Tests to estimate the heat rate effect on the flexural durability of transport vehicle gear wheels

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Abstract. The article presents the test results concerning the effect of thermal loads on the flexural durability of gear wheels of transport vehicle high-loaded transmissions. The tests were performed using a universal hydraulic pulsation machine and a thermal loader at five fixed temperature levels from twenty to two hundred degrees Celsius. As a result of the performed tests, a significant dependence of the flexural durability of gear wheels on their thermal state was established. In the expected maximum temperature area, corresponding to the temperature of the low tempering of the gear wheel material, it decreased sharply more than ten times.

1. Introduction
The reliability and efficiency of multi-purpose tracked and wheeled transport vehicles are determined substantially by the transmission. The application of more powerful engines, in the case if overall dimensions of transmission units are not changed, is achieved by increasing the density of the layout of transmission elements that causes significant heat generation in them. The underestimation of the thermal calculation of transmissions was permissible in the condition of low heat generation in the unit up to 50 kW / m³ [1], being typical of low power vehicles. Currently, due to increase in the transmitted power and angular frequency of rotation of the teeth in the condition of limited dimensions of components and units, the issues of thermal calculation as well as strength are of paramount importance and require common solutions.

To provide the required performance and durability of transmission units of transport vehicles, it is necessary to carefully study their thermal conditions. It includes a complex of design and experimental works necessary to ensure the required level of temperature of parts and the unit as a whole for a trouble-free operation.

The first mention of the damages associated with the heating of gears was made in the middle of the last century. It was noted that the unit's heat exchange is usually based on the oil temperature and not on the coefficient of heat transfer from the oil to the ambient air, on the heat transfer coefficient from the crankcase surface. This can be a significant error, as the crankcase surface temperature differs from the oil temperature and the local temperatures on the housing surface can vary widely enough.

A quantitative measure of the thermal condition of a part, assembly or unit is the temperature, the spatial distribution of which over the entire volume forms the temperature field. Changing the
temperature field over time is called the thermal mode and keeping the temperature within the limits from the minimum allowable to the maximum allowable during the entire period of the operation of transmission elements, providing a given thermal mode.

In the teeth contact zone, the temperature reaches high values of 800-900 °C [2]; the bulk temperature of the teeth is 25-30% higher than the oil temperature and can reach the low-temperature tempering of the steel the gears are made of [3], causing the premature wear of parts due to the reduction of their strength characteristics [4, 5].

12X2H4A, 12XH3A, 20X2H4A, 18X2BA grades of steel and other alloyed chromium-nickel steel are mainly used [6, 7] in units and drivetrain components of transport vehicles. These steel grades are characterized by high physics-mechanical properties, such as: high wear resistance and hardenability during hardening. However, the above-mentioned materials decrease their strength characteristics due to structural changes in the cemented layer [8] during a prolonged operation in the zone of elevated temperatures (if the oil temperature in the crankcase is above 140-150°C). According to [11], the permissible temperature should not exceed 170°C in the case of the mentioned above steel grades. The applied foreign steel (3310, 3310М, Е9310) and that produced in Germany (14NiG10, 14NiG14, 14NiG18) have the compositions and characteristics that are similar to those of above-mentioned steel grades. These allow working temperature not higher than 150 °С [12].

The efficiency of gears, which ensures the guaranteed vehicle mileage during the entire operation period, is connected with the limit of endurance of the teeth while bending. Traditional tests of gear wheels on flexural durability, as a rule, are carried out without monitoring the thermal state and do not provide information how the thermal condition affect the being evaluated parameter.

At the same time, tests of material samples indicate a significant effect of the thermal condition the strength characteristics. The results of such tests in relation to various steel grades are given in reference books [13, 14].

Gear wheels of various drivetrain components and transmission units operate in a wide range of heat rate. Therefore, in order to estimate their durability properly and determine the maximum permissible temperatures, it is necessary to have information about the dependence of the strength characteristics of gears on the thermal state.

From the analysis of the aforesaid it follows that reliable and effective work of elements of transmissions essentially depends on a thermal mode. Exceeding the temperature of oil and parts in the units leads to rapid wear and tear and a reduction in the durability of transmission elements, which is one of the reasons limiting the performance of transmission mechanisms and may be the cause of premature failure of individual parts and units of the transmission as a whole.

Conducting experiments on the influence of thermal loads on the strength properties of parts, such as, for example, the dependence of the bending life of gear wheels, will reveal their dependence in the area of expected operating temperatures. In development of new and finishing of existing constructions, similar tests are extremely necessary for the most heat-stretched elements for the purpose of establishment of maximum permissible temperatures.

2. Gear wheel tests

Based on the foregoing, the objective of the study was formulated as follows: to test the gear wheels and to identify the thermal condition effect on their flexural durability. Full-size sun gears of planetary gear sets of transport vehicle transmission were used as test objects; they were manufactured according to standard technology, including an undercut tooth base, shot peening, cementation and grinding of the involute. Their parameters are presented in Table 1.

The objective was to modify the existing test facilities to estimate the flexural durability of gear wheels in order to determine the effect of the thermal conditions and to conduct tests using the example of a batch of gears of a planetary gearbox.
Table 1. Gear wheels test parameters

| Input values                  | Parameter values |
|-------------------------------|------------------|
| 1. Steel grade                | 20X2H4A-III      |
| 2. Module, m, mm              | 4                |
| 3. Teeth number, z            | 32               |
| 4. Original contour angle, α, degree. | 20            |
| 5. Working teeth width, b, mm | 20               |
| 6. Modification coefficient, x| 0.64             |

The MUP-50 universal hydraulic pulsation machine and a device were used to perform the tests; the diagram is shown in Figure 1.

![Figure 1](image)

Figure 1. Load device circuit: 1 – punch, 2 – tested gear wheel, 3 – forking, 4 – axis, 5 – prism, 6 – roller, 7 – prism base.

The load was applied simultaneously to two teeth. The loaded teeth were selected according to the conditions of application of the load in a place corresponding approximately to the upper boundary point of one-pair gearing.

During dynamic tests, the maximum value of the initial load level per unit, the length of the contact line of the tooth were taken as WFmax≈0.6 Wv.sr. The minimum load value, taking into account the
geometric dimensions, was determined by the technical capabilities of MUP-50 machine (WFmin≤50 kgf / mm).

To ensure the pre-estimated thermal state of the gear wheels under test, the thermal loader was developed and manufactured to cover the loadable teeth from the ends and tops. To reduce heat loss to the environment, a heat shield was installed. The heating temperature was regulated by changing the voltage in the helix power supply system, the loader provided heating of gear wheels up to 200°C.

The load intensity was recorded by the pulsator dynamometer, the maximum load of the WF cycle amounted to 70000 N if the asymmetry coefficient was r-0.33 and the pulsation frequency - 690 cycles / min. All tests were performed at the same load level.

The temperature of the teeth under test was recorded with a potentiometer. A chromel-copel thermocouple installed in the cavity of the loaded tooth was used as a sensor. Asbestos insulation was used to protect the thermocouple from the flow of the heater.

The tests were performed at five fixed temperature levels of the tested wheels: 20, 100, 125, 150 and 200°C. The lower level of 20°C corresponded to the temperature in the laboratory room; the upper level slightly exceeded the temperature of the low tempering of the wheel material and corresponded to the actually possible values during the machine operation under extreme conditions.

To prevent additional thermal stresses in the loaded teeth, which may result from uneven heating of the teeth and punches, the gear wheel was heated to a predetermined temperature, until the teeth came into contact with the punches.

During the tests, the load and the thermal state of the test object were set and the number of loading cycles was determined until one of the teeth broke. At each temperature level, at least 7 tests were conducted. Each point is an arithmetic mean of 7 measurements.

3. Results
The test results are provided in Figure 2. Tests results confirmed the substantial dependence of gear wheels flexural durability on the thermal condition. At the same time, some interesting characteristics were identified. The flexural durability increased 3 times on average as the temperature increased from 20°C to 125°C. At temperatures of 100 ÷ 125°C, the maximum value of flexural durability was recorded. Due to further increase in temperature, within the range of its expected operational values, an intensive decrease in flexural durability of 15 times on average was noted.

![Figure 2. Dependence of Flexural Durability on Temperature](image-url)
4. Conclusion
The explanation of the reasons for the observed dependencies requires additional tests on gears made of various materials and according to different technological processes. However, the following conclusions can be made as the results of the experiment:

1. Refinement of the existing gear flexural durability testing stands by installing thermal loaders allows one to expand significantly the range of conducted tests and to obtain information on the effect of the thermal condition on the estimated parameters.
2. The conducted tests identified a significant dependence of the flexural durability of gear wheels on the thermal state even at a moderate temperature range of 20 ... 200°C.
3. The dependences of the flexural durability of the tested gear wheels on the thermal state are much greater than the similar dependences on the strength characteristics of the material the gears are made of and have a qualitatively different type.
4. In relation to a tested batch of gears, there is an extremum of flexural durability at the temperature range of 100 ... 200°C.
5. The flexural durability of the sun gear changed 11 times from 812,000 to 75,000 cycles at the temperature range of 20 ... 200°C under constant load.
6. If the temperature changes in both directions from the extremum area, the durability drops, and when the temperature increases, it is 6 ÷ 7 times faster than when the temperature decreases.

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