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GEAR QUALITY AND RELIABILITY MANAGEMENT BY FATIGUE RESISTANCE CRITERION

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Abstract

The reliability processes of gears are designed according to the criterion of fatigue resistance and the manufacture of gears is based on the technological classification of parts, which serves as the basis for constructing typical technological processes for the manufacture of gears. Classification is understood as an association into groups and classes of parts that have a similarity of constructive form.

Keywords: fatigue resistance, gears, contact pressure, bending, gearing model.

Introduction

Gears are the most common type of gear in modern mechanical engineering and instrument making. The most typical types of damage leading to failure of gears are: contact fatigue (~40%), bending fatigue (~25%), tooth fracture (~15%), other types of damage (~20%) [one]. Thus, fatigue damage accounts for about 2/3 of all gear failures. As a rule, the evaluation of the performance and durability of gears is carried out separately according to the criteria of contact and bending fatigue [2-6]. However, taking into account that, in reality, gears work on bending and contact fatigue at the same time, it is required to develop a method of combined fatigue tests.

The following three test methods are widely used and recognized by specialists in laboratory tests.

1) On roller machines, the contact fatigue resistance of spur gear models is studied under the action of the contact load F_N (Figure 1). The degree of slip varies by changing the angular velocities ω_1 and ω_2. If p is the contact pressure, then in the general case, the probability of failure F(p) is found according to the wear resistance criteria, which are usually taken as the wear rate I(p) and/or wear life N(p). According to the test results in the coordinates contact pressure - the number of cycles to the limit state, a fatigue curve is built with the determination of the contact endurance limit p_f [3]. The disadvantage of this testing method is that only the contact fatigue resistance is determined as a result, while bending fatigue testing requires a different machine (and different specimens).

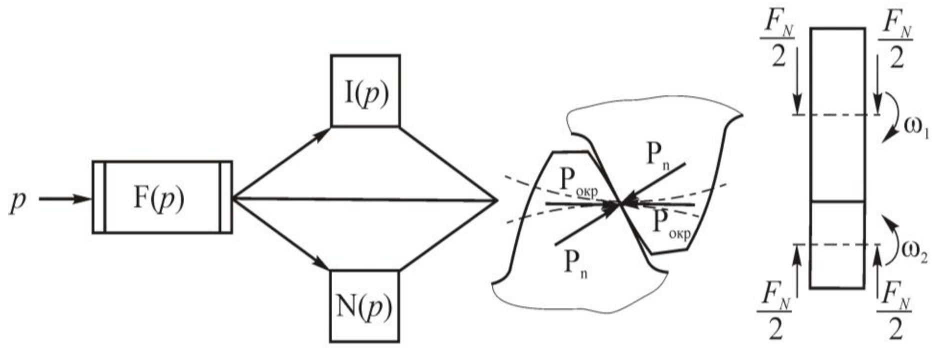

Figure 1 - Method for testing gears for contact fatigue

2) On fatigue testing machines, the bending resistance of flat specimens simulating or simulating a gear tooth is studied (Figure 2). If σ is the effective cyclic stress, then in the general case, the failure probability F(σ) is found

according to the fatigue resistance criteria, which are usually taken as the endurance limit σ_{-1} and / or fatigue life $N(\sigma)$. The endurance limit is obtained by constructing a fatigue curve in the coordinates of the amplitude of cyclic stresses - the number of cycles before failure. Usually, resonant-type testing machines are used, therefore, the endurance limit is determined for a symmetrical voltage cycle [4]. The transition to a pulsating cycle is carried out according to the well-known formula

$$\sigma_0 = \sigma_{-1} - \psi_\sigma \sigma_m, \tag{1}$$

where σ_m – average cycle stress;

ψ_σ – coefficient taking into account the properties of the material under test and known a priori.

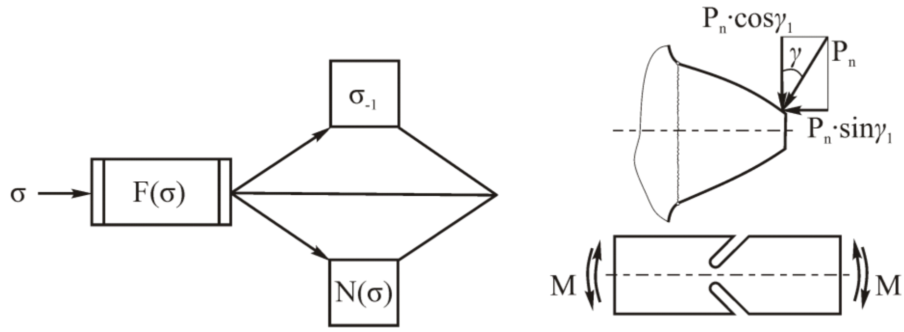

Figure 2 - Test method for bending of a flat sample - tooth models

The disadvantage of this testing method is that only the flexural fatigue resistance is determined as a result, while testing for contact fatigue requires a different machine (and different samples).

3) The combined test method is shown in figure 3; it is implemented on any universal pulsator. The advantage of the method lies in the fact that the tooth of the full-scale wheel is subjected to the test according to the pulsating bending cycle. However, the contact load also changes according to the same cycle, which does not imitate rolling friction. As a result, only the bending endurance limit is actually determined [5]. We add that the test object is a gear wheel, which leads to a serious increase in the cost of testing

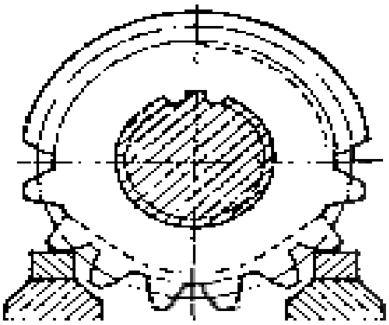

Figure 3 - Test method for natural wheel tooth bending

For the simultaneous experimental determination of the bending and contact fatigue resistance, an original method of combined tests on models was proposed; for its implementation, a special model of gearing has been developed [7-9]. The test method is described below, as well as a method for predicting the risk of gear materials using the test results.

Model of Gearing and Test Method

The gearing model is a test cylindrical specimen 1, made of the material of a gear wheel and imitating a full-scale product, with a contact interaction zone 3 at one end and a bending zone in the form of a fillet 4 at the other end (Fig. 4).

During the implementation of tests (Figure 4a), the sample is cantilevered in the spindle of the testing machine 5 and is rotated with an angular velocity ω_1. Then, rotating with an angular velocity ω_2, a cylindrical counter-sample 2, the axis of rotation of which is parallel to the axis of rotation of the sample, is pressed against the sample by the contact load F_N. As a result, a contact area in the form of a strip is formed in the contact interaction zone 3, which simulates the interaction in a cylindrical gear. The distance L between contact zones 3 and bend 4 is chosen corresponding to the distance between the engagement pole and the tooth base (see Fig. 4a). The force with which the counter-sample is pressed against the sample causes simultaneous contact stresses in the contact zone and bending stresses in the dangerous zone (fillet zone). The magnitude of bending and contact stresses in the sample is selected in accordance with the magnitude of stresses during actual operation.

The modified model (Fig. 4b) differs from the one described above in that the countersample 2 has a profiled surface, due to which a circular or elliptical contact area is formed in the contact interaction zone 3, which is typical for the interaction of gear teeth, for example, in herringbone and hypoid gears. In the modified model, in addition, the cylindrical sample 1 is made in the form of a cantilever, the surface of which serves as a contact interaction zone, which makes it possible to vary the distances (L1, ..., Li, ...) between the contact and bending zones, choosing their values according to the distance between the engagement pole and the base of the tooth in a full-scale product.

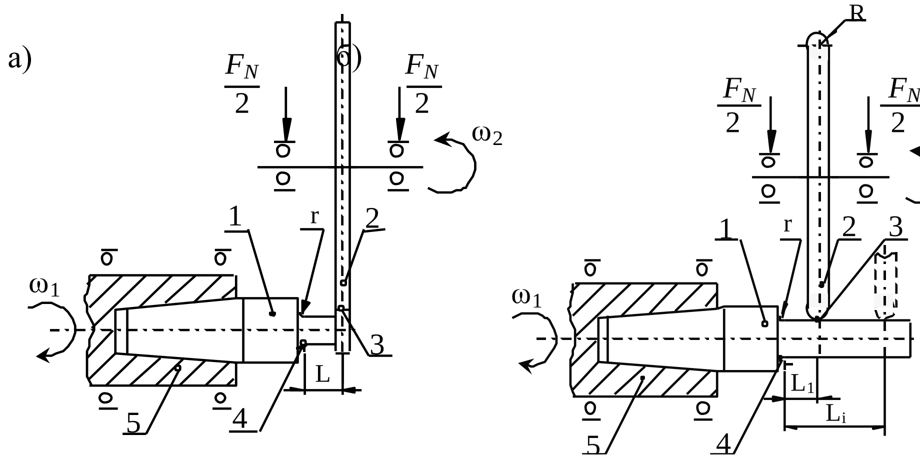

Figure 4 - Model of gears (a) and its modification (b): 1 - sample-model of the tooth; 2 - countersample; 3 - contact zone; 4 - bending zone; 5 – testing machine spidle

Note that the proposed model has the disadvantage that the direction of rolling (and slipping) does not coincide with the direction of maximum bending stress. However, this shortcoming, apparently, cannot be considered significant.

To test such models, a specialized bench UIM was created on the basis of machines for wear-fatigue testing of the SI series [10]. The stand satisfies all the requirements of the standard [11].

Service Life of Gears

In the manufacture of gear wheels in РУП «ГОМСЕЛЬМАШ», alloyed steels 18KhGT and 25KhGT, subjected to carburizing, are widely used. At the same time, according to the fatigue tests performed (according to the bending with rotation scheme), the endurance limit (Figure 5) for both grades turns out to be almost the same. This circumstance served in a number of cases as the basis for replacing steel 25KhGT with steel 18KhGT in the manufacture of gear wheels of the PKK 0135000 box containing highly loaded gears. However, this led to an increase in complaints about the reliability of the gears. Therefore, it seemed necessary to carry out statistical tests, on the basis of which it was possible to study the patterns of dispersion of the fatigue limits of steels under bending and contact loading, as well as to judge the values of the risk indicators and the quality of the use of these materials.

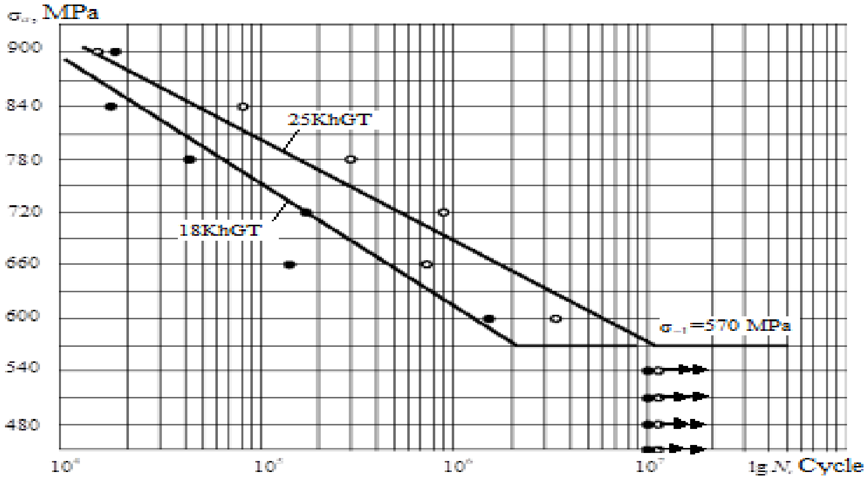

Figure 5 - Curves of mechanical fatigue (during bending) of steels 18KhGT and 25KhGT

Basic Concepts of Risk

In relation to technical objects, the concept of risk arises whenever their operational damage is detected. The sooner the damage approaches a critical value, the closer the emergency situation and the higher, therefore, the risk. Risk is the expectation of damage to objects, systems, processes. Quantitatively, such an expectation can be assessed as the share of “bad” in “good” [12].

If, for example, $P(A)$ – is the probability of the occurrence of an unfavorable event A, and $Q(B)$ –is the probability of the occurrence of the opposite favorable event B, then the risk indicator

$$\rho = \frac{P(A)}{Q(B)} \tag{2}$$

is determined simply by the ratio of the probabilities of these events, which expresses the proportion of "bad" [$P(A)$] in the "good" [$Q(B)$].

From formula (2) it follows that the interval of possible changes in the numerical values of the risk indicator varies within the following limits

$$0 \le \rho \le \infty. \tag{3}$$

Risk, therefore, can be measured by any real number. However, in practice, as a rule, the following interval of change in the numerical values of the risk indicator is used:

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$$0 \le \rho \le 1. \tag{4}$$

Нижняя граница риска $\rho = 0$ соответствует случаю, когда P(A) = 0. Верхнее значение рисков $\rho_k = 1$ ограничено условием, что $P(\bar{A}) = Q(\bar{B}) = 0{,}5$. Значение $\rho_k = 1$ считается критическим.

Согласно стандарту СТБ 1234–2000, статистический показатель качества по данной характеристике x_i механических свойств или сопротивления износоусталостным повреждениям есть вероятность того, что ее величина будет больше нормативного значения x_i^* (рис. 6):

The lower risk limit $\rho = 0$ corresponds to the case when P(A) = 0. The upper risk value $\rho_k = 1$ is limited by the condition that $P(\bar{A}) = Q(\bar{B}) = 0{,}5$. Value $\rho_k = 1$ is considered critical.

According to the STB 1234-2000 standard, the statistical quality indicator for this characteristic x_i of mechanical properties or wear-fatigue damage resistance is the probability that its value will be greater than the standard value x_i^* (Figure 6):

$$\Pi(x_i) = P(x_i \ge x_i^*) = \int_{x_i^*}^{\infty} \varphi(x_i)dx_i = \frac{1}{\sqrt{2\pi}S_{\bar{x}_i}} \int_{x_i^*}^{\infty} \exp\left[-\frac{1}{2} \times \left(\frac{x_i - \bar{x}_i}{S_{\bar{x}_i}}\right)^2\right] dx_i. \tag{5}$$

Then the statistical indicator of quality violation (see Figure 6)

$$D(x_i) = \int_{-\infty}^{x_i^*} \varphi(x_i)dx_i = \frac{1}{\sqrt{2\pi}S_{\bar{x}_i}} \int_{-\infty}^{x_i^*} \exp\left[-\frac{1}{2}\left(\frac{x_i - \bar{x}_i}{S_{\bar{x}_i}}\right)^2\right] dx_i = 1 - \Pi(x_i). \tag{6}$$

We will consider the violation of quality as an unfavorable event, and its observance as an event favorable. Then the risk indicator is defined, in accordance with (2) and (4), as the expectation of a quality violation:

$$0 \le \rho(x_i) = \frac{D(x_i)}{\Pi(x_i)} \le 1. \tag{7}$$

And the safety index Rρ(xi) is defined as a value that complements the risk to one, i.e.

$$R_\rho(x_i) = 1 - \rho(x_i). \tag{8}$$

The numerical values of the safety index are analyzed in the interval

$$0 \le R_{\rho}(x_i) \le 1, \qquad (9)$$

which corresponds to the interval of change of the risk index $\rho(x_i)$.
Zero safety ($R_\rho(x) = 0$) corresponds to critical risk ($\rho_к = 1$). Unconditional security ($R_\rho(x) = 1$) corresponds to zero risk ($\rho(x_i) = 0$).

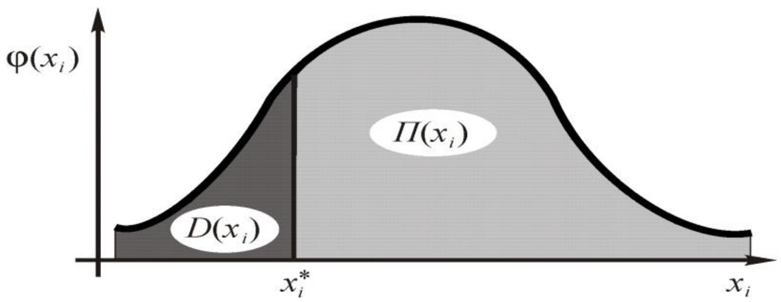

Figure 6 - Distribution of characteristics of properties
(resistance to wear-fatigue damage)

In relation to any wear-fatigue damage characteristic (WFD), a standard risk value [ρ] can be set. It is substantiated by the corresponding technical and economic calculation, taking into account the severity of the consequences in the event of the implementation of certain adverse events. The STB 1234-2000 standard establishes three categories of quality and the corresponding regulatory risk (Table 1).

Table 1 - Categories of quality and risk of use of power systems

Categories	Normative values of indicators		
	[Π(x)], at least	[D(x_i)], %, no more	[ρ(x)]
Higher	0,995	0,5	0,0050
First	0,990	1,0	0,0101
Second	0,950	5,0	0,0526

It should also be noted that risk analysis, compared with quality analysis, has an important advantage $\rho(x_i)$, which consists in the fact that the risk indicator related to one or another characteristic of the mechanical properties of the material from which, for example, this part is made, can be directly linked with the risk index $\rho(t)$ = P(t)/Q(t) of the (full-scale) part itself using the transition parameter λ_x :

$$\frac{P(t)}{Q(t)} = \rho(t) = \frac{1}{\lambda_x}\rho(x_i) \cdot \qquad (10)$$

This ensures the transition from the analysis of the quality and risk of using a material to the analysis of the risk and safety of a full-scale part according to the following model:

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$$\frac{D(x_i)}{\Pi(x_i)} = \rho(x_i) = \lambda_x \frac{P(t)}{Q(t)}. \qquad (11)$$

Note that when analyzing risk, it is not difficult to assess the material damage associated with the adoption of a particular decision, since the risk indicator turns out to be directly related (see (11)) both to the quality and operational reliability of the product [12].

Results of statistical tests

As a result of the statistical tests of gear meshing models, it was found (Table 2) that 25KhGT steel exhibits significantly lower risk indicators and, therefore, a higher quality category is provided than 18KhGT steel.

Table 2 - Characteristics of service properties of gears

Mechanical fatigue								
Endurance limit when bending			Statistical indicators			Categories quality		
Normative σ^*_{-1}, MPa	Average $\overline{\sigma}_{-1}$, MPa	$S_{\sigma_{-1}}$, MPa	Quality $\Pi(x)$	violations quality $D(x)$	risk $\rho(x)$	higher	first	second
25ХГТ								
360	462	48,0	0,9832	0,0168	0,0171	–	–	X
350			0,9902	0,00983	0,00992	–	X	–
335			0,9959	0,00408	0,0041	X	–	–
18ХГТ								
With regulatory requirements the same as for steel 25KhGT								
360	430	47,0	0,9318	0,0682	0,0732	Invalid violation quality		
350			0,9803	0,0197	0,0201			
335			0,978	0,0216	0,0221			
Contact fatigue								
Contact limit fatigue			Statistical indicators			Category quality		
Normative p^*_f, MPa	Average $\overline{p}_f$, MPa	S_{p_f}, MПa	Quality $\Pi(x)$	violations quality $D(x)$	risk $\rho(x)$	higher	first	second
25KhGT								
1000	1304	156	0,9743	0,0257	0,0263	–	–	X
925			0,9944	0,00757	0,00763	–	X	–
895			0,9956	0,00438	0,0044	X	–	–
18 KhGT								
With regulatory requirements the same as for steel 25KhGT								
1000	1269	152	0,9616	0,0384	0,03990	–	–	X
925			0,9882	0,0118	0,01200	–	–	X
895			0,9931	0,00695	0,00700	–	X	–

Conclusion

1. To test gear materials for both contact and bending fatigue, a gearing model and its modification have been developed;
2. A method for testing the materials of gear wheels on the developed models is proposed;
3. Based on the results of a set of statistical tests carried out on these models, a procedure for controlling the IPM of gears was developed.

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