus of elasticity.

## Emission Methods

Exoelectronic and acoustic emission are widely used at the present time [2]. These methods are of considerable interest for analyzing the defects in machine parts after heat treatment and subsequent operation. Exoelectronic emission makes it possible to analyze the surface and thin surface layers of damaged parts, since the deformed volumes are subjected to electron bombardment, thus making it possible to predict the course of cracks running to the surface and located near the surface. Acoustic emission, consisting of sound waves emitted during nucleation and propagation of cracks, makes it possible to determine the location of cracks in the volume of the piece [2].

Proper selection of the heat treatment ensuring high technological strength of critical machine parts requires a large number of tests. The methods of nondestructive testing considered here make it possible to select the optimal technology providing the highest technological and structural strength.

## LITERATURE CITED

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# RAPID ELECTROTHERMAL TREATMENT OF WIRE

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The results of research on the physics of rapid electrothermal hardening generalized in a monograph [1] have been put to practical use to develop methods of rapid heat treatment of steels, permitting a radical overhaul of one branch of the metallurgical industry – the production of steel wire and cable.

The standard heat treatment for steel wire – patenting – makes it impossible to increase the speed of the heat treatment due to the characteristics of phase transformations under isothermal conditions and prohibits the use of alloy steels, thus limiting increases in labor productivity and complicating the production of several types of special wire.

The methods of heat treating wire developed at the Institute of Metal Physics, Academy of Sciences of the Ukrainian SSR (IMF AN UkrSSR) [2-5] are based on electrocontact heating of the moving wire. A schematic diagram of rapid electrothermal treatment with quenching and rapid tempering (RETT) (curve 1) and rapid electropatenting (REP) (curve 2) is shown in Fig. 1. These treatments differ only in the conditions of cooling the austenitized wire. RETT consists essentially of heating the moving wire to a temperature above $Ac_3$, quenching to martensite, and rapid electrotempering. Because of the specific characteristics of the crystal structure of martensite, the formation of martensite decomposition products during rapid heating occurs with retention of a distinct orientation of cementite along planes (112) or (100) of ferrite. For this reason, rapid heating of the quenched steel to 500-550°C leads to formation of an ordered structure of fine lamellar sorbite that resembles the structure of patented steel in outward appearance [2]. However, the dispersity of the

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