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Service Life Assessment of the Cam Mechanisms

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Abstract

Currently, there are higher requirements on the cam mechanisms. Part of the design is a determination of the service life of a cam surface. This paper deals with wear mechanisms at cam mechanisms in its first part, then describes factors affecting the life and the last part deals with a methodology of durability testing. Hertz’s contact theory is the basis for the pressure determination in the contact patch. By means of its value we get the relationship between surface hardness and required lifetime of the cam surface. This information is heading to determination of the materials suitable for the cam mechanisms production, and it is necessary taking into account the working conditions.

Keywords: surface fatigue, contact theory, cam mechanism

1. Introduction

VÚTS, a.s. deals with the calculation of cam mechanisms and cams production more than thirty years. This provides us a lot of experience in design and calculation of both axial and radial cams. In this context, currently we solve the testing methodology of the service life of the cam mechanisms. On this basis, we can determine the life of the cam mechanism respectively time when damage occurs.

There are only three ways in which parts or systems can fail: obsolescence, breakage or wearing out [1]. Most systems are subject to all three types of possible failure. Failure by obsolescence is somewhat arbitrary. Failure by breakage is often sudden and may be permanent. We will address only the failure mechanisms to which the cam-follower interface are typically subject. These fall under the general rubric of wear.

2. Wear mechanisms

Failure by wearing out is generally a gradual process and sometimes repairable [1]. Ultimately, any system that does not fall victim to one of the other two modes of failure will inevitably wear out if kept in service long enough. Wear is final mode of failure that nothing escapes. Thus, we should realize that we cannot design to avoid all types of wear completely, only to postpone them.

Wear is a broad term that encompasses many types of failures, all of which involve changes to the surface of the part. Most experts describe five general categories of wear: adhesive wear, abrasive wear, erosion, corrosion wear and surface fatigue. In addition, there are other types of surface failure that not fit neatly into one of the five categories or that can fit into more than one. [1]

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3. Surface fatigue

The surface fatigue [2], called contact fatigue, occurs in functional surfaces that are exposed to repeated loading during movement of functional surfaces of machine components. It may be a relative rolling movement or a combination of sliding and rolling, what is more common in practice. This way, in the surface layers of strain materials leads to a variable elastoplastic or elastic deformations.

3.1. Surface fatigue types

Pitting is the mechanism of damage, which can lead to the fatigue fracture damage. This type of failure occurs in machine elements, which are cyclically loaded, particularly bearings, gears, cams and rotating components [2].

![Fig. 1. Pitting and micropitting. [3]](image)

Micropitting is the phenomenon of fatigue damage [3], which is manifested by the presence of microscopic pits on the material surface in the contact. They are produced due to the repeated cyclic loading of the contact at which occurs to rolling and sliding and they are formed by plastic deformation of the surface asperities.

Micropitting is more often observed at materials with higher surface hardness [4]. The micropits are small relative to the size of the contact zone (see Fig. 1), typically 10-20 μm deep and usual size smaller than 100 μm.

The micropits can coalesce to produce a continuous fractured surface, which appears as a dull, matte surface during unmagnified inspection. Micropitting is the preferred name for this phenomenon, but it has also been referred to as grey staining, grey flecking, etc. Micropitting may stop but if it continues to progress, it may result in reduced gear tooth accuracy, increased dynamic loads and noise. If it does not stop and continues to propagate it can develop into macropitting and other modes of failure.

Macropitting is the phenomenon, when cracks are formed in a certain depth under the surface [4], where the shear stress is maximal due to Hertzian pressure. This type of the surface fatigue [3] causes the formation of large pits (about 1 mm) on the material surface in the contact. These arise due to the spread of subsurface cracks that leads to flaking larger parts of the material from the surface. Macropitting is more prevalent in highly loaded contacts than micropitting.

Spalling [2], arises by repeated contact of the elements, where the substantial contact pressure acts at the contact surface and the initiation of fatigue failure occurs in a certain depth below the surface. A result is a subsurface crack propagation with consequent plucking or flaking of the material particles from a functional surface, or the peeling of the top layer, respectively.

Galling is transferring of the material from one metal surface to another one [2]. This damage is caused by plastic deformation. This process can be likened to the so-called cold welding or friction welding. At abrasion of a surface with a second one is generated a heat and the friction causes the pairing of each surface imperfections. Galling occurs most frequently in dry and uneven surfaces.

Scuffing is a precursor of galling [2]. The scuffing occurs in a situation where the protective coating breaks down faster than it forms. There is an immediate contact of the surface roughnesses, the surfaces are disturbed in depth. The final amount of the wear is in the order between 10 to 100 micrometers. The main reason of the wear is the surfaces adhesion and fatigue of materials. To avoid the generation of scuffing and galling can be used special additives in the lubricant.

Scoring is characterized by separation of the material due to the particles carried by a stream of fluid, gas or vapor [2]. Scoring is characterized by the uneven damaging surface which is warped and damaged even in hollows.

3.2. Factors influencing the wear

There is not only rolling but also sliding at the cam mechanisms.

Surface cracks [5]: surfaces are never perfectly smooth and always contain some cracks and scratches which have an impact on life of the surface. The primary crack arises on the surface of some weak points. It continues downward along suitable planes. Secondary crack may develop from primary crack or primary crack can possibly combine with existing subsurface crack. If the spreading crack again reaches the surface it releases the wear particle.
Subsurface cracks: the tension at the contact loading can reach directly under the surface the extremely high values, thus produce a crack at a certain distance below the surface, where the tension is strong enough to initiate the crack. The most of technical materials contains inclusions and other defects which act as nucleation sites for the formation of cavities.

Plastic deformation: This type of wear occurs at the excessive plastic deformation (exceeding of the elastic shakedown limit). Large plastic deformations are gradually accumulated through superposition of small uniaxial stresses which are generated during each operating cycle. If the strain exceeds a critical value, the material breaks.

Working conditions: In the absence of lubrication wears the metal surface due to the repeated destruction of the oxide layer and its subsequent reformation. Temperature rise is accompanied by cyclic load. On the surface, where the highest temperature is, occurs the continuous annealing and recrystallization of the material. This eliminates the stress and increases hardness.

Impurities: Significant is the size and amount of hard particles in the lubricating medium. These hard particles pass lubricant and acts as an abrasive.

Material properties: Influence of material imperfections, such as inclusions, brittle grain boundaries and locations of high stress are important sources of initiation sites for the formation and development of cracks.

As soon as a crack created during rolling is facilitated its further growth. And it is thanks to changes in the Hertz contact stress patterns. The presence of cracks disrupts the normal Hertzian stress field of undamaged body and is a high stress concentration at the crack tip. Shear stress supports the growth of cracks. It is thus apparent that the presence of any cracks and microcracks is very favorable for the formation of future large cracks. Once the crack length reaches a size comparable with the diameter of the Hertzian contact or the depth at which is maximum shear stress, will follow a quick crack elongation.

4. Hertz’s contact theory

To the damaging of the surface of the active surfaces of cams and rollers occurs due to contact stress described by Hertz’s theory. In case of cam mechanisms it is about the contact of two cylindrical bodies with parallel axes.

Assumptions of Hertz’s theory [6]:
- initial contact on the line,
- not considered the friction force (between objects does not act tangential forces),
- body material is linearly elastic, homogeneous and isotropic,
- there is a small deformation,
- sizes of the contact area are small compared to the size of the body.

There is a schematic view of the contact of the two cylinders in Fig. 2. There is a contact of cam 1 and roller 2 at the cam mechanism. The length of the contact area is denoted $l$, the radii of curvature at point of contact are $\rho_1$, $\rho_2$ and $N$ defines normal reaction between the particular elements of the pair [7].

![Fig. 2. Force relations at the two cylinders contact [7].](image)

Assuming a uniform load distribution over the length $l$, the load in proportion to the length unit will be (1).
The deflection between two bodies in contact may produce a flat of width $2b$ and length $l$ (see Fig. 2) with coordinates $O, x, y, z$ located in its centre. The flat is situated at the coordinate plane $xy$ where the axis $x$ coincides with the contact area of non-loaded bodies. Contact load distribution $p(x, y)$ along the elliptic cylinder is (2).

$$p = \frac{2q}{\pi b} \sqrt{1 - \left(\frac{y}{h}\right)^2}$$  

Hertzian pressure is a maximum compressive stress $p(x, 0)$ defined as (3).

$$p_H = \frac{2q}{\pi b} = \frac{q(|\rho_2| \pm \rho_1)}{\pi(\delta_1 + \delta_2)\rho_1|\rho_2|}$$  

Unlike the positive radius of curvature of the roller follower $\rho_1$, the radius of curvature of the cam surface in contact $\rho_2$ may attain both, positive or negative values. Actually this fact is defined in relation (3) by quantity $|\rho_2|$. The sign of relation is positive if the centers of curvature $S_1, S_2$ related to the external contact of bodies are located in different halfspaces defined by the plane limit $xy$, and negative in the opposite case.

The quantities $\delta_1, \delta_2$ are the characteristics of elasticity of the elements in the pair (4), where the Poisson’s ratio and the moduli of tension elasticity are denoted as $\mu_{1,2}$ and $E_{1,2}$ respectively.

$$\delta_{1,2} = \frac{1 - \mu_{1,2}^2}{E_{1,2}}$$  

Rearranging relation (3) we get the bisected contact area (5).

$$b = 2\sqrt{\frac{q(\delta_1 + \delta_2)\rho_1|\rho_2|}{\pi(|\rho_2| \pm \rho_1)}}$$  

The reduced stresses $\sigma_{\text{red}}(\psi, \zeta)$ are limited by the actual strength condition, written in the form (6), where $\psi$ is an angular cam displacement and $\psi \in (0, 2\pi)$ and $\zeta = |z|/b \geq 0$.

$$\max \sigma_{\text{red}}(\psi, \zeta) < \sigma_{\text{n}}$$  

For steel the usual values are $\sigma_c \approx 0,33 R_m$ and $R_c \approx (0,55 \text{ to } 0,8) R_m$. However, since the transitory stress limit is $\sigma_{\text{n}} \approx 2\sigma_c = 0,66 R_m$, the relation (6) may be replaced by the inequality (7), where $\psi \in (0, 2\pi)$ and $\zeta = |z|/b \geq 0$. This equation states that no destructive action of elastic deformation is produced in the general pair under operation.

$$\max \sigma_{\text{red}}(\psi, \zeta) < R_e$$  

4.1. Life of the cam contact surface

As mentioned above, no damage causing irregularities like e. g. pits is acceptable on a contact surface under load. We can avoid such damage, if Hertzian pressure is (8), where $K=4777 \text{ MPa}$, $W$ is surface life in million cycles and $H$ is surface hardness.

$$p_H \leq \frac{K}{W^{1/6}} f(H)$$  

Function $f(H)$ expresses the influence of the surface hardness on the permissible Hertzian pressure by means of equations (9).
Quantities HB a HRC are surface hardnesses. The Brinell scale hardness is labeled as HB and HRC is the surface hardness in Vickers scale.

4.1.1. Soft steel cam surface

We note that the metal mechanical properties are constant over the whole cam body. Material choice depends on maximum Hertzian pressure over the operation cycle of the mechanism.

The calculation procedure is such that by (1) we calculate the Hertzian pressure $p_H(\psi)$ (3) depending on the angle of the cam rotation $\psi \in (0,2\pi)$ and from the course of this pressure we define the maximum pressure value (10).

$$p_{H \ max} = \ max \ p_H(\psi)$$

Selecting material satisfying the life requirements $W$ with regard to hardness $H$ we must take into account the condition of resistance against pit formation (11).

$$p_{H \ max} W^{1/6} \leq K f(H)$$

The chosen material should be checked on elastic deformation, as defined in (12).

$$\text{max} \sigma_{\text{red}} = 0,6 \ p_{H \ max} < R_e$$

There are tables with recommended materials and their mechanical properties in the literature [7].

4.1.2. Hardened steel cam surface

The cam contact surface is in relation to metallurgical changes, arising due to thermal or chemical-thermal treatment. Surface hardening, case hardening, nitriding, nitrogen-case hardening are the most frequent processing methods used.

We note that hardness and other mechanical properties of the finished metal, to a defined distance below the surface $h$, differs from those of metal core. The value of the magnitude $h$ should be defined so as to reach the maximum reduced stress $\sigma_{\text{red}}$ at 0,6 $p_{H \ max}$ beneath the finished surface. Surface hardness $H(p)$ has to satisfy the condition of resistance against pit formation (13).

$$p_{H \ max} W^{1/6} \leq K f(H(p))$$

Using Brinell scale for steel, we note that hardness HB is related to strength $R_{m(p)}$ of the surface by setting $HB = 0,3 \ R_{m(p)}$ and the condition of resistance against pit formation has the form (14).

$$p_{H \ max} \leq \frac{1,433}{W^{1/6}} R_{m(p)}$$

Plastic deformation will not occur if (12), where $R_e$ is the limit of sliding tension in the finished metal surface.

For the surface layers is the thickness an important factor. Since overload and breakage of the finished surface might be caused due to permanent core deformations. Thickness of the finished surface should be defined by the condition (15) for $|z| > h$ where $R_{e(j)}$ is the limit of sliding tension in the core metal. The layer thickness must have such value that the plastic deformation of the core occurred independently of its size.

$$\sigma_{\text{red}}(z) < R_{e(j)}$$

When designing a cam in which the surface is a hardened coating, the quantities $H(\psi), p_2(\psi)$ should be computed over the whole operating cycle of the mechanism, which determines the $p_H(\psi), b(\psi)$. The Hertzian stress $p_{H \ max}$ and the required life $W$ are principal factors to be considered when we select a material suitable for intended methods of treatment and having mechanical properties necessary for the hardness of the coating. Recommend materials are listed in literature (e.g. [7]).
At a given sliding tension limit in the core we may check the condition (16) and thus, according to (17) calculate the product \( b_1 \) for intervals of angular displacement \( \psi \) in which the particular condition is satisfied.

\[
\begin{align*}
\alpha &= \frac{R_e(j)}{2p_H} \\
\beta &= \left(1 + \alpha^2\right) / 2 \\
\gamma &= 3 - \beta^2 \\
\theta &= \frac{1}{4} \left[ 2\beta - \beta^2 \right] \\
\varphi &= \frac{1}{3} \arccos \left( \frac{\theta}{\gamma^{3/2}} \right)
\end{align*}
\]

Thus, the attained maximum is the bottom limit of the interval for thickness determination \( h \) expressed as (18).

\[
\max \{b(\psi)c_1(\psi)\} < h
\]

The upper limit of the hardened coating depends on the surface treatment applied, as listen in literature [7].

5. Testing of the service life of the cam surfaces

Cams are standard produced from steels ČSN 12 050 or 14 220. Higher requirements on the cam mechanism lead to the manufacturing of cams by using of new and special materials. We had a goal to find a methodology for the testing of the individual materials and based on the results then determine their suitability for the given application.

The testing result is a series of objective values which allows comparison of the wear of the specimens made of different materials, and testing is carried out under the same conditions.

Service life of the cams and rollers surfaces can be tested in two ways. In the first case are tested the cylindrical specimens made of different materials and in the second case it is possible to test the cam on the stand simulating real cam mechanism. The advantage of testing stand for cylindrical samples (see Fig. 3) is its design simplicity and the higher speed of the service life.
attainment. Each sample is loaded three times. Another advantage is the ability to accurately define a sliding. There is a shape of the tested specimen, where a red color area is loaded by Hertzian pressure (see Fig. 3).

However, a stand simulating a real cam mechanism has the advantage that it is tested a specific shape of the cam with the defined loading. It can be watched not only wear of the cam, but also changes on the roller, the bearings at the roller and cam follower.

According to Niemann empirical relationship the surface will not be damaged by the formation of pits if applies the equation (8). This equation is describing the dependence between Hertzian pressure $p_{H}$, required service life $W$ and surface hardness $f(H)$. The individual values of these parameters were chosen so that, first, the equation was applied, simultaneously was technologically possible to produce the samples plus was tested in real time.

The literature indicates that if the test sample can withstand $10^7$ cycles, it is possible to say that his life is unlimited. We determined by means of the equation (8) that at the surface hardness of HRC $= 53$ the Hertzian pressure should be less than 1,700 MPa on the basis of this value. There is no surface damage and pitting at this values. In order to track the formation of pitting on tested samples, increase Hertz pressure to 2,000 MPa.

One option for monitoring of the wear degree at the testing is to use the accelerometer for vibrations scanning. That is why was located a suitable accelerometer on the test stand. But there is a question if he could record a very small surface wear, which is at the micropitting on the order of less than 100 μm, and if the vibration caused by the damage the accelerometer do not evaluate as a noise. For this reason, we are looking for another possibility of the monitoring of the surface damage and we decided to follow its roughness. Surface roughness we measure before starting the test and then during testing after a certain number of cycles to the destruction of the surface. In addition to these parameters, we continuously monitor the sample surface by an optical microscope and by the mutual comparison we determine the character of the pits and other forms of surface damage. The last step is to compare the theoretical life according to the Hertz’s theory and the real attained life.

This methodology is now used at the testing of samples made from various materials. The actual testing is time consuming and that's why the results are not yet complete. The presentation of results will be a subject of the next publication.

6. Conclusion

The most effective method of protecting against the surface fatigue is reduction of the friction coefficient between two contact surfaces on the value when the tensile forces were not sufficient to delamination during sliding or surface fatigue during sliding. Other very important aspect in the management of surface fatigue during sliding and rolling is the purity of the material. For rolling and sliding should choose materials with the least number of inclusions and imperfections. An increasing of the material hardness may in some cases also help, but this method is limited by embrittlement of hardened material. Materials for the mutual sliding should be selected very carefully. We should avoid sliding between two identical materials, because their identity can provoke adhesive wear [2]. This is difficult to ensure it at the cam mechanisms.

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