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Synopsis of development of wagon materials fatigue failure

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Abstract
The basic part of the rolling stock consists of the freight wagons. However, they are used under heavy conditions (large-tonnage loads, severe atmospheric conditions, aggressive effect of loads, etc.). The load bearing capacity of the wagons should be provided throughout their service life. The main factors affecting the load bearing capacity of wagons are the properties of the corresponding materials and the cross sections shape of the parts. Therefore, the study of fatigue failure of the wagon materials is an important and relevant topic.

The paper presents the features and results of the investigated synopsis of the development of the wagon materials fatigue failures. Thus, the work presents: the factors affecting fatigue limit of wagon parts; the impact of the external factors on the wagon parts strength; the influence of stress concentration; the influence of the absolute dimensions of the part cross-section; the effect of part deformation type and the cycle asymmetry; the effect of temperature; the dependence of strength on time; the influence of the service life of the part and the load condition.

Key words: TRANSPORT MECHANICS, RAILWAY TRANSPORT, FREIGHT WAGONS, WAGON MATERIALS

Problem statement. The physical causes of fatigue failure of the materials are quite complex and not yet completely investigated. Formation and development of the cracks are considered to be one of the main causes of fatigue failure. Recently, a number of the cases of fatigue failure of the materials of the wagons to be in service have increased rapidly.

During operation, the wagons operate under a cyclic load, which leads to their fatigue failure. Therefore, it is important to evaluate the service life at the design stage of the wagons, as well as to determine the residual operation life of the structural elements with the existing failure in the form of fatigue cracks. This problem is especially relevant for the important structural elements, which are critical from the point of view of ensuring their reliable operation.

Statement of the main material

In course of study of the service life of the open wagons bodies construction [1-3] with the use of deformable solid mechanics, two processes are distinguished:

- the first (main) - deformation of the open wagon body under the influence of external loads;
- the second - failure, which can accompany the process of deformation and is determined by the level of plastic deformations.

The process of deformation begins throughout the open body construction [3]. The process of failure refers to local processes, thus the failure begins in a small area of the construction and is determined by the properties inherent in this area.

When considering the course of the failure process at its initial stage, the construction material cannot be considered as a continuous medium.

It is necessary to take into account the material structure.

Metals refer to materials with a polycrystalline structure [4-6], that is, they are materials that consist of a large number of the crystals-grains. The grain of metals is anisotropic. The plastic deformation - slipping in crystals - can occur only in some planes in certain directions. The combination of a plane and a direction is called a slip system. For each of the metals, two or three basic slip systems can be distinguished in the grain. Therefore, depending on the grain orientation in construction, plastic deformation may or may not occur at the same stress level in the grain.

Plastic deformation in a grain of material [5] is called microplastic. Plastic deformation, occurring in volumes comparable to the size of the construction, is called macroplastic, or plastic deformation. The higher the stress level, the more microplastic deformation appears in a larger number of grains. Thus, the transition of the material to the state of plastic deformation (reaching the yield point) means the emergence of the compact groups of the microplastic deformed grains, which overall dimensions are comparable with the dimensions of the construction.

By definition, the fatigue process proceeds at the level of stress below the yield point. Under such conditions of microplastic deformation, the grains separated by at least one grain are deformed elastically.

Fatigue can be described as a gradual failure process consisting of crack initiation and its growth to the size, at which unstable crack propagation takes place.

From the outside, the process of fatigue failure of a part proceeds as follows. If the stress variables reach a level that is higher than a certain value for a given part, the microcrack begins to appear at the weakest point (at the places of highest level of stress or at the places where there are defects in the material) after a certain significant number of the failure cycles. Firstly, the microcrack is very small and not visible to the naked eye. However, over time it develops progressively, penetrates into the interior of the part, and finally the solid section of the part is so weakened that sudden failure occurs.

Figure 1 shows the growth curve of the fatigue cracks on the shaft of constructional steel. If the stress concentration takes place, the crack develops more slowly at the beginning of its formation because in a short time period it leaves the high-stress point, which is concentrated near the source of concentration (hole, groove, thread) in a small volume.

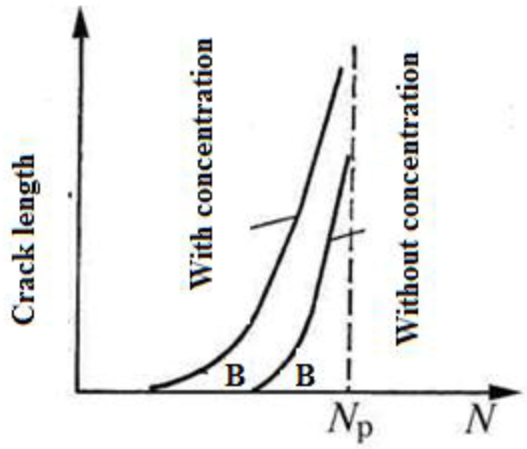

Fig. 1. The nature of the progressive growth of the fatigue crack

The crack occurs shortly before the final failure of the part. Approximately within 70-90% of the total number of cycles necessary for failure, the part operates without crack. After crack formation, the number of cycles maintained by the part is 30-10% of the total number of cycles. If the working conditions of the part are such that the variable stresses reach values sufficient for the development of the fatigue cracks only in some periods, the crack growth occurs only during these periods and the process of fatigue failure can last very long. For example, in the axes of the rolling stock, the growth of the fatigue cracks usually occurs during periods of their overload. Final failure can occur after several years of work.

On the surface of the fatigue fracture, two or three typical zones can be observed. They are shown in Fig. 2 for the cases of shaft or axis failure. Zone A corresponds to the initial stage of the crack initiation, which firstly develops slowly after originating in some microscopic volume in the contour. An increase in the stress at the microcrack location (in connection with the weakening of the section at this point) causes an accelerated (above point C) crack growth along the section of the fracture C (Fig. 2a). After the crack has occupied a certain part of the section, instantaneous brittle failure takes place along the part of the section C. The fracture surface in the section C is flat and

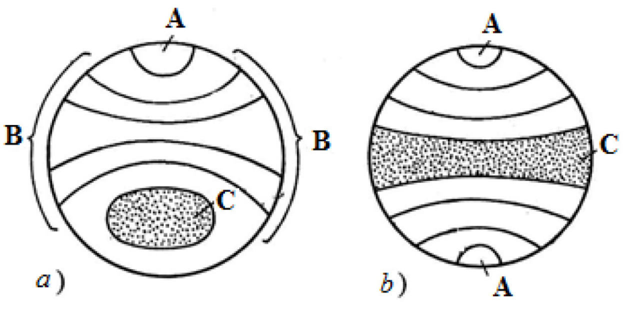

Fig. 2. The fracture type: a - for bending with torsion; b - for plane bending

smooth; this surface is formed gradually as a result of the fatigue crack formation. This is the result of grinding the crack surfaces, which open and close at each cycle under variable loads. The zone of coarse-grained brittle fracture C is formed due to the fact that the crack edge gradually penetrating into the part interior causes a complex stress state that leads to the brittle failure.

The dimensions and shapes of the part of the section C corresponding to the final failure depend on the configuration of the part, the loading conditions and the magnitude of the stresses that cause failure. For round shafts with bending with torsion, the shape of the fracture contour of the final failure is similar to the circle. The higher the stresses that caused the failure, the closer the circle is to the center of the section.

Factors affecting the fatigue limit of wagons parts [2]

When designing the wagon parts, which are affected by the variable stresses, the main characteristic of the strength of the material is fatigue limit, or endurance.

The limit of fatigue (endurance) is the maximum stress that a material can withstand for a given asymmetry of the cycle R during an unlimited number of cycles. To determine the limit of fatigue (endurance) and to reveal the influence of various factors on its value, the tests of the corresponding samples of materials are carried out.

In order to determine the endurance limit, the fatigue samples are tested using special machines that provide variable loads of the sample at a cycle frequency of 2000-3000 min^{-1}. The most common test is pure bending [4] with a symmetrical cycle, for which the endurance limit σ_{-1} possesses the lowest value.

To determine the fatigue limit σ_{-1}, minimum ten specially processed completely identical samples are made from the selected material. Then, the number of cycles N necessary to bring each sample to failure is determined assigning different values of the maximum stresses of the cycles σ_{max}. The test is finished when after gradual decrease in the amplitude of the stresses and an increase in the number of cycles, there is found such amplitude, at which the next sample does not undergo failure at a large number of cycles (of the order 10^7).

A fatigue curve is plotted on the basis of the test results. It is represented by the dependence of the maximum cycle stress σ_{max} on the number of cycles N (Fig. 3).

The greatest number of cycles, at which the test is carried out, is called *the base number of cycles* (for steel and cast iron, the base number is assumed to be equal 10^7).

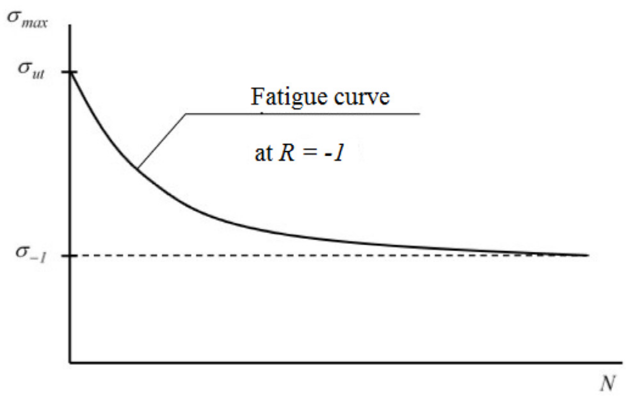

Figure 3. Fatigue curve

If the sample withstands a basic number of cycles, it is considered that the stress does not exceed the endurance limit and it can withstand any number of cycles without failure.

According to numerous experimental data, certain ratios between the endurance limits for the various types of deformations have been determined for some materials. In particular, they are determined between the limits of endurance in case of bending σ_{-1}, torsion τ_{-1} and extension-compression σ_{-1p} in the symmetrical cycles.

Thus, for the smooth samples:

– for steel $\sigma_{-1p} = 0,7\sigma_{-1}$;

– for cast iron $\sigma_{-1p} = 0,65\sigma_{-1}$;

– for steels and light alloys $\tau_{-1} = 0,55\sigma_{-1}$;

– for cast iron $\tau_{-1} = 0,8\sigma_{-1}$.

Due to the fact that the fatigue tests for extension and torsion are conducted not frequently, since they require more sophisticated equipment than the case of bending, the endurance limit for extension σ_{-1p} and torsion τ_{-1} under the symmetrical load cycle is determined from the empirical dependencies of the known endurance limit σ_{-1} for a symmetrical bending cycle: $\sigma_{-1p} = 0,7\sigma_{-1}$, $\tau_{-1} = 0,58\sigma_{-1}$.

In case of absence of these tests, the endurance limit for a symmetrical cycle of bending can be calculated by an empirical ratio depending on the time resistance σ_{ut}: for ferrous metals: $\sigma_{-1p} = (0,4 \div 0,5)\sigma_{ut}$, for non-ferrous metals: $\sigma_{-1} = (0,25 \div 0,5)\sigma_{ut}$

For non-ferrous metals, the term *"relative endurance limit"* is used; it is determined at the number of loading cycles N = 10^8, since for a certain number of cycles (*quite considerable*) the endurance limit of the sample is zero.

The influence of external factors on the strength of the wagon parts

The main factors of external impact on the strength of the wagon parts include temperature, time, pressure, kind of stress state, environment (contact with a reactive substance, ionizing and radiation exposure).

The deformation and strength properties are also affected by the structural and technological factors. This is the size of a solid, loading, alloying, heat treatment.

The influence of the constructive and technological factors is associated with the structure of the material, thus the description of the nature of the change in mechanical properties requires a physical approach to the problem under consideration. As a rule, in engineering calculations the results of phenomenological studies of the influence of temperature, time (velocity), and pressure are used. The experiments show that many factors, such as stress raisers, absolute dimensions of parts, the quality of their surfaces, etc. influence significantly the endurance of the material.

Effect of stress concentration

The sudden changes in the structural forms of the part, holes, grooves, notches significantly reduce the endurance limit in comparison with its value for smooth cylindrical samples. Such a decrease is considered by the effective coefficient of stress concentration, which is determined experimentally. For this purpose, the endurance limits with a symmetrical cycle are determined for two groups of identical samples (the first one without stress raisers, the second one with stress raisers).

The effective coefficient of stress concentration:

$$K_\sigma = \frac{\sigma_{-1}}{\sigma_{-1k}}, \qquad (1)$$

where σ_{-1} – the endurance limit for a smooth specimen under a symmetrical stress cycle;

σ_{-1k} – the endurance limit for a sample with an appropriate raiser under a symmetrical stress cycle.

The effect of absolute cross-sectional dimensions of the part

Experimental studies have shown that when the size of the part increases, the endurance limit decreases. This is explained by the fact that if the volume of the material increases, the probability of the presence of heterogeneity of the structure (*slag and gas inclusions, etc.*) increases, which leads to the emergence of sources of stress concentration.

The influence of the absolute dimensions of the part is considered by the *scale factor*:

$$\beta_{M\sigma} = \frac{\sigma_{-1d}}{\sigma_{-1d_0}}, \qquad (2)$$

where σ_{-1d} – the endurance limit of a part of a given specified size;

σ_{-1d_0} – the endurance limit of a laboratory sample of similar configuration (d_0 = 7…10 mm).

Effect of surface quality

Rough treatment and defects on the surface layers of the parts that are subjected to more frequent stresses are sources of the stress concentration. In this case, the endurance limit can be increased several times due to a decrease in the roughness of the surface of the part.

The influence of the surface state is evaluated by the *surface quality coefficient*:

$$\beta_{n\sigma} = \frac{\sigma'_{-1}}{\sigma_{-1}}, \qquad (3)$$

where σ'_{-1} – the endurance limit for a series of samples under this surface treatment;

σ_{-1} – the endurance limit of the polished sample.

The influence of the type of deformation of the part and the asymmetry of the cycle

In case of different types of deformation - extension, torsion, bending - the limits of endurance of the same parts are different. And the lowest of them is in case of torsion, the next one in case of extension, and the next one in case of bending:

$$\tau_{-1} < \sigma_{-1p} < \sigma_{-1}. \qquad (4)$$

Experiments have shown that the lowest fatigue strength limit is typical for a symmetrical load cycle. If the coefficient of asymmetry of the cycle *R* increases, the fatigue strength limit increases.

Effect of temperature

When the temperature rises, the endurance limit is usually reduced, and when temperature decreases, it increases. For example, for steel at a temperature above 300ºC, the endurance limit is reduced by $15 \div 20\%$ in case of every temperature rise by 100ºC. With a decrease in temperature from 20ºC to –190ºC, the endurance limit for some steels increases more than twice, although their impact resistance decreases.

Dependence of strength on time

Under the action of constant stresses, as well as during cyclic stresses, the failure is accumulated in the material. The ratio of time to failure (static endurance) with the level of a prolonged static load is expressed by the formula:

$$\tau^{m_\tau}\sigma_\tau = C_\tau, \qquad (5)$$

where m_τ and C_τ – material constants.

At equal stress levels $(\sigma_\tau = \sigma_a)$, the static endurance is more than cyclic due to the fact that the static load is significantly affected by the relaxation processes, which reduce the concentration of stresses at the micro and macro levels.

As a rule, the exponent of the equation is $m_\tau < 1/7$; thus, the approximation of the long-term static strength curve is valid by the exponential equation of the form:

$$\tau = A_\tau e^{-\alpha_\tau \sigma_\tau}, \qquad (6)$$

where A_τ and α_τ – material constants.

A typical diagram of the long-term strength at T = const in logarithmic coordinates is shown in Fig. 4: 1 - stage of ductile failure; 2 - stage of quasi-brittle fracture.

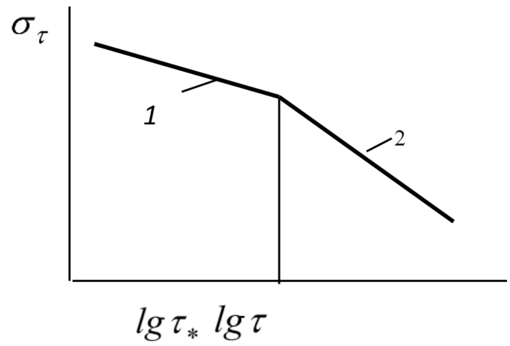

Fig. 4. Diagram of long-term strength at T = const

Long-term static load is also considered as a special case of the polycyclic one with the average cycle stress $\sigma_m = \sigma_\tau$ and the amplitude $\sigma_a = 0$. This shows an analogy of the different types of load.

Conclusions

The results of the presented studies of fatigue failure of the wagon materials allowed us to determine the basic factors. The following factors were emphasized: the impact on the endurance limit, the external strength factors, the stress raisers, the geometric internal and surface properties, the temperature properties.

The determined and presented features of the investigated factors of fatigue failure of the wagon materials are fundamental basis for carrying out the corresponding scientific-research and development works on creation and modernization of the railway rolling stock samples. Moreover, the obtained results will be useful in solving of the similar problems for other objects of transport engineering.

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