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Universal method for contact fatigue determination ☆

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A R T I C L E I N F O

Method name:
Universal method for contact fatigue determination

Keywords:
Contact fatigue
Stress
Wear
Steel
Alloy

A B S T R A C T

In the process of contact wear, pitting is formed, which destroys the surface of the part. Existing methods for assessing contact fatigue (GOST 25.501–78, R 50–54–30–87) reveal a stress level at which pitting does not occur. At the same time, there is no information about surface hardening, which is one of the main ways to increase contact fatigue. In this case, traditional approaches to the study of the wear mechanism do not make it possible to predict the operational evolution of the loaded surface of the part. The authors have developed a universal method for determining the contact fatigue of materials, providing opportunities for resource-efficient design of parts operating under the action of pulsating contact stresses.

- Design and operating principle of the patented testing device.
- Universal methodology for determining the contact fatigue of materials.
- Our novel test method demonstrated a convergence of finite element modeling and real test in terms of crack formation in maximum stress zones.

Specifications table

Subject area:	Materials Science
More specific subject area:	Analysis of materials for contact fatigue and wear
Name of your method:	Universal method for contact fatigue determination
Name and reference of original method:	Test methods are described in Recommendations R 50–54–30–87 «Calculations and strength tests. Methods of testing for contact fatigue» and in GOST 25.501–78 « Calculations and strength tests in mechanical engineering. Methods of testing for contact fatigue» (original method, that was changed)
Resource availability:	- A patented device for testing materials for contact fatigue and wear; - an hour-type indicator with an accuracy of 0.01 mm for direct measurement of the pitting depth; - optical microscope for obtaining images of pitting.

☆ **Related research article:** I. Stepankin, E. Pozdnyakov, D. Kuis, S. Lezhnev, Mechanism and patterns of wear of chrome steels with a surface-modified layer, Materials Letters, 2021, Vol. 303, 130,489. For a published article

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Background

The contact fatigue of metallic materials is an important characteristic of many parts that determine the service life of individual components and products as a whole. The failure time of rolling bearings, gears, railway wheels, die tooling and other similar parts is currently determined by the damage degree of the surface layer. The reason is the effect of pulsating contact stresses of a certain amplitude on it. Determining the wear resistance under the action of pulsating contact stresses of various materials, including those with surface-hardened layers, is an important task [1]. Its solution will allow not only to increase the contact fatigue of a specific surface of a part, but also to determine the level of operating time during which a certain material, as well as its reinforced layer, ensured the maximum level of preservation of the geometric characteristics of a particular part. It is convenient to call such a period in the operation of a part the period of precision stability, during which the loaded surface does not acquire external damage. Traditional approaches are aimed at determining precisely the amplitude of the pulsating contact stress, at which, obviously, no contact fatigue cracks will occur during a given period of product operation [2].

In the process of contact wear, micro holes (pittings) are formed. They gradually destroy the contact surface of the part and combine into deep cavities. Their nucleation proceeds by the mechanism of intracrystalline plastic deformation in the sublayer [3]. Existing methods for assessing contact fatigue [4,5] suggest the identification of a stress level at which pitting does not occur and their appearance on the contact surface is a criterion for testing. The quantitative parameter is the area of the contact surface damaged by pitting. There is no possibility to evaluate structural transformations along the cross-section of the loaded material. There is no information about the interaction of individual structural components with each other, as well as their role in the formation and inhibition of contact fatigue cracks. The relationship between the thickness of the hardened layer and the mechanism of its fracture is not established. Meanwhile, surface hardening, which ensures the synthesis of sufficiently deep diffusion-hardened layers, is one of the main ways to increase contact fatigue. In this case, traditional approaches to the study of the wear mechanism and the identification of a complex of morphological features formed on the surface of material part do not make it possible to predict the operational evolution of the loaded surface of the part.

The proposed methodology reflects scientific and practical aspects aimed at the possibility of managing the life of parts exposed to pulsating contact stresses. The scientific aspect is the ability to evaluate the mechanism, the nature of the origin of fatigue defects and the evolution of structural components as internal structural defects accumulate. The comparison between the quantitative wear parameters – the depth of the hole and the number of loading cycles - allows us to construct wear curves that, for different levels of pulsating stresses and various alloys, with numerous variations in surface modification, give an idea of the predicted resistance to contact wear of certain composite materials. The practical aspect allows us to assess the degree of extreme wear in cases of predicting the failure time of die tooling, which forms complex forgings using the methods of stamping and disembarking. The tolerances for the linear dimensions of these forgings range from 0.1 mm to 0.6 mm or more, which makes it relevant to determine the durability period of the tool during which it will produce suitable forgings. Thus, the authors have developed a universal method for determining the contact fatigue of materials, providing opportunities for resource-efficient design of parts operating under the action of pulsating contact stresses.

Method details

The intensity of accumulation of fatigue damage in the surface layer of the tool during repeated contact with the material was studied at a contact fatigue and wear testing facility [6]. The installation contains a base 1 (Fig. 1), a drive: an electric motor 2, a V-belt transmission 3, a gearbox 4, a sample mounting unit: a faceplate 5 with holes 6 with samples fixed in them 7, a counterbody in the form of a disk 8 and a housing 9 of the loading unit. The disc of the counterbody 8 is placed on the finger 10 in the mandrel 11, which is fixed to the rod 12 of the loading assembly by means of screws 13. The rod 12 is located inside the housing 9 of the loading assembly and is held by a spring 14. The set elastic reaction force of the spring 14 is adjusted using a cup 15, which is installed in the housing 9 of the loading assembly using a threaded connection. The lubricant container 16 is installed under the faceplate.

The installation works as follows. In order to simulate contact interaction during friction without slipping, a counterbody in the form of a disk 8 is mounted on a sliding fit or on a ball bearing in the stem holder 12, and a sample 7 with a flat working surface is mounted in a faceplate cell 5 mounted on the gearbox shaft 4, which ensures its movement along a circular trajectory, and when encountering a spring–loaded disk 8, due to the friction forces, it rotates, eliminating slippage. To ensure a given coefficient of friction in the contact area by using lubricants used in stamping equipment, the working part of the sample 7 is dipped into a container with lubricant 16 located directly under the faceplate 5, and then comes into contact with the disc of the counterbody 8.

The load on the sample – counterbody pair is carried out by changing the stiffness of the spring 14 installed between the rod 12, in which the counterbody disc 8 is fixed, and the cup 15 of the housing 9 of the loading unit. The circular motion of the samples 7 with a linear velocity of 0.035 m/s in the plane of the disc of the counterbody 8 at the moment of contact of the working part of the sample 7 and the contact surface of the disc 8 causes an elastic displacement of the disc 8 together with the holder and the spring-loaded rod 12. The force required for elastic displacement of the counterbody disc 8 during the movement of the sample 7 is determined by the stiffness characteristic of the spring 14 and is regulated by the amount of its pre-compression inside the cylinder by screwing the cup 15 into the housing 9. The pressure at the point of contact between the working part of the sample 7 and the surface of the counterbody disc 8 is calculated in accordance with the actual contact area, which is determined by the thickness of the working surface of the counterbody disc is 8 (the width of the contact spot) and the thickness of the working part of the sample is 7 (the height of the contact spot).

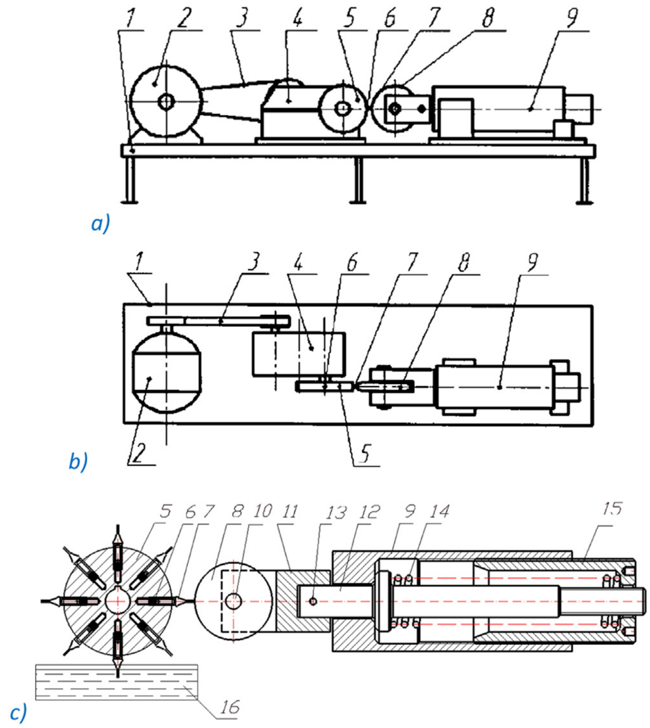

Fig. 1. Device for testing materials for contact fatigue and wear: a – front view; b – top view; c – loading unit for experimental samples.

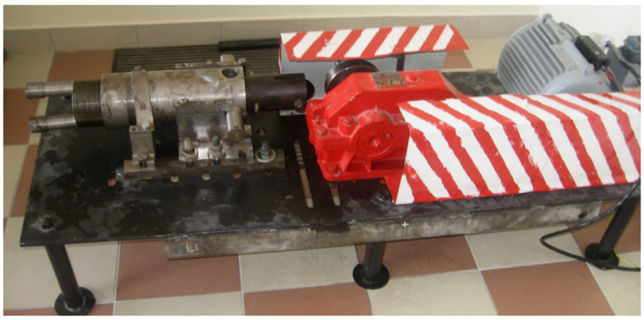

Fig. 2. General view of the contact fatigue testing facility.

The upward fluctuations of the workload caused by the displacement of the counter in the direction of compression of the rod spring by a distance of 0.5 mm do not exceed 4 % of the value of the smallest of the forces created in the experiment. The range of operating forces generated by the spring on the rod is 0 – 7000 N. The choice of the working part of the samples with a thickness of up to 2 mm and the width of the working belt of the counterbody up to 2 mm make it possible to realize pulsating contact loading along the strip, which is used in the study of wear of materials, both under rolling and sliding conditions in the contact zone. The value of the contact voltage generated on the working surface of the sample can be set in the range 0 – 5000 MPa. The contact fatigue of sample 7 is estimated by the number of loading cycles at a given contact load level and reaching a wear hole depth of 0.60 mm, or reaching 30,000 loading cycles. The appearance of the installation is shown in Fig. 2.

The material of the counterbody is P6M5 steel with a hardness of 64–65 HRC. To fully recreate the working conditions of the stamping tool, the working part of the sample is dipped into a container with Rosoil-Shock lubricant (TU 0258–001–06377289–94), used as a process lubricant for cold planting, extrusion and drawing. The number of samples simultaneously tested under identical conditions is mediated by the requirements of statistical processing of experimental samples and corresponds to the number of sockets in the faceplate – 8.

The width of the plate of the working part of the sample exceeds the thickness of the working part of the disk, which makes it possible to accurately calculate the contact area (Fig. 3). The depth of the formed hole on the end surface of the sample reflects

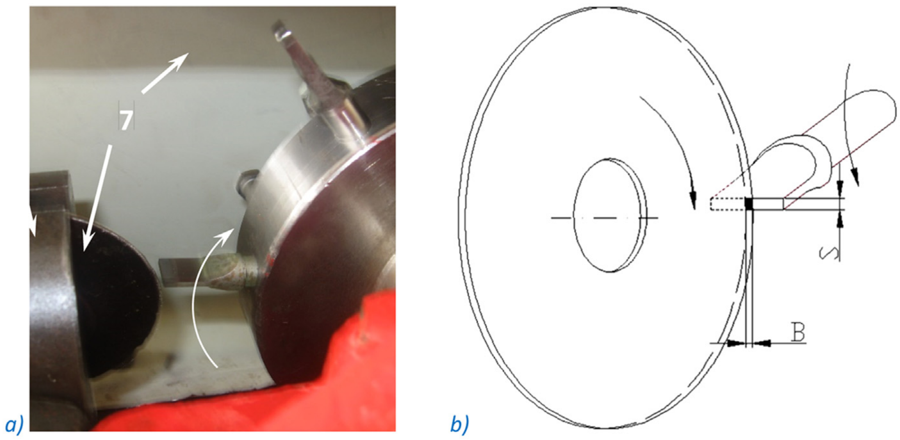

Fig. 3. Image (a) and diagram (b) of the interaction of the sample and the disc counterbody during the contact fatigue test.

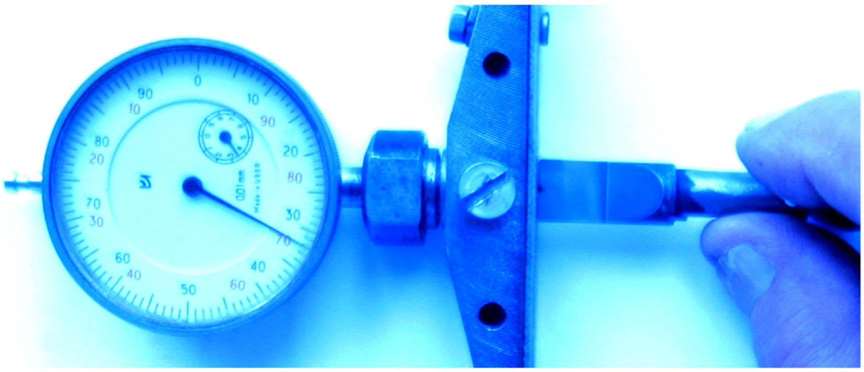

Fig. 4. Direct measurement of the pitting depth.

the degree of fatigue damage to the material. Its determination is carried out by directly measuring the depth of the wear hole using an hour-type indicator with an accuracy of 0.01 mm (Fig. 4). The obtained values are compared with the results of measuring the depth of the well on an instrumental microscope at 50x magnification [7,8]. Each batch subjected to the tests consists of 8 samples. Statistical processing of test results for each operating time level is carried out by interval estimation of the mathematical expectation of the wear value using the Student's criterion with a confidence probability of 0.95. Based on the test results, curves are constructed reflecting the dependence of the depth of the formed well on the number of operating cycles at a given contact load.

The possibility of processing the lateral surfaces of the flat working part of the sample with a rigid base and the use of modern equipment for the preparation of micro-grinders allows monitoring the accumulation of fatigue damage and structural changes along the cross-section of the working part of the sample using an optical microscope. The stress-strain state of the working part of the experimental sample differs in the distributions characteristic of the volumetric physical model. In contrast to the flat model used for numerical modeling in [2], three–dimensional modeling reflects the redistribution of stresses on the contact surface due to the presence of structural stress concentrators - the lateral edges of the contact strip on the end surface of the samples. Such a boundary condition is typical for the operation of a stamping tool in the areas of contact of the engraving with the outer contours of the workpiece material.

Method validation

To verify the experimental results, finite element modeling in the ANSYS program was performed. All geometric and technological parameters fully corresponded to the experimental parameters. To simulate the contact fatigue operation, the Johnson-Cook model was used, which is the most suitable for machining processes [9]. A test calculation in the case of applying a normal stress of 1300 MPa to the contact surface of the sample shows that at the initial moment of testing the level of maximum equivalent stresses is about 1270 MPa. The concentration zone is located at the intersection of the working and lateral surfaces of the sample. In the center of

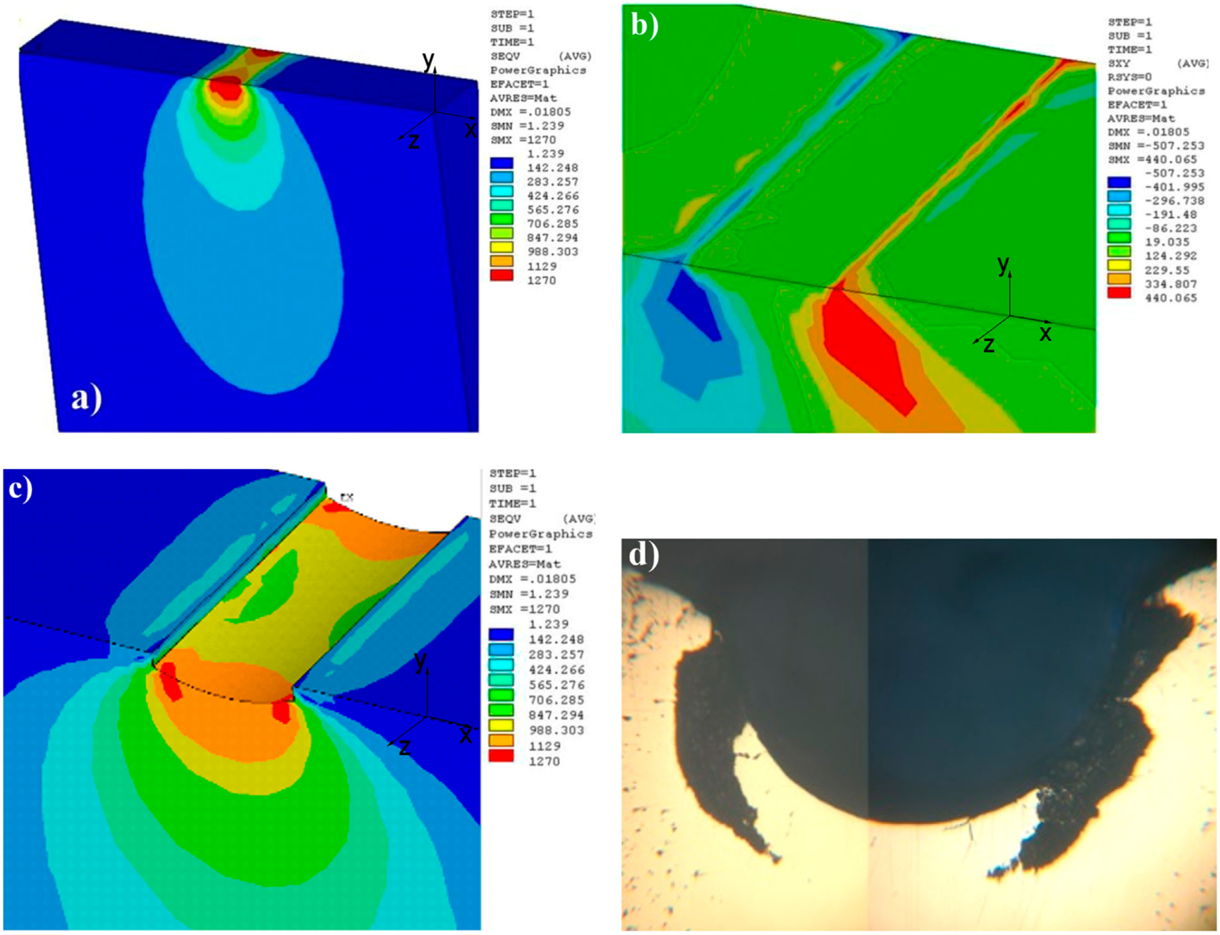

Fig. 5. Distribution of equivalent (a) and tangential (b) stresses over the working surface of the sample at the initial moment of testing, equivalent stresses at a hole depth of 0.2 mm (c) and the pattern of crack propagation in the experimental sample (d).

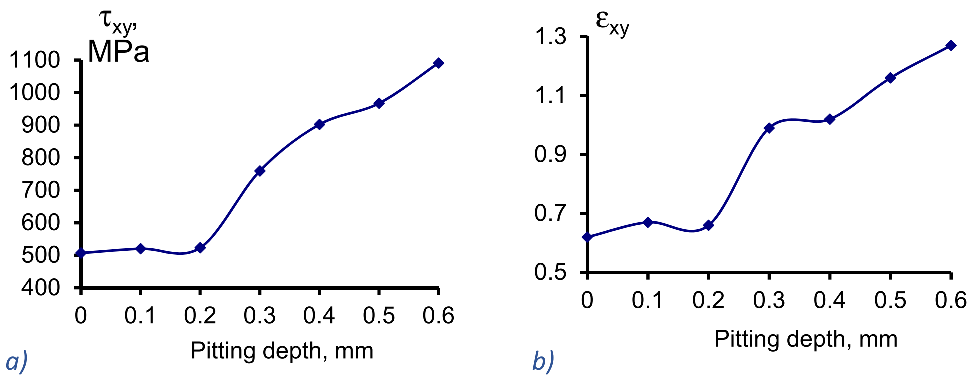

Fig. 6. Change of tangential stresses (a) and shear strains (b) in the lateral plane of the working part depending on the pitting depth.

the contact strip, the stress drops to 1000 MPa (Fig. 5a). The boundary between the area of the working surface with and without an applied contact load is under the influence of maximum tangential stresses, the values of which reach 500 MPa (Fig. 5b). The zones of concentration of tangential stresses are located deep in the metal under the extreme points of application of the load to the surface of the sample (Fig. 5c). Contact fatigue cracks originate and grow in these zones (Fig. 5d).

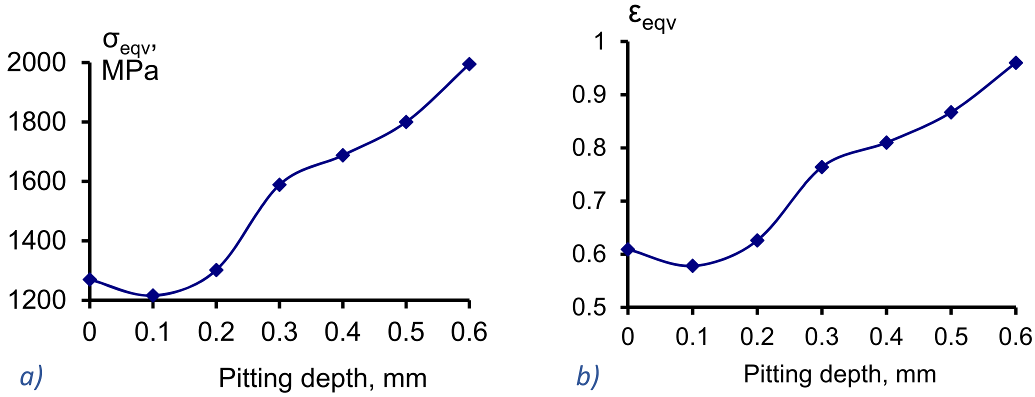

Fig. 7. Change of equivalent stresses (a) and strains (b) in the lateral plane of the working part depending on the pitting depth.

Limitations

The magnitude of the tangential stresses responsible for the occurrence of microplastic deformations under the contact surface remains at 500 MPa at a pitting depth of up to 0.2 mm (Fig. 6a). When the pitting is deeper than 0.2 mm, there is an increase in stresses up to 1100 MPa with a pitting depth of 0.6 mm. A similar pattern was observed for shear strains (Fig. 6b), which vary in the range of 0.6–1.3 %. Thus, tests carried out with wear of the contact surface to a depth of 0.2 mm will be carried out under constant boundary conditions, which is commensurate with the maximum tolerance for linear dimensions of the working surfaces of most cold stamping tools. This statement is supported by dependencies reflecting changes in equivalent stresses and strains, which are also a criterion for evaluating a material's resistance to contact wear (Fig. 7). An increase in the depth of the pitting above 0.2 mm not only increases the concentration of all the noted stresses and strains, but also leads to the localization of the zone of maximum equivalent stresses in the area of maximum tangential stresses.

Testing at pitting depth of >0.2 mm is also important, since the local redistribution of loads across the working surfaces of most stamping tools leads to selective wear of its engraving, and this in turn creates a local stress concentration in the area of the resulting defect. In addition, the analysis of wear intensity, carried out in parallel with the assessment of structural changes in the surface layer of the metal, makes it possible to identify the mechanism of destruction of the modified layer, as well as its interaction with the core material, taking into account the gradient of properties across the section of the hardened material.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Igor Stepankin: Conceptualization, Software, Investigation, Writing – original draft, Visualization. **Abdrakhman Naizabekov:** Conceptualization, Validation, Supervision, Project administration, Funding acquisition. **Evgeniy Pozdnyakov:** Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Dmitry Kuis:** Methodology, Investigation, Writing – original draft. **Sergey Lezhnev:** Formal analysis, Resources. **Yevgeniy Panin:** Formal analysis, Data curation, Writing – review & editing.

Data availability

Data will be made available on request.

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