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LOCAL DAMAGES DURING ROLLING AND MECHANO-ROLLING FATIGUE FOR THE MECHANICAL SYSTEM SHAFT – ROLLER (0.45 CARBON STEEL – 25XGT STEEL, 20XH3A STEEL – 20XH3A STEEL)

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Abstract: The report provides a description of local damages which are formed in the process of wear-fatigue tests. The analysis of local surface wave-like damages during rolling and mechano-rolling fatigue for the shaft-roller mechanical system under steady-state and multi-stage loading conditions is given. It is shown that the study of local wear-fatigue damage was made possible by new methods of testing and measuring wear-fatigue tests and damages, which are described in the report. New characteristics to estimate the parameters of the local wear-fatigue damage are proposed. The concept of local fatigue curves is introduced. The laws of local wear-fatigue damage for the shaft - roller system are analysed.

Key words: Local Damage, Fatigue, Tribo-Fatigue System, Microcrack, Wear-Fatigue Damage, Residual Deformation, Wave-Like Damage, Troppy Phenomena, Local Fatigue Curve

1. INTRODUCTION

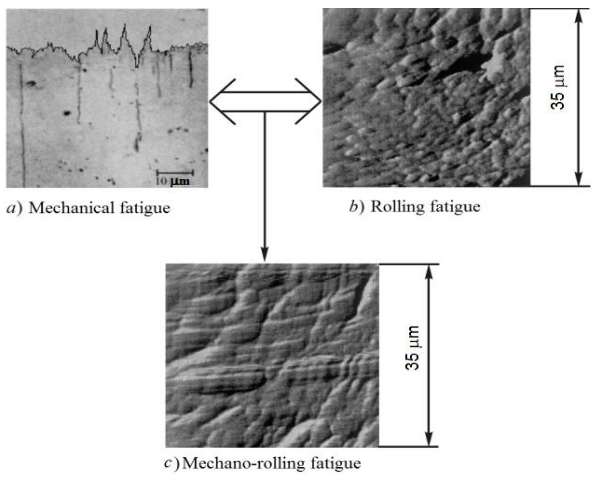

Fig. 1. Local damages under mechanical fatigue (a), rolling fatigue (b) and mechano-rolling fatigue (c) for the roller (steel 25XGT) – shaft (0.45 carbon steel) system

Risk of damage in the small volumes of material is well known to specialists in solid mechanics. Local damages in the form of microcracks, pores, corrosion pits and others lead to a breach of strength at variable loads, and even the complete destruction of structural elements as a result of the merger of microcracks in the main fatigue crack and its development (Fig. 1).Similarly, when the surface of local damage under rolling friction (Fig. 1, 2), sliding or fretting, corrosion the process of gradual degradation of the surface layer of the structural element or component of assembly friction due to damage micro volumes of material, their fusion and development leads to the depletion of the resource of structure or assembly friction (Bayer, 2004; Engel and Adams, 1987; Hogmark and Alander, 1983; Samyn et al., 2008; Yung-Li et al., 2005). An important task is to determine experimentally the local laws of wear-fatigue damage and its prediction.

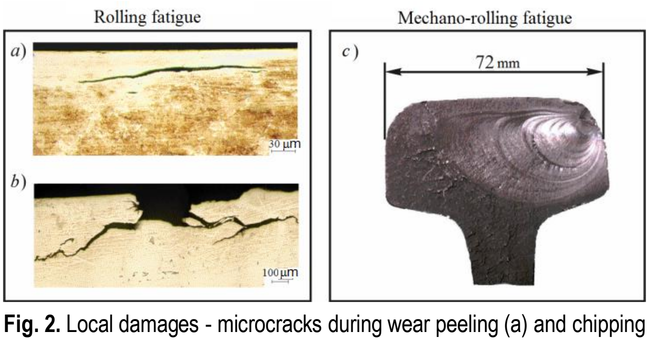

Fig. 2. Local damages - microcracks during wear peeling (a) and chipping (b) during rolling fatigue and photo of the fracture of railway rail from the transverse crack of mechano-rolling fatigue (c)

2. WAVE-LIKE DAMAGES

The tribo-fatigue system roller / shaft undergoes a mechano-rolling fatigue, to a certain extent reproduce the operating conditions of wheel / rail system. It was found a special type of limiting state: formation on the raceway residual wave-like damages during such tests. Let's look at the results of the experimental analysis of this phenomenon (Sosnovskiy et al., 2014; Sosnovskiy and Shcharbakou, 2005; Turin and Sherbakov, 2005). Tested for mechano-rolling fatigue was a tribo-fatigue system 25XGT steel (roller)/0.45 carbon steel (shaft). Properties of steel 25XGT were as follows: the fatigue limit σ_{-1}= 570 MPa, the rolling fatigue limit p_f= 3100 MPa. Properties of 0.45 carbon steel were as follows: the fatigue limit σ_{-1}= 260 MPa, the rolling fatigue limit p_f = 1760 MPa. Thus, the characteristic feature of the tribo-fatigue system was that the strength of the shaft's metal is substantially less than the roller's metal so during testing it was detected residual deformation and damage only in the vicinity of the raceway on the shaft, whereas the roller dimensions remain substantially undistorted.

Bending load Q = 225 N = const corresponds to the stress amplitude σ_a = 225 MPa < σ_{-1}= 260 MPa.Contact load was varied stepwise on program, shown in Fig. 3. Rolling fatigue limit p_f =1760 MPa was exceeded at the III stage of loading.

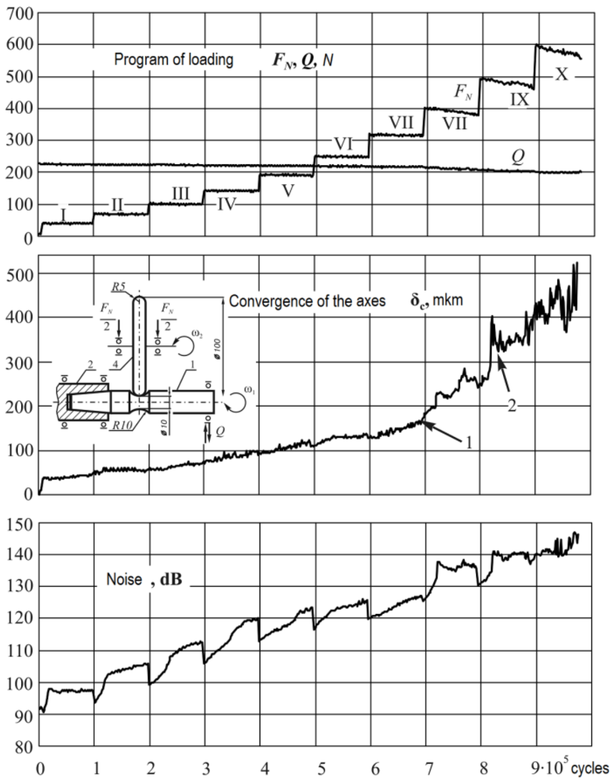

Fig. 3. The test report for the roller (steel 25XGT) – shaft (0.45 carbon steel) system on mechano-rolling fatigue (Sosnovskiy et al., 2005)

Motion of the roller on the shaft was unsteady in the transition from VII to VIII stage of contact loading, i.e. after 700 000 cycles of testing (see arrow 1 in Fig. 3). Residual radial deformations of the shaft in the area of non-stationarity are shown in Fig. 4 as bright points (750154 loading cycles, i.e. in the middle of the stage VIII).There was a loss of stability of motion at the IX stage (see arrow 2 in Fig. 3). Residual radial deformations of the shaft at the loss of stability of motion are shown in Fig. 4 by the crosses (851688 load cycles, i.e. in the middle of the stage IX).The tests were terminated at the X stage at N_Σ = 976 100 load cycles due to unacceptable vibration and noise. Deformations of the shaft after the tests are shown in Fig. 5 and 6.

What are the main features of damage for the shaft? The somewhat peculiar frozen waves of surface plastic deformation are formed on the raceway. They represent a set of irregular holes half-barrel-shaped. None of the wells is not repeated, each of them has its own, different from other sizes in all three dimensions – radial, axial, circumferential. The relative magnitude of plastic deformation (in this experiment) reaches 10% in radial direction and 30% in the axial ones.

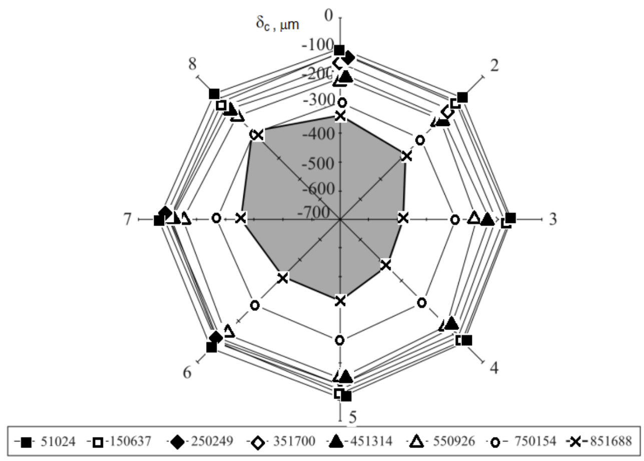

Fig. 4. Changing of radial residual deformation (μm) depending on the number of cycles in 8 points on the diameter of the shaft

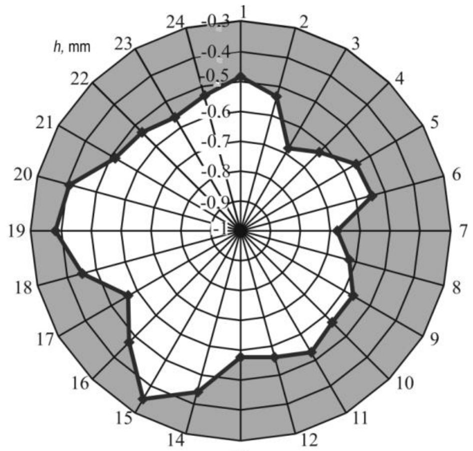

Fig. 5. Radial residual deformation (mm) on diameter of the shaft after testing on mechano-rolling fatigue (N_Σ= 976100 cycles)

Studies have shown that the described damage reversible in the sense that if the strength of the roller material is significantly less than the shaft, the residual damage undulations formed on the roller, whereas on the raceway dimensions remain substantially undistorted shaft. Thus, in these test conditions the surface wave-like residual damage can be regarded as the result of unsteady process elasto-plastic deformation in the contact zone of interaction between two elements of the system. This phenomenon is called troppy (Sosnovskiy et al., 2014; Sosnovskiy and Shcharbakou, 2005), and this nonstationary process is accompanied by three-dimensional transient distortions sizes of raceways of both elements and uneven local resistance of the material

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in different "points" in the path of motion (Fig. 7). The strength of the material evaluated, e.g., hardness, is significantly different in these points, both before and after the test (Fig. 8).

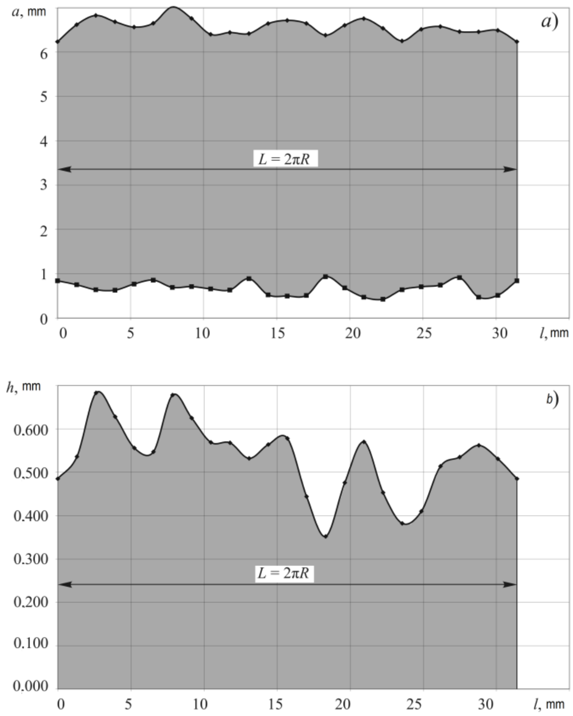

Fig. 6. Axial (a) and radial (b) residual wave-like deformations after testing on mechano-rolling fatigue (N_Σ = 976100 cycles), presented on the net of raceway

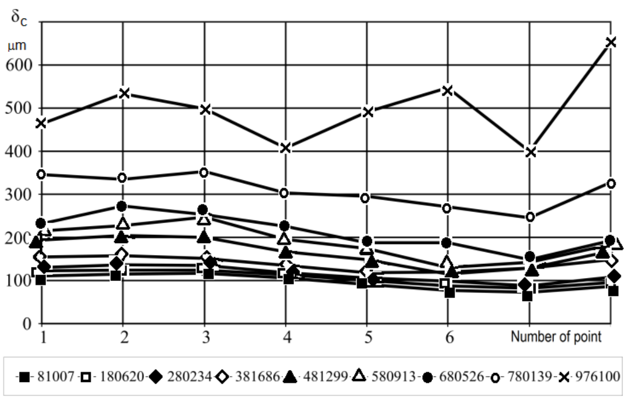

Fig. 7. The convergence of axes of shaft and roller in 8 points on the raceway depending on the number of cycles during testing on mechano-rolling fatigue

It was established experimentally geometry elements and precision in contact are factors that largely shape the emergence of wave-like damage during testing mechano-rolling fatigue.

3. THE CHARACTERISTICS OF LOCAL DAMAGE

Since there is a method of experimental measurement of local damages and some experience of their useful analysis, it was suggested several characteristics of local damage (Sosnovskiy et al., 2014). As you can see in Fig. 4 and 5 the next feature of the surface of local damage: if the circular contour of the test specimen is strictly symmetrical with respect to the center (to test), the contour of local damage, identifies eight measurement points (in these cases) is significantly asymmetric with respect to the same center (after the test).

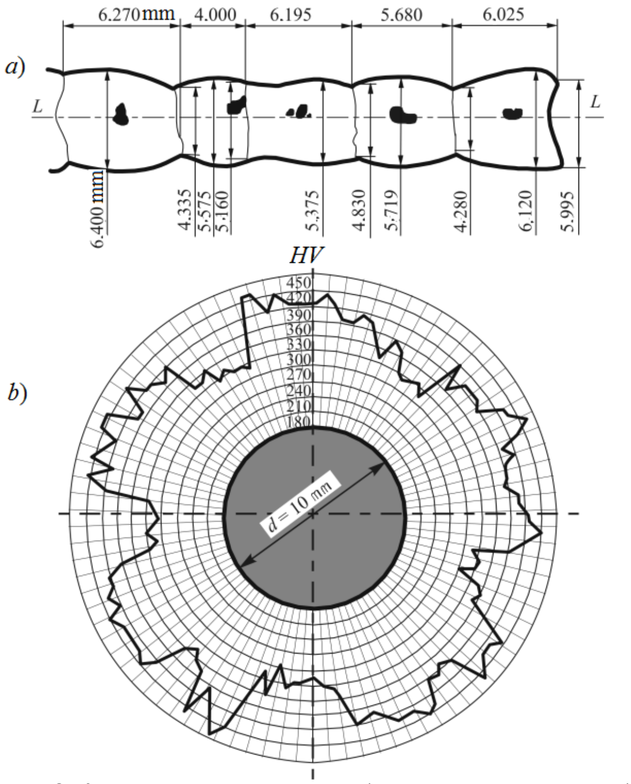

Fig. 8. Surface wave-like residual damage (chipping holes are blackened) (a) and microhardness distribution along the length L of the shaft raceways (b)

The degree of asymmetry generally increases with increasing test time and the integral damage. Let's introduce special integral characteristics of the local process of wear-fatigue damage: asymmetry factor

$$R_a = \frac{1}{4}\sum_{i=1}^{4}\frac{r_{\min(i)}}{r_{\max(i)}} \quad (1)$$

where $r_{\min}$ and $r_{\max}$ are the smaller and a larger radii of the same sample diameter, and the coefficient of unevenness

$$\eta_a = \frac{r_{sm.}}{r_{larg.}} \quad (2)$$

where $r_{sm.}$ and $r_{larg.}$ are the smallest and the largest radii of the sample during one revolution.

The designations specified radii of the specimen, as well as the dependence of the coefficients R_a and η_a from the level of cyclic stresses in the test of 0.45 carbon steel / steel 25XGT tribo-fatigue system on mechano-rolling fatigue at step changing of bending load (and, therefore, the stress amplitude σ_a) in the contact pressure p_0 = 0.7p_f = const. are shown in Fig. 9. It can be seen that the unevenness degree of local wear-fatigue damage increases respectively increasing of cyclic stresses. Note that the unevenness of wear-fatigue damage is greater, the smaller the values R_a and η_a.

It can be used technique of a determination of the asymmetry factor and coefficient of unevenness, namely, write them on the values δ_c:

$$R_\delta = \frac{1}{4}\sum \frac{\delta_{\mathrm{cmin}(i)}}{\delta_{\mathrm{cmax}(i)}}, \qquad \eta_\delta = \frac{\delta_{c\ sm.}}{\delta_{c\ larg.}}. \tag{3}$$

It is easy to see that the coefficients defined by the formulas (3) is not equal to the corresponding coefficients are determined by formulas (1) and (2). The choice of representation of the coefficients R and η is dictated by the specific objectives of the analysis.

The experiment showed that it is possible to detect single and associated local damages; last interconnected raceway. Formation pronounced single local damage shown in Fig. 10. It is easy to understand that the "solid" wavy-like damage is the final stage of development of local damage from a single to associatedones and then to troppy phenomena.

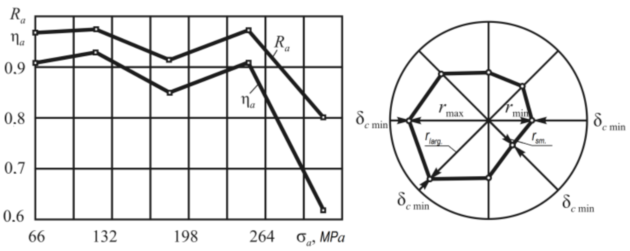

Fig. 9. Dependence of the asymmetry factor and coefficient of unevennessfrom the level of cyclic stresses in the test of 0.45 carbon steel / steel 25XGT tribo-fatigue system on mechano-rolling fatigue at step changing of bending load in the contact pressure p_0 = 0.7p_f = const.; right figure is a diagram for explaining the definition of the η_a and δ_a parameters according to the formulas (1) and (2)

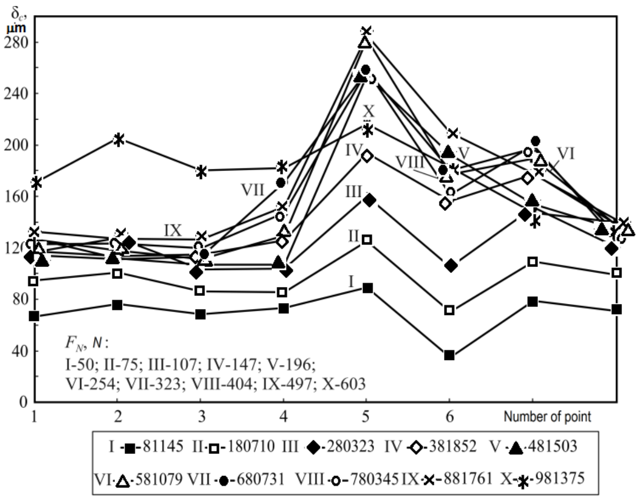

Fig. 10. The convergence of axesin 8 points on the raceway depending on the number of cycles of multystage (I, II, …, X) loading of the roller (steel 25XGT) – shaft (0.45 carbon steel) system during testing on mechano-rolling fatigue

If the limiting state is associated, for example, with a depth h of local damage δ_{lim} = h, it is possible to construct a kind of fatigue curves on the criterion of local damage (Fig. 11) (Sosnovskiy et al., 2014). The numbers 1, 2, …, 8 are designated the points on the perimeter of the raceway, which reached the limiting state (δ_{lim} = h) for the appropriate number of cycles N. Sequence analysis of the location of the points 1, 2, …, 8 leads to the conclusion that they are placed randomly on the graph.This conclusion does not contradict the known statistical mechanical fatigue test results of specimens: scattering increases with decreasing load. We emphasize, however, that the scattering region durability at every level of the stress is determined by the test results for only one pair of friction.

Come to the analysis of the data presented in Fig. 11, from a different perspective, let us build fatigue curves for each of the eight points individually (Fig. 12). Then the solid lines in this figure are local fatigue curves, each of which describes the limiting state at a specific point of the perimeter raceway. Thus, the Sosnovskiy – Bogdanovich – Yelovoy local fatigue curves (see Fig. 11 and 12) describe the heterogeneity of physical and mechanical properties in local areas of the test solid.

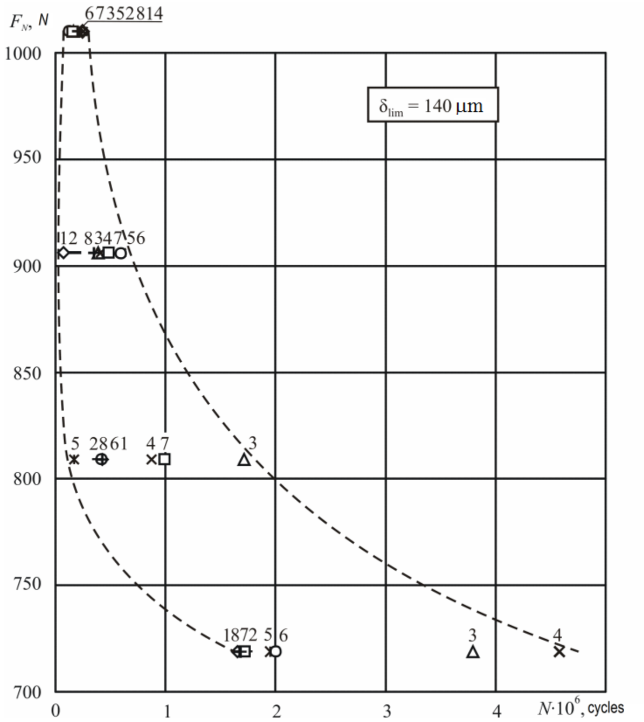

Fig. 11. The rolling fatigue curve for the roller (steel 25XGT) – shaft (0.45 carbon steel) system constructed on criterion of local damage

To learn the basic laws of formation and development of local damages, we dramatically increase the number of points of measurement (Fig. 13). The roller / shaft system made of steel 20XH3A is tested, and initial average hardness of the rolling surface was almost the same for both elements.The test results are shown in Fig. 14 and 15. It is clearly visible both single and associated local damagesin Fig. 14 and wave-like damages – in Fig. 15.

The results of statistical processing of random values of local damage (radial residual strain) are shown in Fig. 16 on normal probability paper (in coordinates of the radial permanent deformation h – the probability P corresponding to the normal distribution law). Tab.1 shows the numerical values of the minimum (h_{min}), average ($\bar{h}$) and maximum (h_{max})strain of the roller (diameter d = 100mm) and a shaft (diameter d = 10mm).

Analysis of the data presented in Fig. 15 and 16 allows us to make the following general and unexpected conclusion: under these friction conditions the roller with diameter of 100 mm is systematically damaged significantly stronger than the shaft

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with diameter of 10 mm; ratio values for said objects varies in 2-10 times.

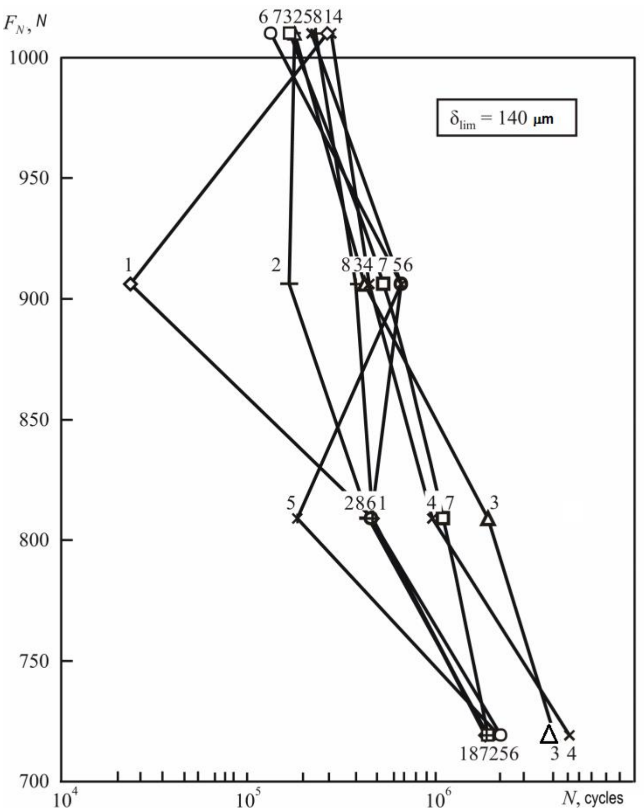

Fig. 12. The local rolling fatigue curve for the roller (steel 25XGT) – shaft (0.45 carbon steel) system

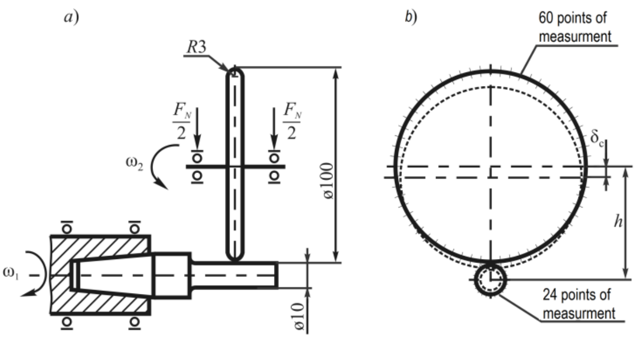

Fig. 13. Schemes of: test (a) and measurements (b) for local damages

Explanation of this fact can't be given to the theory of the scale effect; it suffices to recall that for 1 turn of roller the shaft gets 10 turns (cycles of loading). This means, for example, that when the contact load F_N = 719 N the shaft was $2{\cdot}10^7$ loading cycles (base of test), and the roller was only $2{\cdot}10^6$ cycles. Similarly, when at F_N = 809 N the shaft was $2.4{\cdot}10^6$ loading cycles (base of test) and the roller was only $2.4{\cdot}10^5$ cycles. The friction path for both elements was the same at specified load.

Thus, for equal path friction roller (diameter 100 mm) reaches the limiting state on criterion $\overline{h}$= 84 and 82 μm at the test load F_N = 719 N and 809 N (see Fig. 15), while the shaft (diameter 10 mm) reaches the average damage total only $\overline{h}$= 12 and 24 μm respectively.

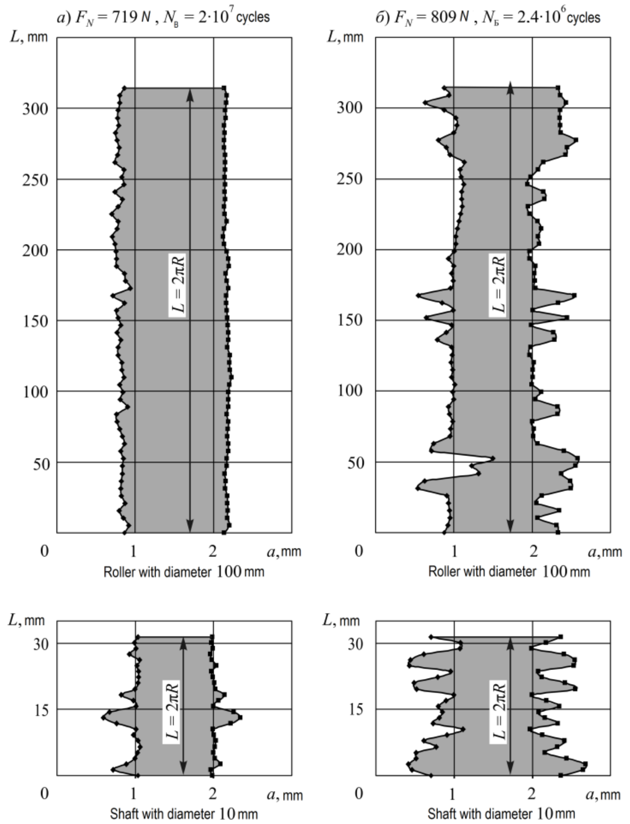

Fig. 14. The local axial residual strain (displacement)after testing of the roller (steel 20XH3A) – shaft (20XH3A) system for rolling fatigue

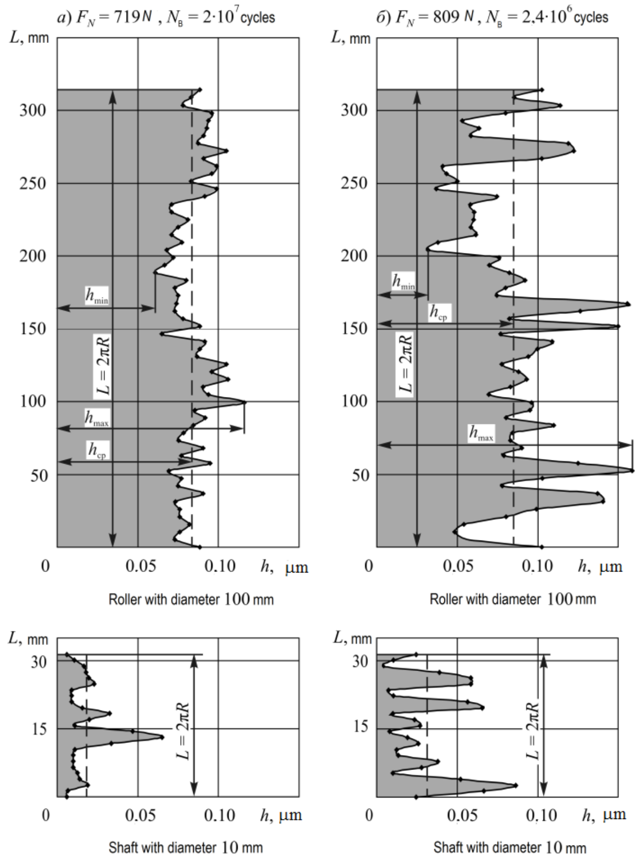

Fig. 15. The local radial residual strain (displacement) after testing of the roller (steel 20XH3A) – shaft (20XH3A) system for rolling fatigue

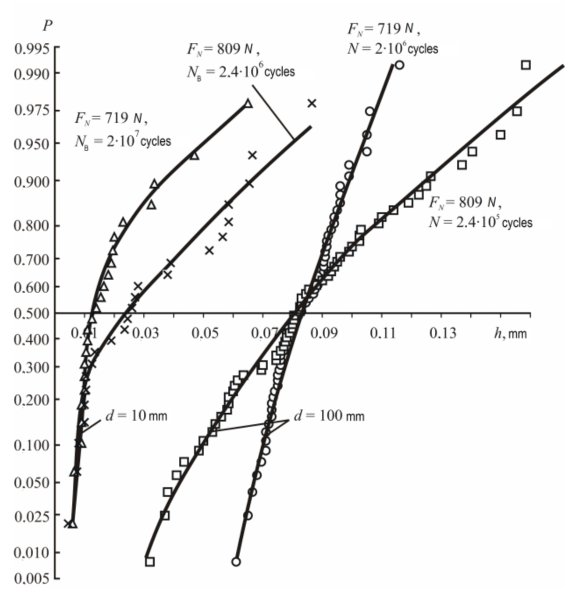

Fig. 16. The empirical distribution function of local radial residual strain after testing of the roller (with diameter 100 mm, steel 20XH3A) – shaft (with diameter 10 mm, steel 20XH3A) system for rolling fatigue

Tab. 1. Statistical parameters of the local damage for the elements of the friction pair steel 20XH3A / 20XH3A

Characteristic of local damage	F_N = 719 N		F_N = 809 N	
	d = 100mm	d = 10mm	d = 100mm	d = 10mm
h_{min}, μm	61	6	32	5
$\bar{h}$, μm	84	12	82	24
h_{max}, μm	116	65	159	87

Search for different causes of damage such two elements (of different diameters) of one pair of friction, provided that the surface hardness of the rolling surfaces for both elements substantially identical led to the hypothesis: the shaft is less damaged than the roller because it is bent during the test, whereas the roller is no.In fact, measurements have shown that in the plane of the contact load shaft deflection reaches 100 μm at F_N = 809 N and 70 μm at F_N = 719 N. This, apparently, is that some of the applied load "costs" not on the contact damage buton bending of the shaft. It follows that it is excited in bending moment counteracting to load F_N. In other words, it appears that the load applied to the conditions of this experiment as it is divided into two components: one of them causes surface damage on the raceway of shaft, and the other causes it bend.

4. CONCLUSION

1. Based on the analysis of experimental results of mechanical system shaft - roller for the 0.45 carbon steel, 25ХГТ, 20XH3A steels basic laws of wear-fatigue damage are installed: discrete, uneven and irregular occurrence and development of entry wear-fatigue damage; the formation of wave-like residual damage during echano-rolling fatigue (and rolling friction) due to excitation of shock-cyclic loading (troppy phenomenon, this phenomenon is typical for the exploited railway and tram rails); reduction of asymmetry factor and the coefficient of unevenness for wear-fatigue damage with time trials and with increasing levels of loading; initiation of emergence and development of wear-fatigue damage in the local areas in which the minimum strength of the material is detected.
2. To build the local fatigue curves describing the limiting state in a particular point of the perimeter of the dangerous section of the test mechanical system shaft – roller it is proposed. Such local rolling fatigue curves on the parameter of the wear limit for the shaft (steel 20XH3A) - roller (steel 20XH3A) are constructed.
3. Special integral characteristics of wear-fatigue damage the asymmetry factor and coefficient of unevenness are suggested.

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