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Analysis of Factors Affecting the Cracking Resistance of Steels for Rods

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Abstract. *The purpose of the study is to determine the factors influencing the fracture toughness of steels in hydraulic cylinder rods. The dependence of the change in the hardness of pre-hardened steel 30KhGSA on the tempering temperature is presented. The hardness values of 30KhGSA steel after surface plastic deformation are presented. The dependences of the heating temperature on the calculated thickness of the sample, on the input energy, and on the level of hydrogen content in steel have been determined. The required heating temperature for steel 20MnV6 has been calculated. The reasons for the formation of cold cracks in steels 45, 40X, 30 HGSA, 20MnV6, 42CrMo have been determined. Recommendations are given for the elimination of the formation of cold cracks under the thermal effect of steels.*

Keywords: *rod, flock sensitivity, cracks, heat treatment, coating, residual stresses.*

Introduction

Special equipment (excavators, drilling rigs) operates in harsh, harsh conditions characterized by high relative humidity, dynamic alternating loads in contact with rocks and soil [1].

The rod is one of the main structural elements of the hydraulic cylinders of special equipment, transmitting the force from the piston. This metal rod is made of structural steel or low alloy steel, with a chrome covering.

The chrome covering provides an additional layer of protection. It is more resistant to negative influences of the environment.

During operation, the rods of the hydraulic cylinders experience large dynamic loads. Despite the chrome-plating protection of the rubbing surfaces of the rod and the cylinder liner, various defects are formed on their surfaces as a result of these loads.

Rods for special equipment are made of the following steel grades: St45, 40X, 30HGSA. The choice of these steels is based on the properties that determine their applicability for such parts, namely, flock sensitivity and tendency to crack formation.

Research methods

The considered group of structural materials (medium-carbon low-alloy steels) is the most common in modern mechanical engineering. The most important characteristics of steels and alloys are indicators of mechanical, technological and service properties.

In the manufacture of hydraulic cylinder rods, steels with an average carbon content (0.25-0.45%) are used, both unalloyed (for example, steel 45) and low-alloyed (30 HGSA, 40X according to GOST 4543-71). These structural engineering steels are used, as a rule, after quenching and tempering and, less often, in a normalized state. The temperature range of application of products from these steels is from – 5 to 60°C. Their toughness remains high enough down to – 60°C. After heat treatment, the strength can reach up to 1100 MGa [2-5].

The critical cooling rate of medium-carbon alloy steels during quenching is much lower than that of low-carbon steels due to a noticeable increase in the range of low stability of austenite. Therefore, when they are cooled, even in air, part of the austenite can be supercooled and undergo transformation below the MH temperature. Under heating and cooling conditions, the heat affected zone (HAZ) during heating even in the most overheated areas with homogeneous austenite at an increased cooling rate can form martensite [6].

In structural carbonaceous, low- and medium-alloyed steels, the nonequilibrium phase – martensite – is of particular importance. It is a supersaturated solution of carbon in α-iron, is formed by a special mechanism and has high strength and hardness (the higher, the more carbon is contained in martensite) and low plasticity and toughness.

In steels with a carbon content of 0.30% and higher, upon rapid cooling of the metal in the heat-affected zone, a solid martensitic or troostite structure is formed, which is much more brittle than the base metal, which creates a danger of brittle fracture both during the manufacture of products (cold cracks) and and during operation.

Structural changes occurring during various heat treatment operations contribute to the change in the properties of steels. A change in the structure, consisting in a change in the size and state of the phase components, determines the changes in the motion and deceleration of dislocations and, thereby, the resistance to deformation and the limiting value of deformation under loading of steel. The presence in the ferrite matrix of an excess phase in a dispersed state or even in a pre-precipitation state leads to a distributed multiple blocking of dislocation motion and thereby to a significant hardening of the steel. In this case, naturally, the ductility and toughness of the steel are reduced [7].

From literary sources it is known about the effect of tempering temperature on the hardness of pre-hardened structural steel 30HGSA. Figure 1 shows a graph of the dependence of the hardness of steel 30HGSA on the tempering temperature. When the hardened structural steel 30HGSA is heated in the temperature range of 200-700°C, a significant decrease in the metal hardness occurs [8].

For a more detailed study of the structure and properties of the metal in the area of softening, samples were made from pre-hardened and tempered 30XGSA structural steel. The heating temperature was determined from the thermokinetic diagram for steel 30KhGSA and amounted to 760°C, which corresponds to the Ac1 temperature for 30KhGSA, at which a section of high-temperature tempering of the HAZ begins to form. This heating simulated the thermal effect on the base metal. The results of measuring the hardness of the samples are shown in Figure 2.

It should also be borne in mind that with an increase in the thickness of the metal, the structural and mechanical inhomogeneity of the material increases, and the likelihood of the appearance of defects increases. In this case, stresses along the thickness of the metal also increase and conditions are created for the transition from a plane stress state to a plane-deformed state. Statistical analysis of the causes of destruction of large-sized thick-walled structures operating under load indicates that in more than 80% of cases, destruction occurs as a result of the formation and growth of cracks in the metal.

The high strength of materials can only be realized in structures when it is combined with a sufficient supply of other properties and, above all,

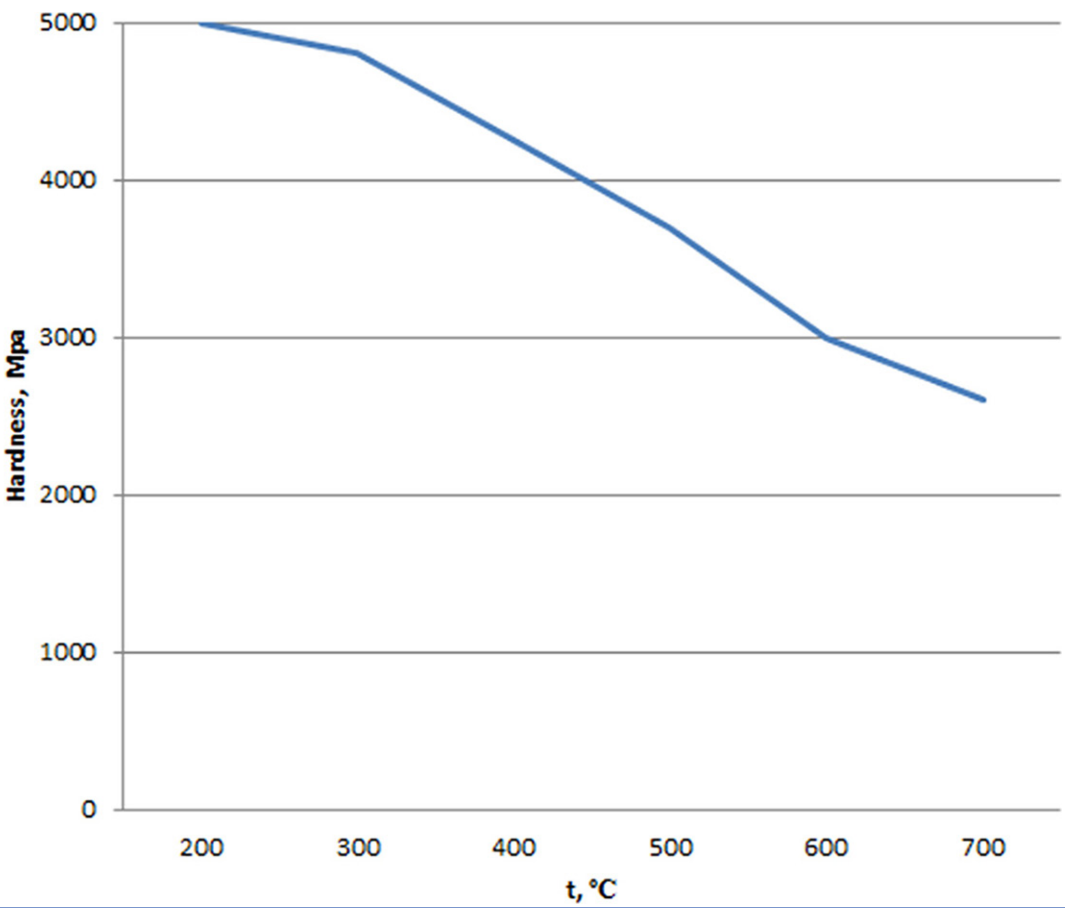
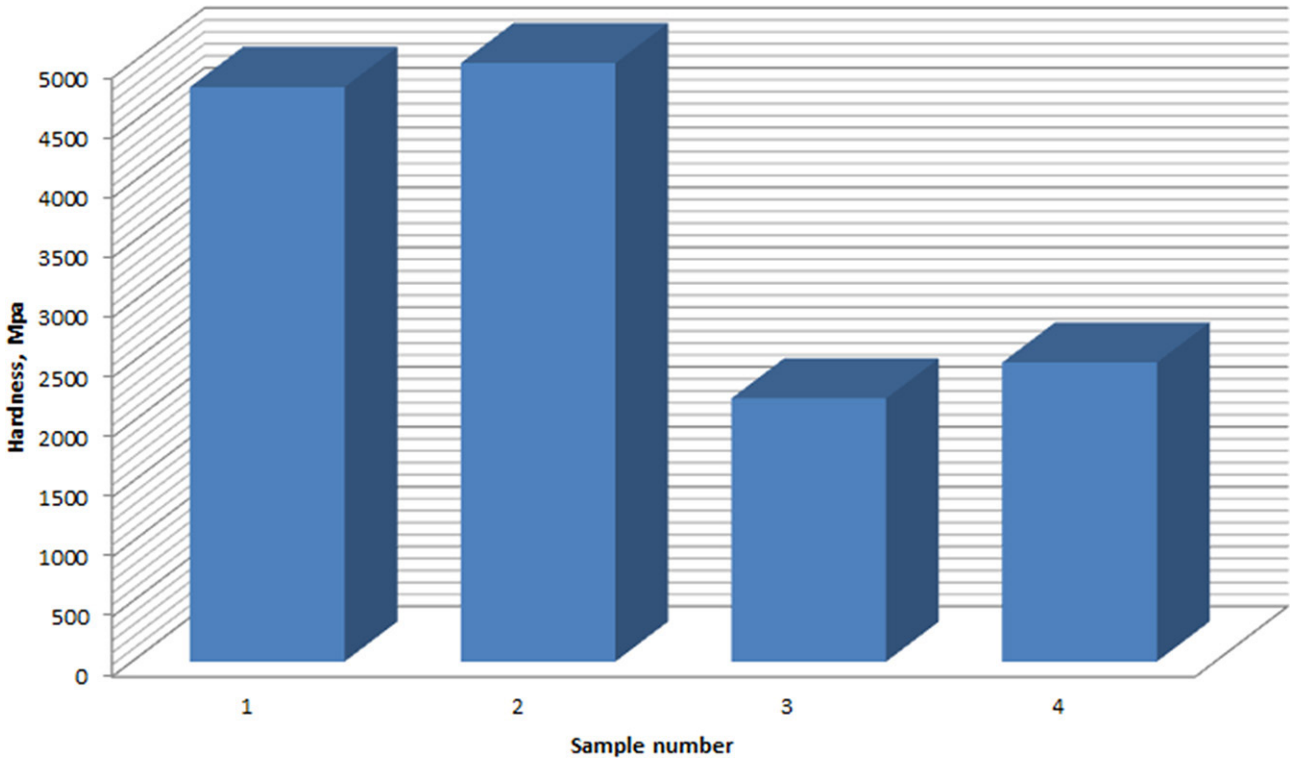


Figure 1 – Dependence of the change in hardness, pre-hardened steel 30HGSA on drawing temperature



1 – value of hardness, hardened and tempered structural steel 30HGSA according to GOST 8479-70; 2 – Sample hardness after hardening and drawing-back; 3 – hardness of the sample after heating to Ac1 temperature (760°C) and subsequent cooling in air; 4 – hardness of a sample subjected to surface plastic deformation

Figure 2 – Hardness of samples of structural steel 30HGSA after various impacts

with the fracture toughness.

It should also be noted that with an increase in the degree of alloying of steels, especially with chemical elements that contribute to precipitation hardening (for example, vanadium, molybdenum, etc.), the likelihood of cracking during reheating of structures during subsequent heat treatment (for example, when remelting coatings) increases significantly. so-called cracks during heat treatment (CHO). The mechanisms responsible for the formation of CHO can be conditionally subdivided into two groups depending on their influence on the direct and relative softening of grain boundaries.

Direct softening is a consequence of grain-boundary segregation of alloying and impurity elements, adsorption of gases, release of brittle phases, the appearance of high-temperature slip and martensitic transformation of a high density of crystal lattice imperfections, and the formation of submicroscopic or microscopic embryonic defects.

Relative softening, which in most cases is the main factor, manifests itself as a result of the precipitation hardening process caused by the release of particles of thermally stable secondary phases. With holding, adopted in the process of heat treatment, precipitation hardening of low and medium alloy steels manifests itself in the temperature range of 500-700°C, in which the appearance of CHO is noted, which is primarily caused by the formation of molybdenum and vanadium carbides.

To analyze the tendency of structures to form cracks upon reheating, the following indicators are used, proposed by various researchers for steels with $C \leq 0.18\%$ and $Cr < 1.5\%$:

$$\Delta G = Cr + 3{,}3Mo + 8{,}1V - 2. \quad (1)$$

At $\Delta G > 0$, the danger of the appearance of CHO increases.

The formation of martensite in the HAZ during heating of medium-carbon, low- and medium-alloy steels is the main reason for the difficulty of their heat treatment due to the tendency to form cold cracks. Cold cracks can appear immediately after thermal exposure (for example, during the application of thermal spray coatings and their remelting) and after some time. The disadvantage of the steels under consideration is also the martensitic structure of the HAZ, which determines the increased brittleness of these areas, which can affect their operation, especially when operating at low temperatures, dynamic loads, etc. [9].

Cold cracks are a type of localized destruction of structures. In the formation of cold cracks, three factors are decisive: hardening structures, an increased level of stresses of the first kind, and the saturation of the metal with hydrogen. It was found that the process of cold crack formation includes three stages: preparatory, incubation and spontaneous destruction. The first two stages characterize the nucleation process, and the third, the crack propagation process.

According to the researchers, cold cracks originate along the boundaries of the actual austenite grain as a result of high-temperature plastic deformation, at which the density of mobile dislocations increases and the elastic energy of structural distortions increases. The subsequent appearance of submicrocracks is the result of sliding along grain boundaries and diffusion of vacancies to the boundaries. Hydrogen and sulfur, which reduce the surface energy of grain boundaries, promote the growth of cavities and submicrocracks [10].

The tendency of steels to cold cracking is associated with their hardenability – an increase in hardness under the influence of a thermal cycle and saturation of the HAZ metal with hydrogen. Since the hardenability of steels increases with an increase in the degree of alloying, the propensity to form cold cracks is roughly estimated by the carbon equivalent index Ce:

$$Ce = C + \frac{Mn}{6} + \frac{Cr}{5} + \frac{Mo}{5} + \frac{V}{5} + \frac{(Ni+Cu)}{15}. \quad (2)$$

It is believed that at $Ce \leq 0.4$, steel is not prone to cold cracking.

Equivalent carbon content affects the critical hydrogen content in the metal of structural alloy steels. The higher the content of carbon and other elements that lower the temperature of martensitic transformation, the lower the hydrogen content, cracks form.

In order to avoid the formation of cold cracks during thermal action of medium-carbon steels, especially alloyed ones, it is first of all necessary to slow down the cooling rate of the metal of the structure during thermal action and to reduce the level of arising stresses. Reducing the cooling rate of the HAZ does not always prevent the transformation of austenite to martensite. But even if the martensitic transformation cannot be avoided, the decomposition of austenite in the martensite zone is transferred to the temperature range closer to Mn (farther from Mk), which makes the formed martensite less stressed and less brittle.

Since the formation of cold cracks is influenced by hydrogen, during the thermal effect of steels of this type, special precautions must be taken to prevent the ingress of hydrogen sources – moisture and scale – into the thermal effect zone. To do this, thoroughly dry and clean the surface of the product before thermal exposure. Technological measures are also advisable, allowing to reduce the level of stresses in the product, heat treatment, most often high tempering, which simultaneously leads to the decomposition of martensite and to reduce residual stresses.

To prevent the formation of cold cracks, it is effective to use heating during thermal exposure. This reduces the cooling rate of the HAZ metal, prevents the formation of martensite, and creates favorable conditions for the removal of diffusible hydrogen.

To estimate the required reheating temperature during thermal action in order to avoid the formation of cold cracks, you can use the recommendations presented in the international standard EN 1011-2: 2002 «Welding – Recommendations for welding of metallic materials – Part 2: Arc welding of ferritic steels». It can be assumed that the thermal effect on the steel metal during the welding process will be similar to the thermal effect during the application of thermal spray coatings and their remelting. The standard [11] presents 2 methods for determining the required heating temperature of steels under thermal action.

The first method for determining the heating temperature according to formula (2).

Let us determine the possible level of hydrogen content in steel according to table 3 [12].

Heating calculation formula:

$$Q^{*} = Q_1 + Q_2 + Q_3. \quad (3)$$

The energy introduced into the steel when the coating is heated to the melting point [13]:

$$Q_1 = C_1 m (t_2 - t_1), \quad (4)$$

where C_1 is the heat capacity of the heated material, J/kgK;

m is the mass of the heated material, kg;

t_1 is the initial temperature, °K ($t_1 = 293$°K);

t_2 is the temperature required when heating the coating to the melting temperature, °K ($t_2 = 1273$°K). Energy introduced into steel during coating melting:

$$Q_2 = m \times \upsilon, \quad (5)$$

where m is the mass of the heated material, kg;

υ is the specific heat of fusion.

The energy introduced into the steel when the

Table 1 – ΔG Steels used in the production of hydraulic cylinder rods

Steel grade	45	40X	30HGSA	20MnV6	42CrMo
ΔG	-1,965	-0,9	-0,9	0,184	0,025

Table 2 – Equivalent of carbon Ce of steels used in the production of hydraulic cylinder rods

Steel grade	45	40X	30HGSA	20MnV6	42CrMo
Ce	0,674	0,833	0,783	0,604	0,873

coating is heated to the melting temperature:

$$Q_3 = C_2 m(t_3 - t_2), \quad (6)$$

where C_2 is the heat capacity of the molten material, J/kgK;

m is the mass of the heated material, kg;

t_2 is the temperature required when heating the coating to the melting temperature, °K (t_2=1273°K);

t_3 is the temperature required when heating the molten coating, °K (t_3=1573°K). According to the nomogram shown in Figure 3, we determine the required steel heating temperature [14].

The second method for determining the heating temperature.

Let's define the carbon equivalent for steel:

$$CET = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40}, \% \quad (7)$$

Required temperature Without heating steel under thermal influence (°C) [15]:

$$Tp = TpCET + Tpd + TpHD + TpQ. \quad (8)$$

Heating temperature taking into account the carbon equivalent of steel (°C):

$$TpCET = 750 \times CET - 150. \quad (9)$$

Heating temperature taking into account the thickness (d) of the product (°C):

$$Tpd = 160 \times tg\left(\frac{d}{35}\right) - 110. \quad (10)$$

Heating temperature taking into account hydrogen content in steel (°C):

$$TpHD = 62 \times HD\, 0,35 - 100. \quad (11)$$

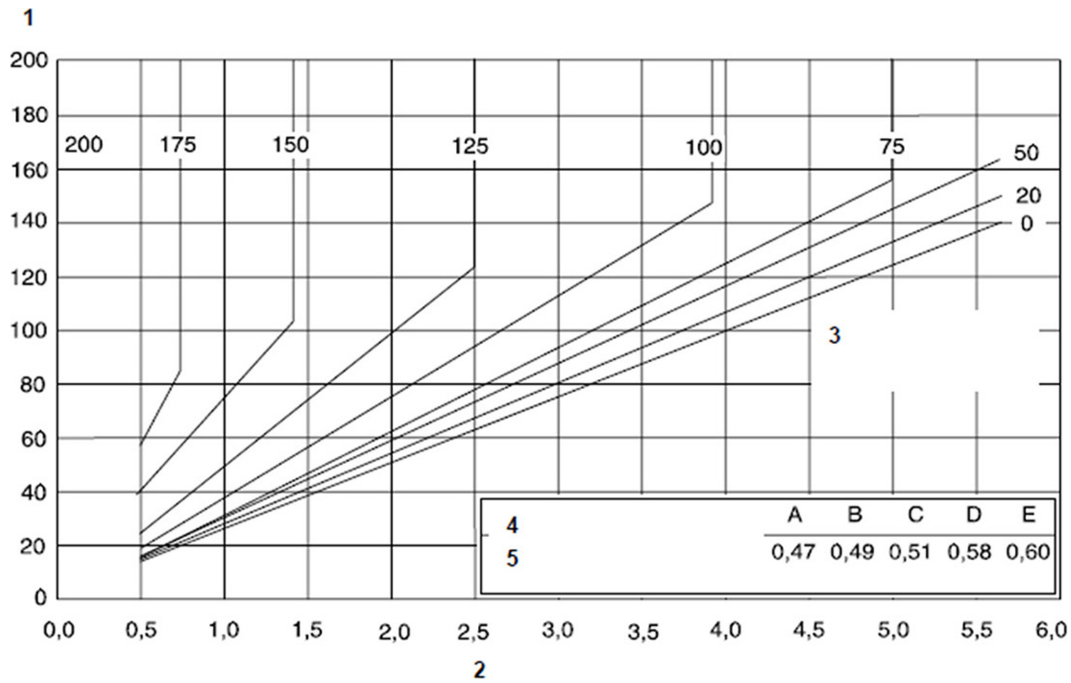
Heating temperature taking into account the energy introduced into the steel during the remelting of the coating (°C):

$$TpQ = (53 \times CET - 32) \times Q - 53 \times CET + 32. \quad (12)$$

After calculating the required heating temperature for steel 20MnV6, the following data were obtained. The required heating temperature of 20MnV6 steel under thermal action (during remelting

Table 3 – The level of hydrogen content in the weld metal

Diffusible hydrogen content, ml/100g of deposited metal	Hydrogen scale
> 15	A
10 ≤ 15	B
5 ≤ 10	C
3 ≤ 3	D
≤ 3	E



1 – design thickness, mm; 2 – introduced energy per unit length, kJ/mm; 3 – minimum required heating temperature, °C; 4 – hydrogen content in steel, ml/100g; 5 – carbon steel equivalent

Figure 3 – Nomogram for determining the heating temperature

of the coating) is 125°C according to the first method, 82°C according to the second method.

Conclusions

When identifying factors affecting the formation of cracks in the steels under study (used in the manufacture of hydraulic cylinder rods 45, 40X, 30HGSA, 20MnV6, 42CrMo), it was found that for steels 20MnV6, 42CrMo, cracking is possible upon reheating. At the same time, evaluating the carbon equivalent of the metal, we can say that all steels (45, 40X, 30HGSA, 20MnV6, 42CrMo) are prone to cold cracking under significant thermal exposure (for example, when remelting a gas-thermal coating). The reason for the formation of cold cracks is the embrittlement of the steel metal at an increased cooling rate, thermal stresses and hydrogen in the steel metal. In order to avoid the formation of cold cracks during thermal action of steels, it is necessary to slow down the cooling rate of the metal of the structure during thermal action and to reduce the level of arising stresses. In this case, to prevent the formation of cold cracks, it is effective to use preheating during thermal exposure [16].

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Түтіктер үшін сынықты болатқа әсерлейтін факторларды талдау

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***Аңдатпа.** Зерттеудің мақсаты – гидравликалық цилиндр өзектеріндегі болаттардың сынуға төзімділігіне әсер ететін факторларды анықтау. Алдын ала беріктендірілген 30KHGSA болатының қаттылығының өзге-*

руінің шыңдау температурасына тәуелділігі ұсынылған. Беттік пластикалық деформациядан кейін 30KHGSA болатының қаттылық мәндері келтірілген. Үлгінің есептелген қалыңдығына, берілетін энергияға және болаттағы сутегі құрамының деңгейіне қыздыру температурасының тәуелділігі анықталады. Болаттың 20MnV6 қажетті қыздыру температурасы есептелген. 45, 40Х, 30 ХГСА, 20МнВ6, 42СрМо болаттарында суық жарықтардың пайда болу себептері анықталды. Болаттардың термиялық әсерінен суық жарықтардың пайда болуын жою бойынша ұсыныстар берілген.

Кілт сөздер: *баған, флокуляция, жарықтар, термиялық өңдеу, жабын, қалдық кернеулер.*

Анализ факторов, влияющих на трещиноустойчивость сталей для штоков

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Аннотация. *Цель исследования – определение факторов, влияющих на трещиностойкость сталей в штоках гидроцилиндров. Представлена зависимость изменения твердости предварительно закаленной стали 30ХГСА от температуры отпуска. Приведены значения твердости стали 30ХГСА после поверхностной пластической деформации. Определены зависимости температуры нагрева от расчетной толщины образца, подводимой энергии и уровня содержания водорода в стали. Рассчитана необходимая температура нагрева стали 20МнВ6. Установлены причины образования холодных трещин в сталях 45, 40Х, 30 ХГСА, 20MnV6, 42CrMo. Даны рекомендации по устранению образования холодных трещин при термическом воздействии сталей.*

Ключевые слова: *шток, флокочувствительность, трещины, термообработка, покрытие, остаточные напряжения.*

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