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Short Communication

Structural Foundations for Improving Reliability and Durability of Machine Parts

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Abstract

Various methods and methods of increasing the reliability and durability of products, machine parts and tools are considered: gear gears, sprockets, camshafts of cranes, gate valves. The prospect of activating the mechanisms for creating dislocation constructions of cellular-polygonal type is shown. Products made of the following steel grades are considered: 38KHN3MA, 5KHNM, 20X13, 40KHN according to GOST 4543-2016.

Keywords: Products; Structural strength; Reliability; Durability; Adjustable thermoplastic hardening; Mechanical- heat treatment; Dislocation constructions

Introduction

Chemical and petroleum engineering products are operated as part of complex technological lines of large tonnage for the production of various acids, carbamides and other refined products in the harshest climatic conditions, constantly exposed to high pressure, aggressive environments and temperature changes. These are equipment for the chemical industry, hydrocracking plants and intensive oil and gas production in Western Siberia, the Far North and in Kazakhstan [1].

Regardless of the destination, the pipeline network is important an engineering structure, each part of which carries a certain functional load and is responsible for the quality, safety and continuity of the network. However, the main line is not only pipes, they also need pipeline fittings.

The service life of many machine parts is associated with their resistance to cyclic contact loads. The wear of the working surfaces of these parts can lead to discoloration, increased vibration and noise, and subsequently to the failure of parts and machines.

To increase the resistance of the surface layer to repeated contact loads, it is necessary to increase the hardness of the part by strengthening physical and mechanical processing. However, increasing the hardness against contact loads increases the risk of brittle fracture, therefore, simultaneously with high hardness, the approved top layer must have a certain margin of safety and fluidity.

Such parts are gear gears of gearboxes, sprockets, camshafts of cranes, valves, etc. used in petrochemical production and made of the following steel grades 38KHN3MA, 38XH3BA, 38X2MYA, 38KHNZMFA, 20X13, 40KHN, 5KHNM according to GOST 4543-2016 [2], etc.

Material characteristics

40KHN - chrome steel was subjected to the study - nickel structural alloy steel 42, belonging to the group of improved and hardened steels, i.e., products with a diameter of 50-

125mm, amenable to a given heat treatment: quenching, tempering, normalization, was subjected to the study.

The chemical composition of steel according to GOST 4543-2016, in addition to nickel and chromium, the 40KHN brand includes several other elements. Below is the ratio of elements in hundredths of a percent: carbon - 0.36-0.44%; silicon - 0.17-0.37%; manganese - 0.5-0.8%; nickel - 1-1.4%; sulfur - up to 0.035%; phosphorus - up to 0.035%; chromium - 0.45-0.75%; copper - up to 0.3%.

The specific weight of steel grade 40KHN is 7820kg/m^3.

Material hardness - HB 10 -1=207MPa; temperature of critical points - Ac 1=735 °C, Ac 3 (A cm) = 768, Ar 3 (Ar cm) = 700 °C, Ar 1=660, Mn=305 °C; machinability by cutting: in the hot-rolled state at HB 166-170 and σv = 690MPa, Ci t v. spl=1.0 and Ci b.st=0.9.

The main area of application of 40KHN steel is the production of parts for mechanisms operated under constant load conditions, when mechanisms operate at high sliding speeds and high vibration. For example, such as: connecting tubes and couplings for mechanisms in the oil industry, piston rods, axles, and shafts. Gears, hydraulic cylinder rods and similar parts are also made of 40KHN steel, as it ensures high quality of the final product.

And even such serious details as pipeline fittings, rotary, crankshafts and gear shafts used in aircraft construction, parts of air-cooled engines operating at temperatures above 500 °C (degrees Celsius) are made of this steel grade. The physical and mechanical features of 40KHN steel make it suitable for the manufacture of products, one of the properties of which should be the strength and viscosity of the material during operation.

This steel grade is one of the best examples of structural steel. Due to the combination of nickel and chromium, 40KHN steel is used in such critical parts as axles, shafts, connecting rods, gears, excavator shafts, couplings, transmission shafts, spindles, bolts, levers, rods and cylinders that are subjected to vibration and dynamic loads and require increased strength and toughness. Rolling rail-block and large-grade mills for hot rolling of metals.

Nickel contributes more to the hardness and strength of ferrite than chromium, since it is completely soluble in a solid solution of steel, which is especially important, quenching here is also accompanied by an increase in the plasticity of the materials of the product. The simultaneous presence of nickel and chromium in 40KHN steel leads to a good combination of mechanical properties (strength and viscosity) in addition to high hardenability.

Products made of 40KHN steel are widely used in the petrochemical industry for the manufacture of critical components, such as: heavy lifting, drive and intermediate shafts, gear couplings, gears, small gears for drilling rigs, plates and rollers of bushing-roller chains, axes of hoisting blocks, trunks of swivels, latches and axes of elevators.

When using chromium-nickel steels, it should be borne in mind that they are particularly prone to embrittlement in the temperature range 450-550 °C. Therefore, parts made of this steel after high-temperature tempering should be cooled quickly (in water or oil). The addition of a small amount of molybdenum to 40KHN steel reduces the tendency to temper brittleness. Forgings and forged blanks for petrochemical engineering are manufactured and supplied according to: GOST 4543-71, GOST 1133-71, GOST 8479-70. Rolls OST 24 013.21-85. Pipes OST 14-21-77.

Purpose: in cemented and improved condition, 40KHN steel is used for the manufacture of critical parts requiring high strength, toughness and wear resistance, as well as for parts, exposed to high vibration and dynamic loads. Products made of this steel are used in industrial conditions, at operating temperatures from minus 70 °C to plus 450 °C [3,4].

Research of the material

One of the solutions to this problem is to create an inhomogeneous reinforced structure on the surface layer with a certain distribution of hard and soft (visco-plastic) areas. The advantage lies in the fact that under the action of a cyclic contact load, the visco-plastic material suppresses brittle cracking in solid structural elements. In addition, the depth of the surface hardened layer should exclude its deformation and penetration, i.e., it should be directly dependent on the contact loads., tested by the part. Therefore, for heavy-loaded parts, a sufficiently deep hardened layer from 4mm to 8mm is required, for other high-loaded parts - more up to 10-12mm [5].

Currently, there is no universal technology that can effectively ensure the hardening of materials (steel products) with a wide range of surface layer thickness (from a few micrometers to 6-8mm). In this regard, it is advisable to use combined, mutually compatible and complementary technologies that have a different physical hardening regime and collectively provide a certain diagram of changes in the properties of the gradient surface layer of the product [5,6].

To increase contact endurance, the technology of hardening by surface plastic deformation (PPD) has proven itself to increase the durability of contact due to the formation of a hardened surface layer with high hardness (6200-6700MPa) and residual compressive stresses that favorably affect the action of cyclic loads. The surface hardened layer has a smooth transition to non-hardened metal after hardening by surface plastic deformation, which leads to a lack of concentration stresses at the boundaries and, consequently, to the absence of fatigue cracks [4].

Other advantages of surface hardening by plastic deformation include the possibility of machining parts of any size and configuration, the possibility of local hardening of sections of parts, productivity, ease of execution and the possibility of mechanization and automation of the process. Plastic deformation of surfaces is widely used in combined hardening, as it allows the full use of the potential of other technologies [5].

Hardening by a combination of surface plastic deformation and chemical-thermal treatment (especially carburization) is very promising. Explaining the physics of this process, it should be noted that the characteristics of the structural elements formed during saturation of the carbon surface, their number and location also depend on the initial structural state of the surface layer, i.e., on the energy state of the atoms, which can vary significantly. Application of combined hardening of the plastic surface deformation. The diffusion process can be intensified before carburization to achieve higher values of carbon concentration in the diffusion zone [6].

The time and energy costs of the carburization process can be reduced. Surface layers hardened as a result of combined treatment of surface plastic deformation and carburizing hardening may have additional resources to improve the performance characteristics of parts [7].

Technological methods for improving the reliability and durability of machine parts and tools include measures to improve the properties of materials used in this design. The properties of parts are formed during processes such as casting, welding, forming and machining. These processes set the strength characteristics and other indicators of the durability of future machine parts and tools. All subsequent manufacturing operations of the part are reduced to improving the properties of the workpiece material. Therefore, before applying improvements in processing, it is necessary check the correctness of the materials and methods used to obtain them from the workpiece.

The classical principle of metallology - the connection of various properties of metal alloys (mechanical, physico-chemical, technological, etc.) with their structure - is being further developed due to the emergence of new criteria for evaluating structural strength and improving methods for analysing substructure, which has a significant impact on the formation of alloy properties.

Substructures and features of group dislocation structures, which define the concepts of the internal structure of grains, polygons, cells and blocks, can have a stronger influence on the complex properties of the alloy than all other possible structures (macro-micro, interatomic).

Structural strength (determined on samples) characterizes the operability of the steel structure under conditions as close as possible to the actual operating conditions of the product in which the studied steel grades are used [3,4].

Structural strength is characterized by many mechanical properties of the product, which can be conditionally divided into two groups: 1) reliability group; 2) durability group. The strength criteria of materials depend on the operating conditions. The strength criteria under static loads are the tensile strength σ_B and the yield strength $\sigma_{0,2}$ (σ_T), which characterize the resistance of materials to plastic deformation.

With prolonged cyclic loading during operation, the strength criterion is the strength limit σ_R (σ_{-1} for symmetrical circular bending). The permissible operating voltage is calculated based on the value of the selected strength criterion. The higher the strength of the material, the higher the permissible operating stress and the smaller the size and weight of the finished part.

The stiffness criterion characterizes the ability of the product material to resist deformation. Dimensions of parts that must maintain their exact dimensions and shape during operation, for example, machine stands, housings gearboxes and other parts are determined by this criterion, and not by the criterion of strength. In order to reduce elastic deformation, the materials of these parts must have a high modulus of elasticity, which is the criterion of rigidity [6,7].

Reliability is mainly the ability of a part during operation to resist brittle (sudden) destruction or fracture toughness (crack resistance), when loaded in various ways. To avoid brittle destruction, products made of structural materials must have sufficient ductility (δ, ψ) and impact strength (KCU, KCV, KCT). However, these reliability criteria are determined on small laboratory samples cut from products (excluding operating conditions of a specific part) and are sufficient only for soft materials with low strength indicators. For less ductile materials with an increased tendency to brittle fracture, it is necessary to take into account additional factors affecting plasticity and toughness and increasing the likelihood of brittle fracture. Examples are the presence of KCT stress concentrators (notches), low temperatures, dynamic loads from the impact of large dimensions of the parts themselves (scale factor).

Durability is the property of the product material to resist the development of progressive destruction, ensuring the operability of finished products for a certain time of operation (resource). There are various reasons for reducing the service life, such as the development of fatigue processes of the material, wear of the surface layer of the product, creep and corrosion.

Durability is determined by the number of cycles to failure during endurance testing (fatigue survivability), the rate of development of a fatigue crack in the steady (second) section of the kinetic diagrams of fatigue failure, wear resistance, heat resistance, heat resistance. However, of the many indicators of structural strength of a steel material, the two most important are resistance to plastic deformation (yield strength) and resistance to sudden brittle fracture (fracture toughness, or crack resistance).

These indicators of structural strength do not depend additively on the chemical composition or structure of the steel itself of the product. Factors that increase the yield strength, prevent the easy movement of dislocations in the steel structure, at the same time lead to a dangerous concentration of internal stresses and, consequently, to reduce the fracture toughness of the finished product.

Research Results

The indicated difference in the change of these two most important characteristics of structural strength (simultaneous hardening and embrittlement of the material) becomes even greater in the case of operation of high-strength steels at subzero temperatures. In order to successfully find rational ways to reduce embrittlement, when strengthening the steel structure, it is possible to establish the influence of individual dislocation hardening mechanisms on two important mechanical properties of the structure of steels - σ_τ and K_{IC}. (σ_τ - the ultimate strength of the material from the effects of loads; K_{IC} - the critical coefficient stress intensity from deformation).

Dependency analysis:

$$\sigma_\tau, K_{Ic} = f(\sigma_{Ä}, \sigma_P, \sigma_\phi, \sigma_3)$$

it shows a special perspective of the mechanisms of activation and creation of dislocation constructions of cellular-polygonal type $(\sigma_{Ä(\Pi,ÿ)})$, dispersed hardening phases or zones $(\sigma_{\phi(Ä,\phi)})$, structural barriers by moving dislocations due to the crushing of grain or structural components (σ_3), this creates the theoretical basis for obtaining optimal structures (substructure) of alloys, providing a significant increase in their structural strength. Dislocation mechanism $(\sigma_{Ä(\Pi,ÿ)})$, constitutes the essence, or physical content, of the theory of substructural hardening of the structure of metals of industrial steels.

The necessary substructure can be created in steel directly, for example, during mechanical and thermal treatment (MTO), the meaning of which is to develop the mechanism of polygonization, after cold plastic deformation, or by inheritance from hot-deformed austenite in the implementation of various schemes of thermoplastic hardening [6-8].

In the latter case , two options can be considered for the formation of a steel structure:

a) direct inheritance (transfer) of substructural dislocation structures in the austenite structure by its constituent martensite during mechanical and thermal treatment of steel;

b) indirect influence of the substructure created in hot-deformed austenite on the kinetics and mechanism of pearlite and intermediate (bainite) transformations in steel, using the developed varieties of thermomechanical processing. High-temperature thermomechanical isothermal treatment is the isothermal formation of bainite. High-temperature thermomechanical treatment - the formation of perlite during continuous cooling and in the process of isothermal exposure) [6-8].

Combined hardening methods based on a combination of several effective dislocation mechanisms operating simultaneously are of great interest for scientific and practical application. For example, the reduction of the negative effect σ_P (solid-solution hardening) and activation of mechanisms σ_ϕ and $(\sigma_{Ä(\Pi,ÿ)})$ allow obtaining high structural strength of the finished product on martensitic steels [7,9], etc.

That is, the idea of combined hardening with the simultaneous use of two effective dislocation mechanisms can be implemented - $(\sigma_{Ä(\Pi,ÿ)})$ and σ_3, that is, the creation of a developed substructure in a fine recrystallized austenite grain in the process of controlled thermoplastic hardening.

To determine the possible schemes of such a process and the development of technology and optimization of hardening treatment modes, a complex of studies of the process of hot deformation of austenite steels of various compositions, structural changes occurring during plastic deformation and isothermal exposures, the influence of substructures created in austenite on the kinetics and mechanism of its decay during continuous cooling and isothermal exposures was carried out [3,4,6-8].

The formation of a substructure in a fine grain stimulates the decomposition of austenite in the area of perlite transformation (at a cooling rate from 28 to 52 degrees / s, the temperature of the beginning of the transformation increases from 14° to 22 °C). This ensures an increase in the number of perlite nucleation centers, which leads to the appearance of new structural elements - perlite subcolonies, i.e. participants inside perlite colonies separated by sub-boundaries with small misorientation angles (from 0.75° to 5.2°).

The change in the kinetics and mechanism of pearlite and bainite transformations during the implementation of controlled thermoplastic hardening, in contrast to conventional heat treatment, causes the formation of a special substructure of hardened steel and, as a result, a significant increase in the fracture toughness of the finished product.

With the obtained values of impact strength, as a result of the product testing, for these indicators and values, calculations can be made with which the deformation energy is released, or the work of the energy released per unit area of the fracture surface in the material: increases from 1.75 to 2.25 times, the temperature of the visco-brittle transition decreases - from minus 72 °C up to minus 83 °C [8,9].

The use of the method of controlled thermoplastic hardening (RTU) in industry makes it possible to obtain for carbon steels the level of physical and mechanical properties characteristic of alloyed improved steels after a full cycle of their heat treatment (quenching and tempering) or for low-alloy steels after controlled plastic deformation on rolling mills, i.e. rolling, forging.

Establishment of the physico-mechanical nature of hardening using combined methods based on the activation of effective dislocation mechanisms, under the action of which stable subgrain constructions of polygonal-cellular type are formed $(\sigma_{Ä(\Pi,ÿ)})$, structural barriers are created, σ_3 and dispersed hardening phases are distinguished σ_ϕ, which opens up wide opportunities for the development of new methods for increasing the structural strength of steels in order to increase the reliability of products and durability of machine parts, tools and various structures [7-9] used in chemical and petrochemical production.

Conclusion

All types of pipe fittings are designed for specific operating conditions, contribute to the smooth and safe operation of various systems in all fields of activity, make them more reliable and workable. Thus, the methods currently used to improve the reliability and durability of the operability of parts, products, machines during their operation in industrial conditions can be effective against wear and destruction. The considered methods not only extend the service life, but also allow the use of parts in more severe operating conditions and more aggressive environments.

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