

# Bending strength assessment of chemically-heat-strengthened Novikov gearing

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**Abstract.** The article is devoted to the refinement of the flexural strength assessment of surface-strengthened gears with Novikov's engagement. For standard involute wheels the results that were calculated in accordance with existing regulations and experiments could differ by an order of magnitude, or even more, then for Novikov's transmissions, only partial recommendations based on experiments are relatively reliable. The influence of several factors, such as the possible initiation of flexural fractures under the action of contact stresses on the tooth's leg, as well as the peculiarities of cyclic loading of gear teeth with two lines of engagement, have not been studied in practice. The purpose of this article is to assess the influence of tensile stresses on the boundary of the instantaneous contact spot in the conditions of reducing the plastic properties of the material due to thermal (chemical-thermal) treatment. The presence of a dangerous cross-section on the border of the active and transitional sections of the tooth profile is presented, which may not coincide with the area of action of the maximum tensile stresses, in which two essentially different types of stress-strain state will alternate, which considerably complicates the assessment of accumulation of fatigue damages.

## 1 Introduction

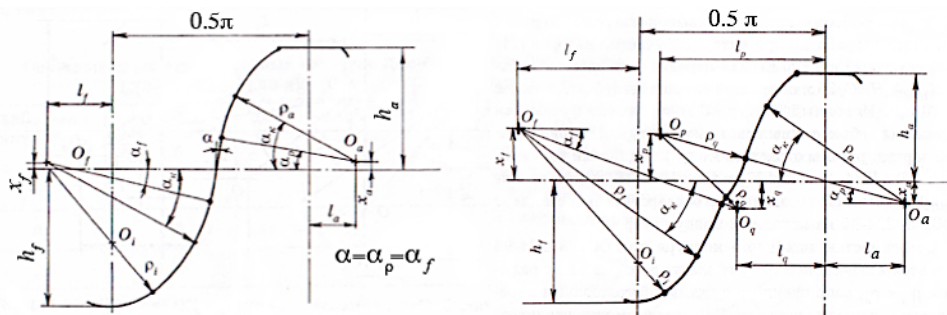
For gears with hardness  $H \geq (57 \dots 58)$  HRC, the tooth strength is often limited by the bending stresses. But even for standard involute wheels with more than a century and a half experience and a design model in a modification adopted in most calculation regulations (for example, DIN-3990 - Germany standard or GOST 21354-87), the results of calculations differ from the experimental data by an order of magnitude, and even more [1]. The area of the destruction is often "supernumerary" - a rounded bulge - a sponge cut, which indicates not so much about the bend as about the cut.

Even more significant difficulties related to the evaluation of the loading capacity of Novikov's gears, the insufficient bending strength of which in some cases did not allow them to realize their high contact resistance. Unsuccessful attempts were made to introduce the surface strengthened Novikov double line engagement transmissions with an original contour of the GOST 15023-76 type (Figure 1a), which is very effective in the heat-

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improved version. Qualitatively, the problem was solved by the development of the design of the teeth with a mutual displacement of the head and the tooth, which significantly increased the base of the tooth. By this principle, several contours were developed [2], included RGU-5 (Figure 1b).



**Fig. 1.** The schemes of Novikov's initial transmission contours: a) with a rectilinear transitional section; b) with a mutual displacement of active sites.

Studies of the flexural endurance of the teeth of Novikov's gears were conducted both in the direction of creating semi-empirical engineering formulas based on the results of experiments [3], so on the refinement of the stressed-deformed state of the teeth of complex shape [4]. However, many factors that significantly affect the flexural endurance of Novikov's transmissions have not been studied in practice, namely, the feature of cyclic loading of the teeth of Novikov's gears, the initiation of a fracture under the influence of contact stresses, and the effect of defectiveness of the diffusion layer due to thermal or chemical-thermal hardening.

Recently the problem of assessing the condition and working capacity of machines and structures becomes increasingly important [5]. Modern trends in engineering, such as the increase in the number of machine parts, the compaction of details, price and expenses for operation, the use of machines for mechanization and automation of the transformation of materials, energy and information, as well as for moving them in space invariably lead to the emergence and subsequent increase in the negative technogenic impact. So, the special importance of the problem of monitoring the technical condition of machines and structures becomes to prevent the emergence [6,7]. It is obvious that the assessment of the technical state of load-bearing machine parts should be systematic and allow for the evaluation of their characteristics at any time [8-10] with the special devices [11].

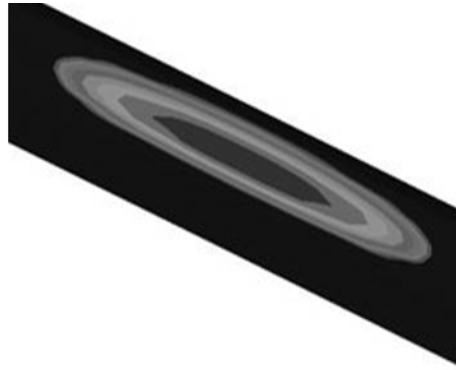
The purpose of this work is to investigate the features of the stress-strain state of the teeth of Novikov gears subjected to heat treatment or chemical heat treatment: the evaluation of the influence of tensile stresses on the boundary of the instantaneous contact spot in conditions of a decrease in the plastic properties of the material, justifying the need to consider the boundary of the instantaneous contact patch on the gear tooth two lines of engagement as potentially dangerous along the fracture.

## 2 Materials and methods

The local nature of the load applied to the tooth, characteristic of Novikov's gears, creates a higher level of the tooth stress-strain state than the theoretically linear contact. It is determined by the solution of the volumetric contact problem with a previously unknown contact area for the circular surfaces of the teeth in conditions of multi-pairing of the engagement.

Figure 2 shows the contact spot in Novikov's cylindrical transmission according to GOST 15023-76 obtained based on computer simulation.

The region of localization of the maximum flexural stresses in Novikov transmissions is not generally defined in the general case. But when the instantaneous contact patch is used, it spreads (up to 80%) to the active profile. The boundary of the instantaneous contact spot, if not coincident with the region of action of the maximum flexural stresses, is very likely to be near.



**Fig. 2.** Instant spot contact Novikov transmission.

We consider the possible effect on the example of the Hertz contact problem. The stresses on the surface in the region of contact are everywhere compressive, except for its boundary. At the ends of the main axes of the conditional contact ellipse, equal stresses are formed - radial (tensile) and circumferential (compressive) stresses. Equivalent stresses according to the Mises criterion for the circular region are  $\sigma_{io}=0,4 P_{max}$  at the center of the contact spot and  $\sigma_{io}=0.225 P_{max}$  at the boundary ( $P_{max}$  is the maximum pressure). But the role of shear stresses in the process of destruction decreases with increasing brittleness of the material. Hardness here is no longer a sufficient indicator of the strength of steel - it is necessary to consider its plastic properties. This is of importance for estimating the loading capacity of the diffusion layer after chemical-thermal treatment with its pronounced heterogeneity of structure. In these conditions, for the evaluation of strength, the use of generalized stress-strain criteria is most promising, the Lebedev-Pisarenko test.

$$\sigma_e = \chi\sigma_i + (1 - \chi)\sigma_1 A^{1 - \frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_i}} \leq \sigma_{e+} \quad (1)$$

where  $\sigma_e$  - ultimate effective stress at  $\sigma_1 > 0$ ;  $\sigma_{e+}, \sigma_{e-}$  - failure stresses of the material under uniaxial tension and compression, respectively;  $\chi = \sigma_{e+}/\sigma_{e-}$  - the plasticity parameter of the material, taking into account the degree of shear deformation participation in the microfracture;  $A$  - statistical parameter of defectiveness, its value for hardened steels  $A=0.7...0.8$ ;  $\sigma_1, \sigma_2, \sigma_3$  - principal stresses;  $\sigma_i$  - intensity of octahedral stresses. For ductile materials  $\sigma_{e+} \approx \sigma_{e-} \rightarrow \chi = 1$  and formula (1) reflects the Mises criterion. For brittle materials, when,  $\chi \rightarrow 0$ , there is a transition to the criterion of maximum normal stresses.

### 3 Results

For hardened alloyed structural steels at  $H \approx (60 \dots 62)$  HRC and the plasticity parameter  $\chi=0.7$  by criterion (1), the equivalent stresses are  $\sigma_{eo} = 0.26P_{max}$  at the center of the contact spot and  $\sigma_{eb} = 0.118P_{max}$  at its boundary. According to the Mises criterion:  $\sigma_{ib} / \sigma_{io} = 0.563$ ,

by criterion (1):  $\sigma_{eb} / \sigma_{co} = 0.715$ . The relative tension of the border zone increased by more than 25%.

In addition, the threshold value of equivalent stresses, determined from uniaxial tension experiments (in the limit  $\sigma_{1max} = \sigma_i = \sigma_y$ ), is correct only for plastic materials. When the plasticity decreases, the yield and strength limits converge (under tension):  $\sigma_y \rightarrow \sigma_{u+}$ , and at  $\chi \approx 0.7$  we have  $\sigma_{1max} = \sigma_e \approx 0.9\sigma_y$ .

But it's not limited only the relative tension area increase: the boundary of the instantaneous contact patch, especially in materials with reduced plastic properties, gives rise to radial microcracks that do not close when the load is removed, growing with repeated stresses, even insignificant [4]. With reference to gear transmissions, this issue has not been specifically investigated.

Another negative factor is the spread of the instantaneous contact patch in the region of the tooth's foot to the root zone (in the limit - up to abutment to the fillet). As is known, a definite decrease in hardness is observed in the immediately near-surface zone of the hardened layer. It can be insignificant and can reach hundreds of units. In any case, this is evidence of the presence of defects formed during the chemical-thermal treatment. The consequences are seen from the following.

Bending tests of cemented involute gears showed a significant increase in the durability of the specimens at a much lower thickness of the hardened layer: the effective thickness (up to  $H_c = 550$  HV) of the hardened layer -  $h_{te} \approx 0.35$  mm in the first version and  $h_{te} \approx 1.3$  mm in the second. But after blasting the fillets (the transitional surface of the tooth's foot - the area of destruction) of the samples of the second variant, they showed a durability commensurate with the durability of the samples of the first one.

Considering the reduction in the thermal or chemical-thermal hardening of the steel of its plastic properties promotes fracture fractures of the teeth under the influence of already contact stresses. The substantiation of the presence of a dangerous cross-section on the border of the active and transitional sections of the tooth profile is presented, which may not coincide with the area of action of the maximum tensile stresses, in which two essentially different types of stress-strain state will alternate, which considerably complicates the assessment of accumulation of fatigue damages. A negative factor is also the inevitability of the presence of technological defects in the heat treatment in the near-surface layers of the fillets.

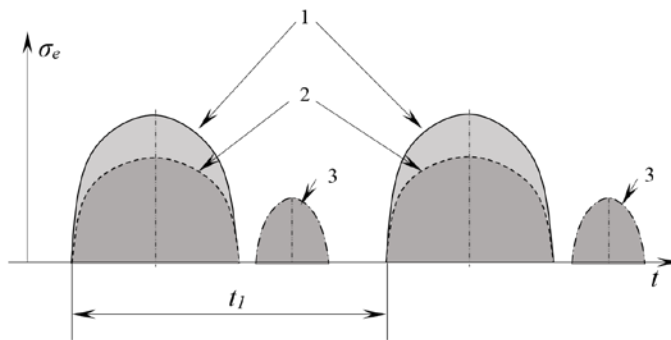
## 4 Discussion

Metallographic studies in a thin near-surface zone showed the presence of defects in the form of a troostite grid along the grain boundaries. This is so-called "internal oxidation". In addition, decarburization of the solid solution takes place in the surface zone. When nitrocarburizing, the main cause of defects in the near-surface zone is the formation of so-called dark component - a dotted grid, which is either pore filled with graphite, or complex oxides, which reduce the limit of the flexural endurance of steel by 30-70%. Defective inclusions are formed at the saturation stage, and the subsequent types of heat treatment do not change the depth of the defect zone. The holding time of the samples of the first variant was 12 hours, and the depth of surface oxidation reached 26 micrometers. For samples of the second variant at a residence time of 3 hours, the oxidation depth did not exceed 14  $\mu$ m.

The implementation of the high contact strength of Novikov transmissions requires an increase in the thickness of the strengthened layer. The aging time increases - the depth of defect formation also increases. If the defectiveness of the layer on active sites can be neutralized by subsequent run-in, then for the transition zone the problem of neutralizing it is difficult: there is no running-in, mechanical removal, for example by grinding fillet, is unacceptable because of the danger of burning, and methods of surface plastic deformation

or electrolytic labor-consuming and expensive. For Novikov transmissions, the imperfection of the fillet represents an additional danger due to the localization of the instantaneous contact spot.

The subject of a thorough investigation of the peculiarities of cyclic loading of the teeth of Novikov's gears by a double linkage line was not been provided. Theoretically, the correct linkage takes place when the common by the normal of the conjugate profiles of the instantaneous center of rotation intersect. The distance between the projections on the pole line of successive theoretical contact points located on different lines of engagement depends on the parameters of the initial contour, and on the angle of the tooth's inclination is a variable, but not equal to zero. Simultaneous contacting is realized in different sections of the tooth. As the gears rotate, the contact points will move along their engagement lines to the left end. Thus, in each section along the boundary of the instantaneous contact patch, two essentially different types of stress-strain state will alternate in the region of the tooth's foot (figure 3), which complicates the evaluation of the accumulation of fatigue damages. However, the phases of their joint influence are not ruled out. The stresses in the fillet zone with a load applied to the tooth leg are negligible and are not shown in the diagram.



**Fig. 3.** The nature of the loading of the teeth during the localization of  $\sigma_{Fmax}$  in the fillet zone during a single cycle  $t_l$  of wheel revolution: 1 - equivalent stresses  $\sigma_e$  in the fillet zone with a load applied to the tooth head; 2 -  $\sigma_e$  on the border of the instantaneous contact patch of the tooth's foot under the load applied to the tooth head; 3 -  $\sigma_e$  on the border of the instantaneous contact patch of the tooth's foot under the load applied to the tooth's leg.

## 5 Conclusions

As a result of the studies, the following conclusions can be drawn.

Considering the influence of the plastic properties of the layer material, it was possible to increase the reliability of predicting the level of load capacity of heat treatment and chemical-thermal treatment of hardened gears, not only in contact strength but also in bending. Evaluation of strength should be carried out using the criteria of the limiting state and considering the change in the parameter  $\chi$ .

It is shown that under certain conditions, contact stresses can initiate bending fractures. At the boundary of instant spot contact, tensile stresses arise in the case of theoretically point contact, the influence of which increases as the plastic properties of the material decrease, and unclosed cracks appear during unloading. The zone of risk will be not only the region of localization of the maximum flexural stresses but also the boundary of the instantaneous contact spot adjacent to the fillet, which is under the successive action of load cycles with different characteristics. A negative factor is the inevitable, due to the chemical-thermal treatment, the defectiveness of the near-surface layers, in connection with which it is advisable to provide blast cleaning of the fillet.

In the present work qualitatively analyzes the little-studied factors that negatively affect the flexural strength of Novikov's transmissions. Elliptic (according to Hertz) contact area in Novikov transmissions, used in engineering calculations, can be recognized rather arbitrarily. When the real surfaces of teeth are approximated by surfaces of the second order, the error in determining  $P_{\max}$  for transmissions with the original contour is known from [12] and is considered by the introduction of correction factors. But to evaluate the flexural strength, reliable information on the stress-strain state of peripheral zones of real contact spots is needed. The implementation of these recommendations is intended to contribute to the development of a refined methodology for calculating Novikov transmissions for bending strength.

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