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FRETTING PHENOMENON BASED RELIABILITY FOR DESIGN

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Abstract: *Reliability for design presents the specific approach to reliability of machine systems modeling oriented to design parameters definition of the system components. Reliability at the elementary level is connected to possible certain failure in the form of complex probability combined of service conditions probability and of this failure probability. Overall reliability of the system is combination of minimal elementary reliabilities of all components of the system. Randomness of fretting phenomenon is specific and needs specific approach in this elementary reliability modeling. The article contains presentation of theoretical background of the fretting process and also a few examples of machine parts failure caused by fretting. Presentation and analysis of testing and measurement results leads to specific model creation for presentation of elementary reliability in relation to fretting wear.*

Keywords: *fretting, reliability for design, engineering design, tribology.*

1. INTRODUCTION

Fretting is phenomenon which producing surface failures and significant material wear without visible causes. In machine parts contact surface roughness are coupled and oscillatory micro-motion take out the small surface pieces and transforming material into dust of dark red color. Relative micro-motions in the surface contacts are result of elastic deformations of machine parts exposed to dynamic loads, result of vibrations, and similar effects. In Figure 1 is presented the shaft assembly with spline joint and fretting failed shaft. The spline flanks are significantly outworn in the form of chamfer in the region of spline joint contacts. This fretting also caused cracks and produced the fracture of the shaft paces – fretting fatigue. The shaft and other parts in this assembly contain the set of fretting failures [1].

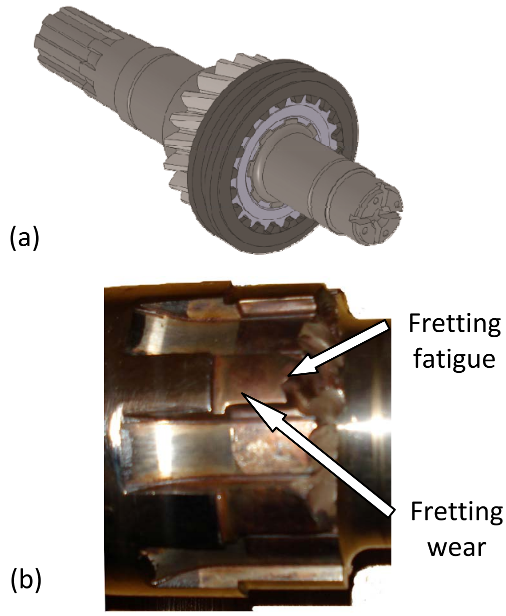

Figure 1. The shaft failure caused by fretting

In the Figure 2 is presented example of claw coupling where the claws are outworn by fretting. Figure 2a shows claws before operation and Figure 2b claws outworn 1/3 of claw thickness and Figure 2c 2/3 of claw thickness.

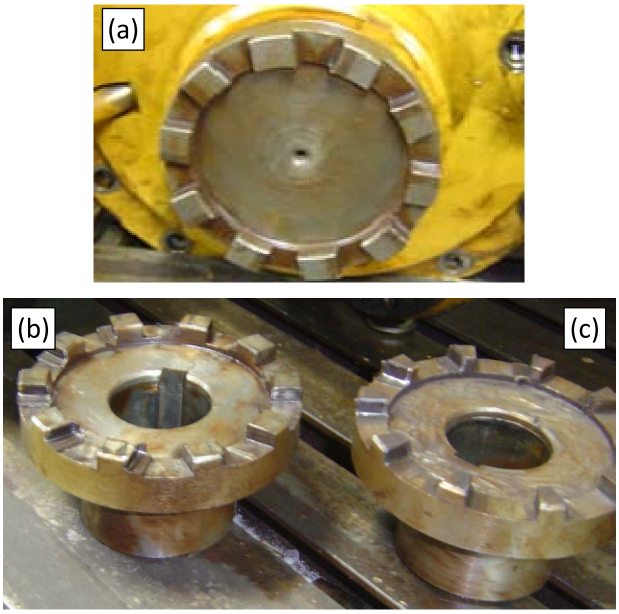

Figure 2. The claw coupling failure caused by fretting

In mechanical joints of various components existing possibility for fretting failure arise. In reference [2] is presented and analyzed fretting process in turbine blade nut joints and in bolted joints. Fretting failure is characterized by missing of operating processes directly responsible for this failure such as loads, motions etc. It is necessary to find out specific reasons for it, and to identify probability of this failure appearance and degree of failure.

Mechanical structures, especially machine systems contain a lot of various possible failures. The model of overall reliability for design involves elementary reliabilities connected to each of certain expected failure in the system. Elementary reliability for design for the certain expected failure is the complex probability combined of probability of corresponding operating condition, such as operating stress, and of failure probability under this stress [3,4]. These reliabilities are the main constraints in design parameters definition of structural components. The procedure and model for this elementary reliability definition are precisely defined for the gears, bearings and similar components [3,4]. This approach it is not easy to apply in the cases of possible failures caused by fretting. The main objective of this work is to discuss about the problem and to suggest haw to solve it.

2. FRETTING PROCESS AND TESTING

The main heading for fretting is relative micro-motion in machine parts contacts, but this process is quite complex due to a number of effects discussed in numerous research articles. In general, the fretting has the two kinds of the damage manifestation. The first one is wear and loss of material from contacting surfaces (Figs. 2b and 2c) – fretting wear. The second one is fretting fatigue. After beginning of wear starts rapid crack nucleation and propagation inside of machine part (Fig. 1b). The second group of fretting failure (fretting fatigue) is much more interesting for research but it is not the matter of this work.

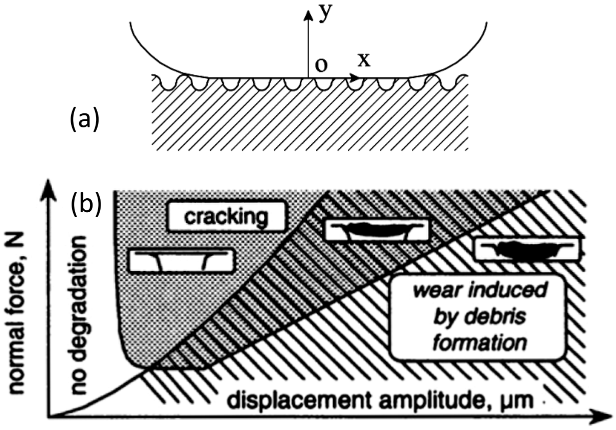

Figure 3. Fretting process: (a) model [5] and (b) areas of cracking and wear [6]

According to [5] the fretting wear can be modeled as presented in Figure 3a, where surface roughness's under pressure and oscillatory micro-motion take away the small pieces of material and transform into the powder. Intensity of this process is in relation between surface pressure and possible oscillatory micro-motion. In Figure 3b are presented fretting areas in relation of macro-motion (surface sliding) and normal force (pressure) [6]. High level of pressure (normal force) and higher displacement amplitude produce the cracks in contacting surfaces.

More high amplitude of motions also produced fretting wear (overlapped areas in Fig. 3b). Clean fretting wear is result of higher motion amplitude with the same or the less normal force (contact pressure). Presentation in Figure 3b also shows that very small displacement amplitude or total absence of micro-motion eliminates degradation (any failure) of the contact surfaces. This is the way haw it possible to eliminate possibility for fretting phenomenon appearance. Pressure joints (feet joints) prevent relative motion between contacting surfaces. These and similar joints are the only guaranty for prevention of fretting phenomenon appearance in mechanical structures. Otherwise micro-motions can always occur due to the influence of the influences as well as elastic deformation, vibration, etc.

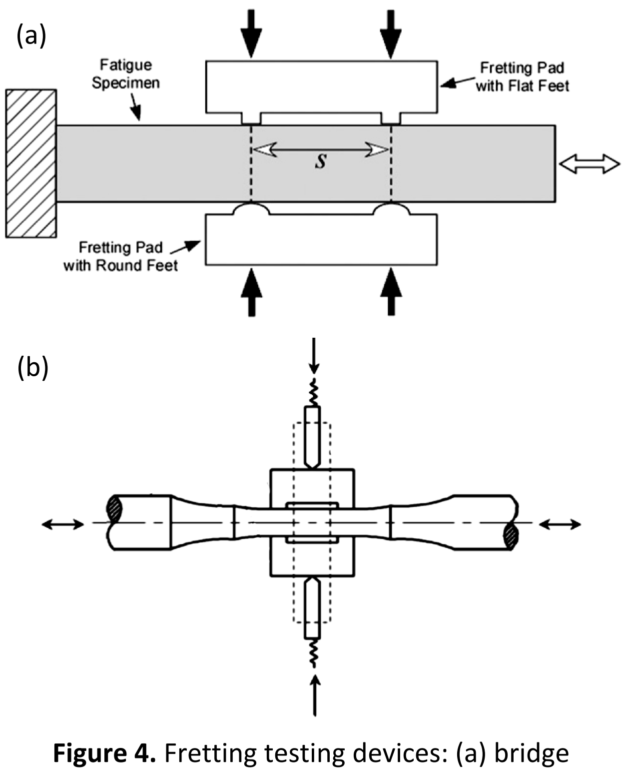

Figure 4. Fretting testing devices: (a) bridge principle [6] and (b) fretting fatigue testing device [7]

The basic principles of the fretting failure testing are standardized. The fretting contacts in these testing principles can be point contact, line contact and surface contact. In order to provide normal force balance in the testing device, suggested contacts are symmetrically in relation to testing sample. Contacts can be in one section of testing sample (single clamp) or in the two sections in the form of bridge-type and grip-type of device. One of these tests principles with bridge contact in line or in surface is presented in Figure 4a. The principle provides possibility to vary normal force (contact pressure) and oscillatory micro-motion [6]. The testing device for fretting fatigue, presented in Figure 4b, is combination of fatigue test sample and bridge components which produce fretting effect. Micro-motion is result of elastic deformations caused by tension load. Results of this kind of testing (fretting fatigue testing) are available in much greater number of references [5-9] comparing to fatigue wears [10-11] which is subject of this work.

3. FRETTING WEAR ANALYSIS

The fretting wear has the similar result as common sliding wear, i.e. material transformation into small pieces – the dust (Figs. 1 and 2). The difference between these wears is consequence of the different kind of relative motion of contacting surfaces. The common sliding wear is result of continual macroscopic sliding motion, but fretting wear is result of microscopic oscillatory motion. Example in Figure 1 presents assembly in automotive gearbox which contains the three spline joints with clearance in the contacts. In the course of the gear teeth wear testing in back-to-back testing rig, vibrations produced by gear teeth meshing created oscillatory micro-motions in the spline joints contacts and rapidly fretting wear. This wear also encompassed cylindrical contacting surfaces of the shaft and gear and also the other spline joints. Example in Figure 2 is much more evident identification of fretting wear failure. This is the parts of the two claw couplings. Misalignment of the two coupling halves produced oscillatory micro-motion in every revolution of coupling. Relative motion in the claw contacts was combination of angular and translator displacement which produced significant wear. Both coupling halves, presented in the Figures 2b and 2c, was exposed to the same operating load with the same revolution number in the course of exploitation. The main reason that coupling in Figure 2c is much more worn out than the coupling presented in Figure 2b is that misalignment was much higher. Higher amplitude of oscillatory motion produced higher intensity of fretting wear.

The complex fretting wear process is in relation with various effects connected to operating conditions of machine parts and their contacts and also in relation to design, technological conditions and material characteristics. This complexity not easy to be identified by analytic approach but it is possible to recognize directions of the mine effects. Some of these efforts contain the reference [11], but offered results are not enough for practical application for design of mechanical structures. In the absence of such data, probabilistic approach in practical application is necessary.

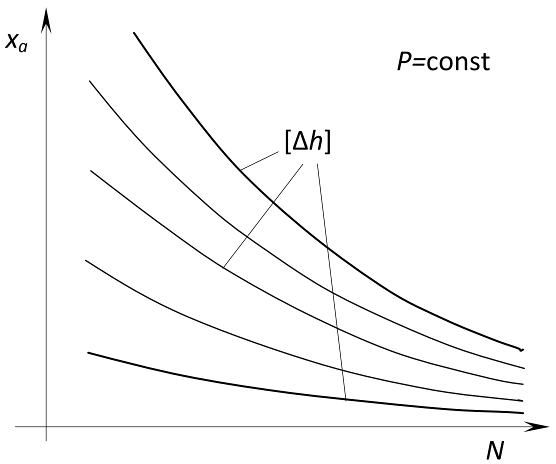

Figure 5. Relations of fretting wear parameters

As already mentioned, the mine parameters of the fretting wear are: the amplitude of oscillatory motion x_a, cycle number of oscillations N, thickness of worn layer Δh, pressure in the surface contacts p, hardens and strength of material, friction coefficient and lubrication conditions, etc. In Figure 5 are presented general relations between displacement amplitude x_a and amplitude cycle N necessary for wear of surface layer thickness Δh with the same pressure p. Higher level of pressure increase worn thickness but increase of machine parts hardness reduce it. Precise relation wasn't identified. Analytical approach of this research and fundaments of fretting wear theory are presented in reference [11] and discussion is continued in [1]. The base of this theory is the energetic rate (work rate) which has to be used for wear of volume unit of material (volumetric wear rate losses). Analytical calculation involves possibility of normal force variation and sliding speed variation in the time period of this values integration. For the practical use insuperable problem is precise identification of the time functions of force and the sliding speed variation. In this form relations in [11] can direct way of the fretting wear process analyses but in this form can't to offer significant help for design solution search. However, this work is directed to create link between theoretical fundaments and practical application. For this purpose are calculated and presented values of specific wear coefficient which contains effects of operating conditions of mechanical structure. Farther analyses and calculations involves effect of material characteristics, shape of contacts, effect of impact, sliding and oscillatory motion in various directions, temperature effects, etc. Results of calculation are bring in relation with calculated and concluded that existing good correlation. Nevertheless, deterministic treatment of fretting wear process needs much more analytic investigation.

In the absence of practically acceptable theoretical results, the rule is to use a statistical approach of experimental results treatment and experience. In order to create this approach for identification of possible fretting wear failure in mechanical joints, it is necessary to carry out extensive laboratory testing. The results can be the base for reliability modeling and statistical prediction of fretting wear in mechanical structures. In the meantime these results will give support to theoretical research of fretting wear and provides interactive control and compare of analytical and analytic research.

4. FRETTING WEAR RELIABILITY FOR DESIGN

The meaning of the term "Reliability for design" is explained in [3,4]. This model adapted for unreliability calculation in relation to fretting wear is presented in Figure 6. The model contains probability of oscillatory motion p_i and fretting wear probability for certain experimental conditions P_{Fi} (number of oscillations $n_{\Sigma I}$ and amplitude value x_{ai}). Elementary unreliability for design F_p is the sum of probability products for all levels of amplitude displacements.

$$F_p = \sum_{i=1}^{k} p_i P_{Fi} \; ; \; p_i = \frac{n_{\Sigma i}}{n_\Sigma} \; ; \; P_{Fi} = 1 - e^{-\left(\frac{x_{ai}}{\eta}\right)^{\beta}} . \quad (1)$$

This is general model which includes random values of displacement amplitude modeled in the form of amplitude spectrum (Fig. 6a) and of random process of fretting wear obtained by laboratory tests (Fig. 6b). Fretting wear failure probability in Figure 6b is distributed into the range bounded by the line with failure probability P_F = 0.1 and P_F = 0.9. This range is defined for the certain material including thermal treatment and other technological effects. Also the range is defined for the certain thickness of worn surface layer. For the certain number of oscillatory motion cycles $N = n_{\Sigma i}$ failure probability distribution is presented by Waybill's distribution function with parameters η and β.

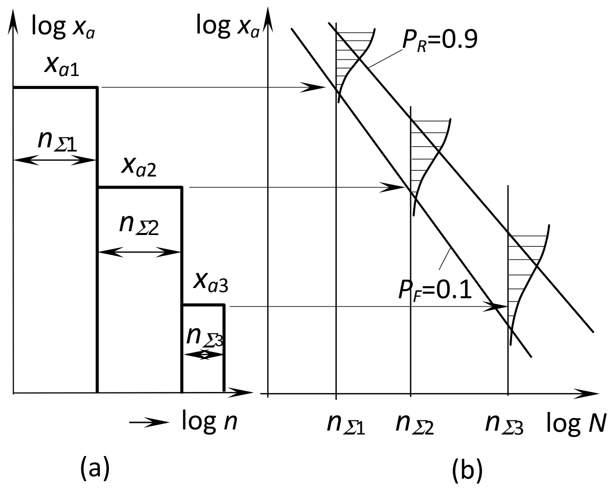

Figure 6. The model for calculation of fretting wear reliability for design

Presented general model for fretting wear unreliability calculation, it is not easy to apply. For its existing various reasons. Oscillatory motions in structural components contacts are various and complex. Motion amplitude is predominantly random and not easy to create the amplitude spectrum presented in Figure 6a. Also for various surface conditions (material, mechanical and thermal treatment) it is necessary to provide fretting wear experimental data for various thickness of surface worn layer. Its need extreme extensive laboratory testing process. All these facts are the reason that it is necessary to search for more simple model and procedure of this reliability identification. The model has to provide acceptable exactness in fretting wear reliability prediction and to be easy for practical application. The next two approaches provides these terms.

If the model in Figure 6 is the first step of simplification, the second step considers that the all motion amplitudes are equal between each other (constant amplitude of oscillatory motion). The first step of simplification was presentation of random amplitude with amplitude spectrum (Fig. 6a). For constant amplitude of oscillatory motion x_a, in Figure 6 exist just one Waybill's function of failure probability, for one total cycles number of oscillation $N = n_\Sigma$ in the course of design structure operation life. Unreliability in relation of fretting life is

$$F_p = P_F = 1 - e^{-\left(\frac{x_a}{\eta}\right)^{\beta}} . \quad (2)$$

The example presented in Figure 2 is very suitable for application of this approach. Amplitude of oscillatory motion is proportional to claw coupling misalignment and reliability is related to this amplitude i.e. misalignment. Mixed types of oscillatory motions are simplified as one type of oscillation. Load (pressure) level and surface conditions contains Waybill's function of wear failure probability.

The thread step of simplification is laboratory testing of the typical mechanical joints such as spline joints (Fig. 1), key joints, bolted joints, etc. for various loads, clearances, worn layer thickness, etc. For this data, unreliability can be calculated in relation with revolution number $N = n_\Sigma$ in the course of operating life. This unreliability F_p and reliability R are

$$F_p = P_F = 1 - e^{-\left(\frac{n_\Sigma}{\eta}\right)^{\beta}} \; ; \; R = 1 - F_p \,. \qquad (3)$$

Parameters of Waybill's function η and β have to be identified according to testing for certain load and other conditions in the joint. This fact reduces the scope of application of the data which are obtained by extensive testing.

5. CONCLUSIONS

Fretting is specific kind of failure of mechanical structures because it is not in direct relation with design parameters and operating conditions. Design parameters definition based on Robust design and Axiomatic design, can't directly use Reliability for design in relation to fretting wear, as Design constraint. However this elementary reliability is important for the model creation of overall reliability of the system.

The article specifies various aspects of the fretting phenomenon and kinds of fretting failures, including testing and calculation procedure. Discussion is supported by the two practical examples.

The main contribution of the work is presentation of the three approaches for calculation and prediction of elementary reliability connected to fretting wear failure. The first is similar to elementary reliability calculation used as design constraint. The other two are simplified approaches suitable for practical application in order to include in reliability model fretting as extreme complex failure process.

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