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Improving open toothed weels

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ABSTRACT

Purpose: Investigations include results of research opportunities of improving the quality of open toothed wheels using advanced technologies of surface by ion nitriding in hydrogen-saturating media and subsequent heat treatment with the creation of the material in the surface layer of optimal residual compressive stresses.

Design/methodology/approach: Researches on high-cycle bending fatigue were performed on the smooth cylindrical samples with a diameter of 5 mm using IMA-5 engine in pure bending with rotation (50 Hz) in the 3% NaCl solution and midair.

Findings: The analysis of the operating conditions and the stress-strain state of open toothed weels showed that different portions of the surface of the teeth take different in size and type of stress. The most dangerous areas of the surface have a leg and depression between the teeth.

Practical implications: Experience of operating gears indicates that the vast majority of failing of open gears occurs as a result of breakage of teeth from bending. Currently, there are many ways to improve the wear resistance and durability of the gears, but the problem is not solved until the end and it is urgent.

Originality/value: In order to improving the quality of open toothed wheels by hardening the surface of the toothed wheels and especially in hazardous areas due to the deposition of hardening coatings with a gradient structure in depth, authors create a surface layer of residual compressive stress with optimal value and strengthening the core of the toothed wheel.

Keywords: Ion nitriding; Wear; Pressure; Bending; Gear; Outdoor gear

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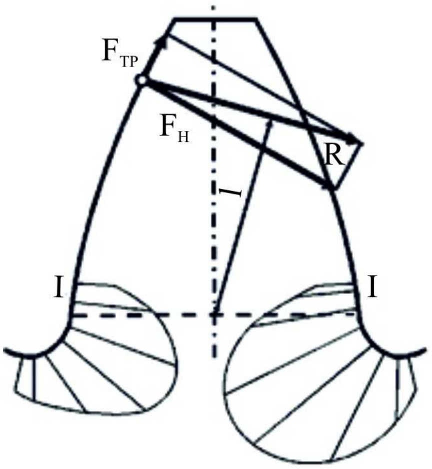
Properties

1. Introduction

Gears are widely used in engineering. Their durability and reliability often determine reliability and durability of the entire machine. Experience of operating gears indicates that the vast majority of failing of open gears occurs as a result of breakage of teeth from bending. Currently, there are many ways to improve the wear resistance and durability of the gears, but the problem is not solved until the end and it is urgent.

During operation of open gears, the surface layers is destroyed by the action of cyclic bending stresses and wear on the sliding contact surfaces of toothed wheels. The maximum bending stresses arise when the entire load is sustained by a pair of prongs, and its point of application is located at a position of the farthest from the tooth root. In this case the maximum bending stress is concentrated at the base of the tooth and in the zone of fillet stress concentration occurs (Fig. 1). For spur gearboxes the maximum bending stress reaches 85 MPa [1], and for cemented heavily loaded gears-up to 2500 MPa [2]. The excess of the actual bending stresses of allowable stress causes damage to the teeth.

a)



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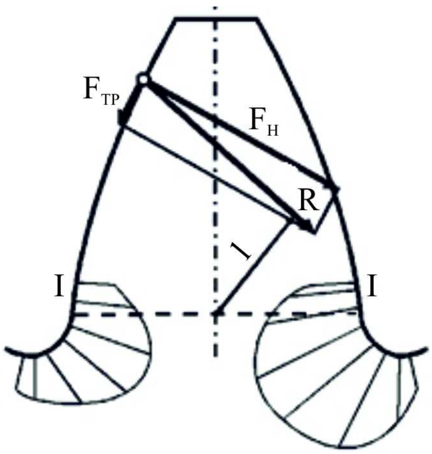

Fig. 1. Shoulder application of the resultant force R on the action of the normal force and frictional force F_H for driving the F_{TP} (a) and slave (b) of the teeth in the dangerous section

In the toothed pairs the joint roll only occurs at the pole. Since the direction of movement of the contact lines and the gear wheel are opposite, the slippage occurs between them. Sliding speed is equal to the velocity difference of the gear wheel bearings, and increases the transmission ratio. Slippage of the surfaces of contacting teeth causes friction in the contact zone and wear material.

One of the busiest sections of the profile of the gear is the transition zone from the involute portion to depression. In this zone tooth engagement occurs. Studies [3 - 5] showed that the properties of the material in the cavity between the teeth define not only the flexural strength of the teeth, but also greatly affect the strength of the contact teeth surfaces. Tension in the contact area can be reduced if the material in the cavity between the teeth will be more durable. Wear resistance and durability gear depend on material properties of the core teeth (cavity between teeth). In this regard, one of the promising ways of increasing and stabilizing properties of the gears is the use of selective hardening methods that will improve the physical and mechanical properties of the entire configuration of the tooth, providing its full strength, wear resistance and contact fatigue.

Thus, the analysis of operating conditions of gears shows that the durability of the gear to a large extent depends on the detailed study of the working conditions of the engagement, the nature of the stress-strain state of the various areas of gears and the proper selection of materials and methods of strengthening these areas in accordance with the size and nature stress state.

Many authors [1 - 5] show that the maximum stresses in bending and contact stresses arise in the surface layers, which leads to the appearance of microcracks and fracture. both the surface and design in general, due to the development and propagation of microcracks in the surface of the core (Fig. 2). Therefore, to improve the wear resistance and durability of the structural elements, in particular toothed wheels, should enhance the surface and the core, but with different physico-mechanical characteristics-more or less on the surface of the core. That is, the design of hardened layers should have a gradient structure in accordance with the stress-strain state, which appears in the details.

Currently gears are hardened by means of electrolytic precipitation and ni-carbing of low-carbon steel with subsequent thermal treatment of the material, providing a significant increase in their wear resistance and endurance. However, these techniques are applied in media containing large quantities of hydrogen, providing an adverse effect on steel resistance.

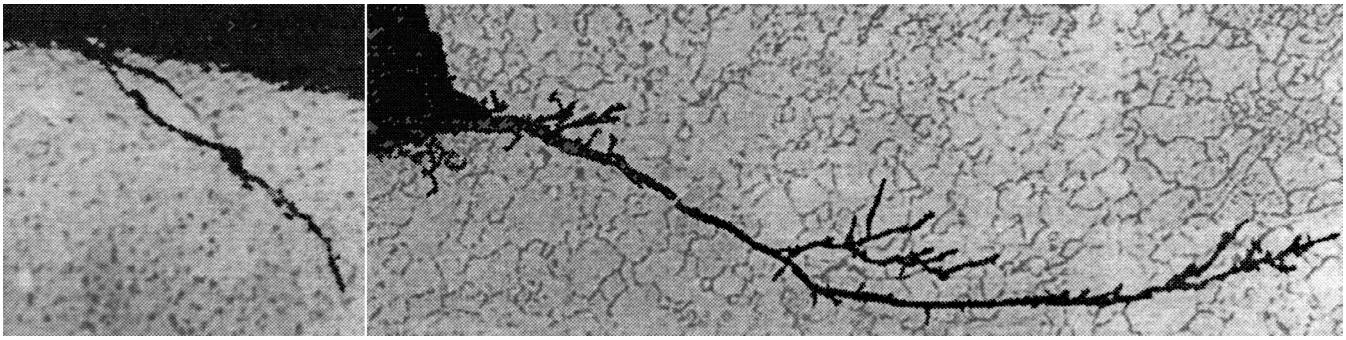

Fig. 2. Origination and propagation of micro-cracks in the surface coating of the gear, x500

According to modern ideas [6-9] hydrogen can be accumulated in steel for a very long time as ions (protons), and molecules. Small quantities of hydrogen accumulated in steel provide no significant properties changes. Hydrogen concentration increase in steel higher than a certain limit, depending on the quality of steel, changes its physical and mechanical properties and can cause defects affecting its resistance. Hydrogen accumulated in steel changes its mechanical properties under short-term and long-term static loading, as well as re-exposure and applied shock [6-9].

Among the various manifestations of hydrogen effects on the mechanical properties of metals, a specific place is held by its effect on fracture toughness. Defects, which are completely safe under normal conditions, due to hydrogen exposure can become dangerous and lead to an unexpected brittle fracture of a product [6]. According to dislocation-decohesive concept by Troiano Orion hydrogen that passed to the metal, primarily fills the most advantageous places from an energy point of view - dislocation cores. There the hydrogen concentration can reach high values. In this case, a cohesion weakening, that takes place in the core of fracturing dislocation, can be evidenced, i.e. traction decrease, which is then observed as a counting function of hydrogen in a dislocation or superlattice dislocation core zone due to changes in the electronic structure of the metal, cluster formation and the formation of metal-hydrogen bonds of hydride type. The combined effect of these three actions represents the main mechanism of hydrogen decohesive effect on the metal lattice.

The follow-on technology of material surface hard-facing is a hydrogen-ion nitriding in low hydrogen saturating media (mixture of nitrogen and argon) [10], the use of which eliminates the harmful effect of hydrogen on the metal.

We have carried out experimental research of high-cycle fatigue of various steels specimens, nitrided in hydrogen and low hydrogen saturating media during bend loading and ware resistance of samples in terms of sliding friction that occurs in the gears rolling with slippage.

2. Methods and results of the research

Researches on high-cycle bending fatigue were performed on the smooth cylindrical samples with a diameter of 5mm using IMA-5 engine in pure bending with rotation (50Hz) in the 3% NaCl solution and midair. Samples have been made of S45, the parts of which were subjected to ion nitriding (60 vol.% N_2+40 vol.% H_2) and hydrogen-free (60 about % N_2+40vol.% Ar) media due to the uniformity of the other process parameters (T=540°C, p=80Pa, τ=240 min).

The results of the research are shown in Fig. 3, they show that the endurance limit of the samples subjected to the preliminary ion nitriding in hydrogen-free medium during the testing midair increased in 1.9 times (from 190 to 370MPa), and during the testing in 3% NaCl solution in 3.6 times (from 30 to 110MPa) in comparison with the same values for the un-nitrided samples. The endurance limit of the samples nitrided in hydrogen-containing medium (curve 3) during the testing in 3% NaCl solution are at 25% lower in comparison with the samples nitrided according to the similar methods in hydrogen-free medium. The reason for reducing the fatigue limit is the harmful hydrogen effect, which can cause metal lattice decohesion, the interaction of hydrogen atoms in the metal with dislocations, pressure of molecular hydrogen in the microcavities steel, chemical reaction of hydrogen with alloy components and hydrogen-phase release [6-9].

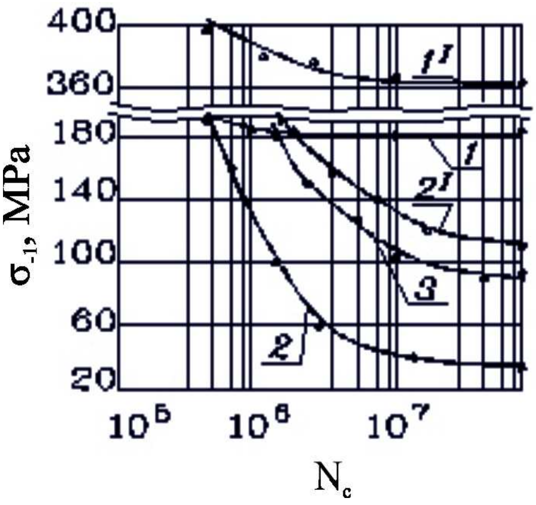

Fig. 3. Fatigue curves midair (1 and 1^I), in 3% NaCl solution (2, 2^I, 3) S20 during the testing for pure bending of cylindrical samples without chemical heat treatment (1 and 2), nitrided in a glow discharge in hydrogen-free (60 about % N_2+40 vol.% Ar) (1^I and 2^I) and hydrogen (60 vol.% N_2+40 vol.% H_2) media (3) at the other constant process parameters

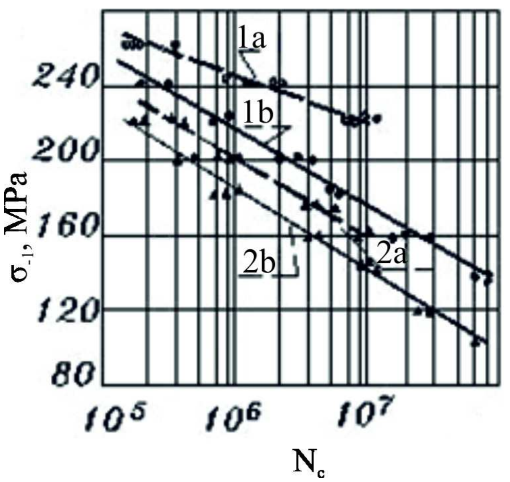

Fig. 4 Multicyclic resistance of the notched flat steel 45H: 1-nitrided (T=570°C, P=265 Pa, τ=240 min, the medium 75 vol % N_2+25 vol% Ar); 2-superior; a-in air; b-in acidic medium (pH 6.5)

Cycle fatigue tests with a stress concentrator were conducted on flat samples of S45H at booth with electromagnetic excitation EDS-200 with cantilever bending of the sample in the same plane surface and resonance according to the mode of vibration [11]. Stress concentrator (cut to a hardening groove deep 1 mm with an opening angle of 60° and a tip radius of 0.2mm) was of effective concentration ratio by Neuber, equal to 3.22. The tests were conducted midair and in an acidic medium (buffer solution of citric acid, 5g/l of sodium phosphate disubstituted and 10g/l) pH 6.5 at a loading frequency of 350-400Hz. 10^7 and $5{\cdot}10^7$ loading cycles were the fiels of the research midair and in acid medium. The researches have stopped when the crack length of 0.5mm was achieved. It was fixed by microscope MBS-1 (x88).

According to the test (Fig. 4) the endurance limit of S45H samples by ion nitriding in hydrogen-free medium increased by 37% during the testing midair and by 31% in acid medium. A significant increase of high-cycle samples fatigue after ion nitriding is caused not only by the formation of nitride phases on the metal surface, but also due to the appearance of residual compressive stresses in the nitrided layers. The magnitude of compressive stresses in the ion nitriding is up to 800MPa [12] and can be varied within wide limits by changing the process parameters of the diffusion saturation the maximum effect from the residual compressive stresses is achieved due to their optimal value.

The research of steel back-to-back endurance was hold on a basis of special facility of rolling friction [13], that was mounted on the vertical-type machine. The balls with 0.4% slip coefficient or cylindrical rollers with 17.6% slip coefficient influenced by different loads on the rolling elements and the spindle rate speed of 900min^{-1} were rolled on the cyclical lane of the plain samples of the facility. The various samples of steel were investigated after ion nitriding in the hydrogen and hydrogen-free media with different thermal treatment.

The results of comparative studies of samples' resistance and back-to-back endurance are shown in Fig. 1. Figure 1 shows that the samples' back-to-back endurance after ion nitriding in hydrogen-free media is 1.4-1.5 times bigger than non-nitrided samples' and 14-25% higher compared to the nitriding in the hydrogen media. Reduced back-to-back endurance of samples, nitrided in a hydrogen media is explained by harmful effects of hydrogen on metal. 45 steel samples after hardening and subsequent nitriding had much higher back-to-back endurance and resistance, compared to non-hardened samples, that is explained by the high hardness of the metal basis on which the nitrided layer was hold. The surface coating with a low stiffness has a higher hardness and is rapidly destroyed due to the large plastic deformation of the base. This dramatically increases the value of the total depreciation, which is clearly seen from Fig 1.

Table 1.
Physico-mechanical and tribological characteristics of the samples after ion nitriding heat treatment, and their durability tests on the rolling friction in the lubricant I-20, the pressure on the ball 150N (contact pressure p_0=3180 MPa)

N.	Type of steel	Type of heat treatment and technology	Microhardness h_{100}, Mpa			thickness of the coating, μm	Wear rate, $I \cdot 10^{-11}$	Durability until pitting, $N \cdot 10^6$ cycles
			surface	basics	race way after the test			
1	20 x 13	without heat treatment	2550	2370	3460	–	620	0.58
2	20 x 13	ion nitriding in an environment of 60%Ar + 40% N_2	7380	2370	3650	260	570	0.88
3	45	without heat treatment	3200	2450	3290	–	600	0.60
4	45	ion nitriding in an environment of 60%Ar + 40% N_2	7440	2450	4100	280	452	0.96
5	45	hardening	5100	5100	5230	–	21.2	9.1
6	45	hardening+ion nitriding in an environment of 60%Ar + 40% N_2	7460	4400	7200	290	16.1	12,9
7	45	ion nitriding in an environment of 60%Ar + 40% H_2	8420	2450	4050	290	440	0.75
8	45	hardening+ ion nitriding in an environment of + 60%Ar + 40% H_2	B560	4410	8210	300	15.4	11.2
9	20 x 13	ion nitriding in an environment of 60%Ar + 40% H_2	7640	2370	3670	280	580	0.70

The total wear rolling with slippage involves plastic deformation of the contact surface wear of sliding friction at slip. In the initial period of the total amount of wear of the plastic deformation of a major share and increases sharply with increasing load on the rolling elements. During the investigations of the wear beads was negligible slippage due a small coefficient of slip (0.4%). When it is used as a rolling element of cylindrical roller slip ratio amounted 17.7% and the occurrence of wear before pitting was predominant in comparison with the plastic deformation of the surface layer. Open gears wear from slipping further in connection dust and other abrasives in the friction zone. Wear at the same time during the period of operation reaches hundreds or thousands of micrometers and gears fail by not pitting and wear and fatigue failure in bending teeth.

Effective means to reduce wear of the friction surfaces in sliding is ion nitrided in the optimal regime, taking into account the operating conditions. Fig. 5 shows the curves of wear change and steel wear rate 45H in oil I-20, depending on the friction lane. The changing technological parameters of nitride ion allow you to select a mode of hardening, which significantly reduces the steel wear rate. The wear rate 45H steel after ion nitrided on modes 5 and 6 decreased by more than 3 times as compared to the improved wear rate of steel.

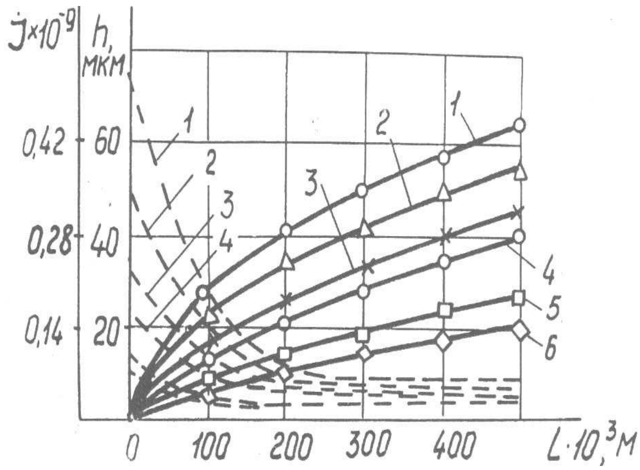

Fig. 5. Kinetics of steel wear 45H in oil I-20 at a specific pressure of 4MPa and a sliding speed of 1 m/s: 1-was to improve; 2, 3, 4-nitriding steel (100% N_2, P=265 Pa, τ=4 hours) at temperatures of 520, 560 and 600°C respectively; 5, 6-nitrided steel (T=560°C 75 vol.% N_2+25 vol.% Ar, τ=4 hours) at a pressure of gaseous medium 450 and 80Pa respectively

3. Conclusions and recommendations

The analysis of the operating conditions and the stress-strain state of open toothed weels showed that different portions of the surface of the teeth take different in size and type of stress. The most dangerous areas of the surface have a leg and depression between the teeth. Therefore, it is obvious that these areas require different surface properties of the surface layer and the residual compressive stress for maximum wear resistance and durability of the gears. In order to achieve this goal by hardening the surface of the toothed wheels and especially in hazardous areas due to the deposition of hardening coatings with a gradient structure in depth, we create a surface layer of residual compressive stress with optimal value and strengthening the core of the toothed wheel. We should use a heat treatment of the material of the toothed wheel with an increase of the hardness of its core applied nitrided ion in the hydrogen-free media at the best technology and to take account of operating conditions.

Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

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