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EXPERIMENTAL STUDY OF FATIGUE LIFE OF STEPPED SHAFTS

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Abstract- During operation, some structural elements are subjected to cyclically varying stresses (impacts) depending on time. As a result of this effect, mechanical fatigue of structural elements, as well as machine parts, occurs. The simplest example of this process is the movement of the wagon wheel along with the axle (shaft). Since the wheel axis is also stepped and rotates with variable angular velocity, it is subject to cyclical change. The ultimate limit of fatigue occurring in a material is fracture. The occurrence of failure does not depend on the number of cycles, but on the magnitude of the stresses. The article experimentally investigated the issue of the resistance (endurance) of a stepped shaft during fatigue. Such approaches have always existed for metallic materials, and they still exist today. But nonmetals, modern composites, and polymers have not been studied enough. For this reason, the issue discussed in the article is both relevant and scientific. The aim of the work is to study the effect of the radius of the transition surfaces and surface quality parameters of stepped shafts on the fatigue life. For this purpose, fatigue experiments were conducted on stepped shafts with different junction radii and surface quality parameters. Three types of shafts with a radius of transition surfaces of 0.5 mm, surface quality parameter R_z = 4 μm; radius of 2 mm, surface quality parameter a R_z = 4 μm and radius of 2 mm, surface quality parameter R_z = 20 μm were selected as test specimens. The experiments were conducted on a WP140 fatigue testing machine. The surface roughness parameter R_z was taken as an indicator of the quality of the shaft surface. The *Rz* parameter characterizes the height of the roughness protrusions at the 10 lowest and highest points along the shaft surface. The experiment was repeated 3 times for each type of test specimen. During the experiment, the test specimen rotates and a force F = 200 N is applied to one end. The experiment on each type of sample is continued until the sample breaks. It was determined that the maximum value of the stress in the test samples occurs in the zones where the transition surfaces have radii. For all three types of test samples, cracks appear and fracture occurs starting from the end point of the junction radius (the surface with a smaller diameter). It was determined that samples with small values of the junction radius (r=0.5 mm) and the surface roughness parameter (R_z = 4 μm) fracture in a smaller number of cycles, while samples with large junction radius (r=2 mm) and a small numerical value of the surface roughness parameter (R_z = 4 μm) fracture in a larger number of cycles. The stress distribution area increases with the radius of the transition surfaces, and thus the probability of crack formation as a result of fatigue decreases. The effect of the junction radius and roughness parameter of the shaft transition surfaces on the fatigue resistance is shown in the form of tables and histograms. The obtained results show that the numerical value of the surface quality parameters formed during the technological process of shaft manufacturing and the correct selection of the radius of the transition surfaces can increase the fatigue life of stepped shafts during operation.

Keywords: Fatigue, Stepped Shaft, Stress, Crack, Fracture, Bending Moment.

1. INTRODUCTION

Stepped shafts are widely used in modern machines and mechanisms to transmit power and rotational motion. The diameter of stepped shafts varies along the length. Transition radii are formed in the zones where the diameters change. Stepped shafts used in machines and other types of structures operate under the influence of various types of variable loads during operation. Cyclically varying stresses arise from the influence of these loads. Stress concentrations are mainly formed in areas with transition radii of the shafts. Although these stresses are less than the strength limit of the stepped shaft material, cracks appear in the parts after a certain period of time. These cracks develop over a certain period of time and fracture occurs. This process is associated with a decrease in fatigue life. Cracks and defects formed in shafts used in automobiles, aircraft and other types of structures are mainly related to fatigue. Approximately more than 70% of shaft failures occur as a result of fatigue. In addition to external loads, the following factors affect fatigue resistance:

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- Mechanical properties and chemical composition of the stepped shaft material;
- Structural structure and design of the stepped shaft
- Technological parameters of the forming methods (casting, forging, stamping, etc.)
- Technological parameters of the mechanical processing of the stepped shaft
- Quality indicators of the surface of the stepped shaft
- Operating conditions of the stepped shaft, environmental influences, temperature, etc.

The numerical value of the above factors exceeding the norm, improper design of the part, non-compliance with the requirements for operating conditions reduce the fatigue resistance of the parts. During fatigue, initial cracks mainly form in zones with high surface roughness (at the bottom of rough surfaces), on the bottom surfaces of notches, in zones with sharp transitions of surfaces (900 transitions). Proper design of shafts, proper development of the mechanical processing technological process and selection of materials prevent the formation of cracks during fatigue and weaken their development. Fatigue processes occurring in structural parts have been investigated in many scientific research works.

The selection and application of the type of oil to increase the wear resistance of shaft surfaces during machining on a lathe was investigated in [1]. The effect of wear of shaft surfaces on fatigue resistance was also studied. In [2], a mathematical model of the distribution field of stresses formed on notch surfaces was presented to predict the fatigue life of shafts. A methodology for calculating the stress gradient coefficient in different notch profiles made of different materials was developed. A methodology was also developed to diagnose the fatigue process of shafts. In [3] and [4], the fatigue process of shafts used in rotating mechanical systems and the effect of geometric parameters of notches on shafts operating under complex operating conditions on fatigue life were studied. Regression models were built to predict fatigue life. In [5], [6], a methodology for increasing the fatigue resistance of shafts using the ion implantation method was developed. Deformation processes occurring in shafts were also studied. In the papers [7-9] the durability problems of shaft-type parts with different cross-sectional dimensions were studied experimentally and theoretically. The optimal values of the controlled external factors were determined to increase the fatigue life.

In articles [10, 11], the issue of the influence of material heterogeneity on the stress-strain state of cylindrical structural elements, as well as their wear caused by the environmental impact on the structural element, was studied. In the works [12-15] complex mathematical methods were used to determine the stress-strain states of various structural elements caused by different methods (the Hamilton-Ostrogradsky variation principle, the Kirkhov-Love plane section principle, the Navier-Stokes equation, the Bessel equation and its functions, the Theory of optimal processes, the Ferrari method, the Newton method for numerical calculations, etc.) were solved by applying. In the above-mentioned works, in order to increase the working resources of cylindrical structural elements, not only cases of mechanical fatigue occurring in these structures, but also cases of relaxation and creep were studied.

The goal of modern engineering is to design systems that are not only strong, but also long-lasting and fail-safe. To meet this requirement, the availability of both theoretical models and experimental data on the fatigue behavior of stepped shafts serves as a valuable resource for engineers. The main objective of this study is to determine the effect of the radius of convergence of the transition surfaces and the surface quality parameter on the fatigue resistance of stepped shafts and to obtain practical results in this area.

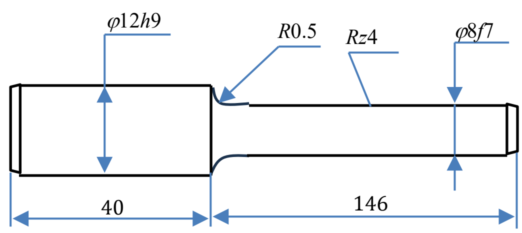
2. DESIGN OF EXPERIMENTS

In this work, experiments were conducted on 3 types of shafts with different radii and surface quality indicators of the transition surfaces in a fatigue testing machine. The test specimens were made of C35E steel material. The shafts were machined by rolling and mechanically processed on a program-controlled lathe. The lathe mainly performed rough and clean turning operations. The surfaces of the first and second test specimens given below were polished to ensure the given quality indicators (R_z=4 μm). The roughness of the shaft surfaces was measured using a BP-7669M profilograph profilometer. The structural dimensions of the test specimens selected for the experiment are given below.

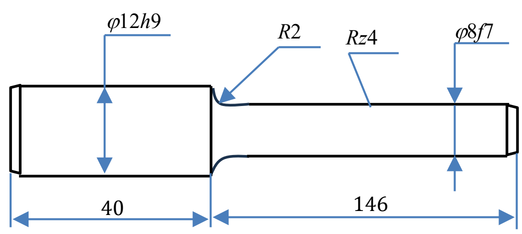
Test sample No. 1. Radius r=0.5 mm; Roughness R_z=4 μm, diameter of large step D=12h9, diameter of small step d=8f7, length of large step l=46 mm, length of small step L=146 mm.

Test sample No. 2. Radius r=2 mm; Roughness R_z=4 μm, diameter of large step D=12h9, diameter of small step d=8f7, length of large step l=46 mm, length of small step L=146 mm.

Test sample No. 3. Radius r=2 mm; Roughness R_z= 20 μm, diameter of large step D=12h9, diameter of small step d=8f7, length of large step l=46 mm, length of small step L=146 mm.



(a)



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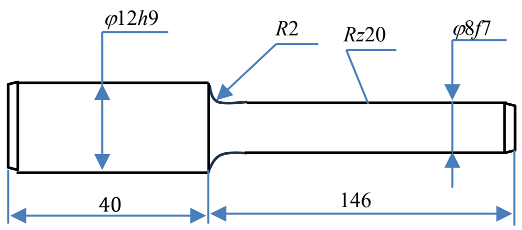

(c)

Figure 1. Structural drawing of test specimens, a) specimen 1, b) specimen 2, c) specimen 3

The structural diagram of the shaft-type specimens selected for fatigue testing is shown in Figure 1. The fatigue experiments in this work were conducted on a WP140 fatigue testing machine. The structural structure of this machine is shown in Figure 2.

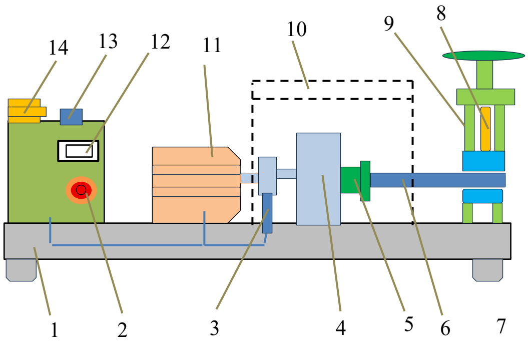

Figure 2. Structural diagram of the machine used for fatigue tests: 1-body; 2-off switch; 3-sensor; 4-transmission mechanism; 5-head to which the test sample is attached; 6-test sample; 7-movable support; 8-scale indicating the value of the force; 9-loading mechanism; 10-protective cover; 11-electric motor providing rotation of the test sample; 12-counter measuring the number of cycles; 13-electric socket; 14-switch

The external load applied to the testing machine is assumed to be F=200 N. During the testing process, the sample 6 is fixed in the holding head 5 along the surface with a large diameter. The other surface (with a small diameter) is placed on movable supports 7 in contact with the loading mechanism 9. The rotational movement of the test sample is given by an electric motor 11, and the transmission is provided by a transmission mechanism 4. An external load is applied to the sample by the loading mechanism 9. The numerical value of the load is read from the scale 8 located on the loading mechanism 9, and the value of the number of cycles is read from the counter 12.

During the test process, the protective cover of the device must be closed. When the test sample is broken, the sensor informs the engine control system and the electric motor stops automatically. The number of revolutions is read from the counter.

3. EXPERIMENTAL RESULTS

The effect of the radius of convergence and surface roughness of the transition surfaces of the shaft on the fatigue life was studied through fatigue tests. For this purpose, 3 types of test specimens with different radius of convergence and surface roughness and step lengths were used. Experiments were repeated 3 times for each type of test specimen. Experiments were conducted until the test specimens broke. During the experiment, the test specimen is fixed in a holding head at one end. A concentrated force of F=200 N is applied to the other end. During the test, the sample is subjected to rotational motion. At this time, the stress varies according to the cyclic sine law. The results obtained during fatigue experiments are given in Table 1.

Table 1. Fatigue experiment results

Radius, mm	Surface roughness, R_z, μm	Applied external load, N	Number of cycles until the sample breaks
Specimen 1, No. 1			
0.5	4	200	11250
0.5	4	200	11360
0.5	4	200	11600
Specimen 1, No. 2			
2.0	4	200	18120
2.0	4	200	17600
2.0	4	200	18200
Specimen 1, No. 3			
2.0	20	200	15100
2.0	20	200	14150
2.0	20	200	15333

The bending moment varies according to the law of a constant straight line. The moment is equal to zero at the end point of the specimen, and takes a maximum value at the points of convergence of the radius of convergence of the transition surfaces. The maximum stress value is observed in the zones where the radius of curvature (junction) is located. The stress distribution in these zones is indicated by red, yellow and blue lines, respectively (Figure 3).

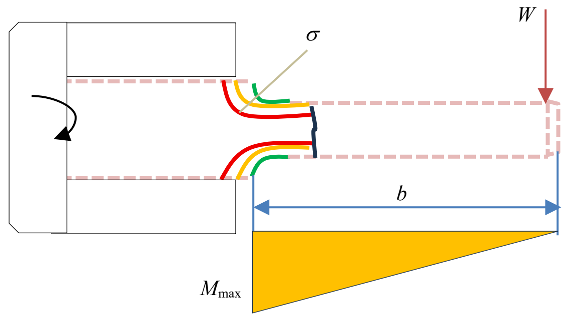

Figure 3. Distribution of stress and bending moment along the surface of a loaded test specimen

The experiments were carried out until the samples broke and the number of cycles (number of cycles) at the moment of breaking was recorded.

4. ANALYSIS OF EXPERIMENTAL RESULTS

The number of cycles before failure of a sample characterizes its life. The life of the shaft can be predicted based on the results of fatigue experiments. As can be seen, the least number of cycles before failure was observed in sample 1, and the greatest number of cycles was observed in sample 2. The average number of cycles before failure in sample 1 was $N_1 = 11400$, in sample 2 was $N_2 = 17973$, and in sample 3 was $N_3 = 14861$.

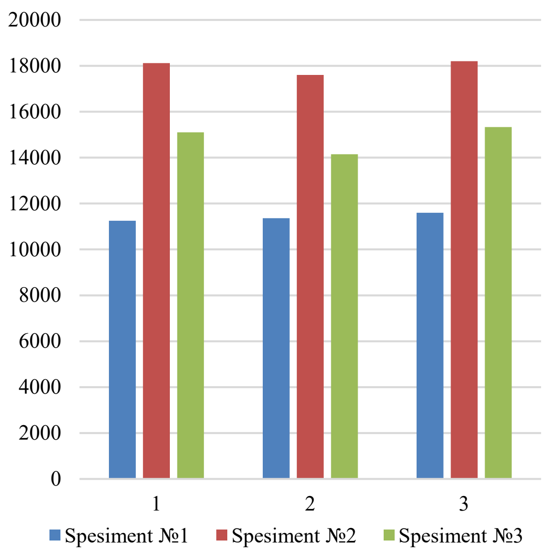

Figure 4. Distribution of the number of load cycles until the sample breaks

Figure 4 shows the distributed values of the number of cycles to failure of the test specimens for all three experiments. As can be seen from the histogram, the specimens with a small radius and a clean working surface had the shortest life (sample 1), while the specimens with a large radius and a clean surface had the longest life. Based on the results obtained, we can say that the factor that most affects the fatigue resistance (life) of the shaft is the radius of the mating surface and the roughness of the surface. As the mating radius increases, the fatigue resistance of the shaft increases.

Table 2. Analysis of variance of the results obtained from fatigue experiments

Source	Sum of squares	Percentage of influence of factors on shaft fatigue life
Radius of transition surfaces (r)	4.9420	57.48
Surface roughness (R_z)	1.0709	17.85%
Other factors	3.8546	24.67%

Adjusted final sum of squares	Adjusted averages	P-values
4.9420	1.4315	0.002
1.0709	0.7806	0.074
3.8546	0.1231	0.638

A variance analysis of the fatigue experiment results was performed in the "Minitab program." During the experiment, two levels of the radius (0.5 and 2.0) and two levels of the roughness factor (4 and 20) were used as the controlled factor. As a result of the analysis, the effect of surface quality indicators and the radius of the transition surfaces on the fatigue life of the stepped shaft was determined (Table 2). As can be seen from the analysis results, the factor that has the greatest impact on the fatigue life of a stepped shaft is the radius of the transition surfaces. The percentage of influence of the radius on the fatigue life is 57.48%. The impact of the roughness factor of the other surface is 17.48%. These values can be used in the production, design and mechanical calculations of shafts.

5. CONCLUSION

When designing shafts, the numerical values of the junction radii of the transition surfaces and the surface quality indicators (surface roughness) formed during mechanical processing are the main factors affecting fatigue resistance. Based on the results of fatigue experiments, it is possible to improve the design of shafts and predict their life. For this purpose, in the article, experiments were conducted on a fatigue testing machine (WP140) to determine the effect of the junction radius and roughness parameter of stepped transitions of shafts on fatigue resistance, and the following main results were obtained.

1. At the values of the junction radius r=0.5 mm and the roughness parameter R_z=4 μm, the test samples broke faster. Here, the number of cycles before the sample broke was $N_1 = 11400$.
2. At the values of the junction radius r=2.0 mm and the roughness parameter R_z=4 μm, the test sample broke in the number of cycles $N_2 = 17973$. As can be seen, without changing the numerical value of the surface roughness parameter, increasing the junction radius by 0.5mm leads to a 57% increase in the number of cycles.
3. At the values of the junction radius r=2.0 mm and the roughness parameter R_z=20 μm, the test sample broke in the average number of cycles $N_3 = 14861$. Without changing the radius, increasing the numerical value of the roughness parameter from r=0.5 mm to R_z=20 μm (R_z=16 μm) led to a 17% decrease in the number of cycles to failure.
4. The results of experiments conducted on three types of samples show that the shaft life increases as a result of an increase in the radius and a decrease in the roughness parameter. The main factor affecting the fatigue life of the shaft is the radius of convergence of the transition surfaces (57%) and the roughness parameter (17%).
5. It was determined that the maximum stress value is concentrated in the zones with the radius of convergence. It was observed that cracks in all three types of samples started from the end point of the radius of convergence (along the small diameter) and gradually developed inward.

As a result of the tests, it was determined that increasing the transition radius causes the maximum stress to spread to a wider area at the local level, which prevents the initiation of cracks. At the same time, reducing the numerical value of the surface roughness parameter (R_z) significantly reduces the probability of cracks forming at single points by reducing the stress intensity. According to the results, the average fatigue life of stepped shafts with a transition radius of r=2.0 mm and a surface roughness of R_z=4 μm was approximately 1.57 times higher than that of shafts with a radius of r=0.5 mm. The study also showed that the fatigue life of stepped shafts can be significantly increased by selecting the correct radius in the production processes and applying optimal processing technologies for precise processing of working surfaces. These results allow for more reliable and accident-free operation of mechanical systems in real industrial applications, especially in the automotive, aviation and energy sectors. The results of the article help determine the main design criteria for optimizing stepped shafts and contribute to the development of safer, longer-lasting machines and mechanisms.

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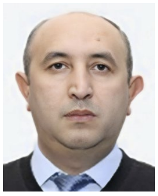

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