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INFLUENCE OF TRIBOLOGICAL PAIRS ON STRUCTURAL AND MATERIAL DAMAGE
UTICAJ TRIBOLOŠKIH PAROVA NA OŠTEĆENJE MATERIJALA I KONSTRUKCIJA

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Abstract

Failure may result from mechanical or chemical reactions of structural materials with aggressive environment, moisture or other impact, or as a consequence of reducing the surface energy of the body. Problems in calculating the impact of the aggressive environment on the extension of cracks are solved by introducing a stress intensity factor that is treated as a material/environment system constant. The reduced toughness depends on the adsorbed chemical substance that is a function of the concentration and time in which the cracked material is exposed to aggressive fluid (lubricant, tribology matter). The choice of material is very important for structures operating in salty environments. Fatigue also occurs as a result of temperature change (principally varies in regions of low and high temperature). At low temperature a relatively stable composition and structure are retained (increased service life), and at high temperatures, various phase transformations are present (aging, creep and recrystallization), where as a rule tensile and fatigue strength both decrease. These aspects of crack propagation due to cyclic loading or environmental impact highlight the significance of fatigue in the integral design, including tribology aspects.

Izvod

Lom može biti posledica mehaničkih ili hemijskih reakcija strukturnih materijala sa agresivnom sredinom, vlagom ili drugim uticajem, ili posledica smanjenja površinske energije tela. Problem proračuna uticaja agresivne sredine na proširenje prsline rešava se uvođenjem faktora intenziteta napona, koji se tretiraju kao konstanta sistema materijal/sredina. Smanjenje žilavosti materijala zavisi od adsorbovane hemijske supstance, koja je funkcija koncentracije i dužine vremena u kojem je materijal sa prslinom izložen agresivnom fluidu (lubrikanti, tribološki problemi). Vrlo je važan izbor materijala za konstrukcije koje rade u slanim sredinama. Zamor materijala može da nastane i usled temperaturskih promena (principijelno različit u oblasti niskih i visokih temperatura). Pri niskim temperaturama materijali zadržavaju relativno stabilan sastav i strukturu (povećava se vek trajanja), a pri visokim temperaturama prisutne su različite fazne transformacije (starenje, puzanje i rekristalizacija), gde po pravilu dolazi do pada zatezne i zamorne čvrstoće. Navedeni aspekti propagacije prslina usled cikličnih opterećenja ili uticaja sredine imaju za cilj da ukažu na važnost zamora pri integralnom projektovanju sa uključenjem triboloških aspekata.

INTRODUCTION

Moving parts of machines, equipment and systems such as bearings (sliding, rolling), gears, guides, chain conveyors and steel ropes, are exposed to relative movement which occurs by various surfaces with mutual direct or indirect contact. The movement can be:
– slide of surface (one surface slides on the other);
– rolling of the element on a flat surface (wheel, ball and roller rolling on a flat surface);
– combined movement (whenever a coupling of bodies in the different movements is formed, basically sliding and rolling).

In the contacts, as a rule, in complex situations the mechanical, thermal and chemical phenomena appear as a result of the developing friction process in contact surfaces, and wear of the material from the surface of the structures may occur (for bodies in conjunction).

Based on widespread and generally available research results, it is possible to achieve the set of standards, recommendations and guidelines, which can be based on different concepts of real construction and engineering applications. It is possible to express the arguments at the level of identification of representative models with an emphasis on the phenomenological dimension of the defect formations in the structure and quantification of the reduction factor of material and structural characteristics at the level of considered reliability, structural integrity and life. Here, the problems are not passively observed but expertly considered in different fields: tribology, corrosion, fatigue, structural integrity and life, in the interest of finding corrective actions that lead to the emergence and application of advanced materials, technologies and processes, which in different contexts occur as a precondition for reliable development, manufacture and rational exploitation of high performance and quality products. Of course, after standardizing materials, processes for their preparation and implementation, benefits may appear in the reduction of costs and achieving acceptable product prices.

This set of topics contain enough important elements that should lead aspects in theory and in practice, regarding proper design of technical systems and their ecological dismissal. Starting from the general tribological model, an overview of the factors that lead to structural damage are given (especially considering fatigue) and various parameters are considered regarding the identification of sources of degradation of applied materials, as well as the proposal of possible measures to mitigate or eliminate causes for the reduced technical characteristics and proper environmental treatment with more effective use of materials.

The paper predominantly uses information and data from literature related to the phenomena and situations that arise in connection functioning, disruption and degradation of structures and materials in different technical systems /1-3/.

GENERAL TRIBOLOGICAL MODEL

General tribological conceptual models can be set at the level of kinematics and dynamics. Kinematic models are related to skating, rolling or a combination of these two shapes of motions. Integrated tribological models are still based as dynamic and as models of deformable structural systems. In connection with the previous, it is possible to identify several standard models which in turn are associated, in addition to meeting basic conditions (coupled to tribological systems that operate efficiently and reliably), contained mechanisms for identifying unwanted behaviour, actions and outcomes, that must qualitatively and quantitatively identified and selectively placed in the design and planning of preventive action (prevention or reduction of their impact causing adverse effects), or corrective action for mitigating and eliminating consequences. Of course, from the first moments of the research, at the level of laboratory or industrial tests of real technical systems with materials and solutions that imply a reasonable price for the intended mission, problems in the work are based on the tribology concept (as a rule, plus ecological aspects), but the thing is that the system must be with the right function and reaction (properly designed system) of the lubrication subsystem according to the principle of automatic control that leads the work process of coupled elements in the desired direction. The basic process is focused on the functioning of technical systems which could be more sustainable over a longer period of time.

Wear of surfaces (mostly a result of friction) of mechanical elements is the result of their mutual contact (complete or partial) and contact with the surrounding environment.

Aggression of oxygen and moisture, influence of all types of solid contaminants significantly contributes to increased wear of structural element surfaces (specific types of wear). The lubricant with the flow along the surface of the elements, their energy of movement and specific hydraulic and rheological phenomena, also contributes to certain types of surface wear. Global distribution of wear is typically performed as: mechanical and chemical wear. Mechanical wear is known in practice as wear and chemical wear is known as surface corrosion.

Surface damage is treated by lubricants which act to amortize variable loads and reduce wear. Lubricants (as media in installations) are placed in the lubrication systems (especially as a system of central lubrication - SCL).

Table 1. Classification of wear and damage of surfaces, /2, 3/.

Wear (mechanical)	Adhesive wear	- Normal adhesive wear - Difficult adhesive wear - Easy seizure - Difficult seizure - Welding (blocking)
	Abrasive wear	- Highly abrasive wear - Easy rebating - Difficult rebating
	Stream (current) erosion	- Fluid erosion - Impact erosion - Cavitation erosion
	Wear fatigue	- Initial Pitting - Progressive pitting - Breaking (fracture)
	Electrical erosion	
Corrosion (chemical)	Diffuse wear	
	Oxidation corrosion	- Direct oxidation corrosion - Vibration corrosion (fretting)
	Electrolytic corrosion (rust)	
	Reducing corrosion	- Corrosion of weak acids - Corrosion of strong acids - Corrosion S-P-Cl
Thermal wear	High thermal erosion wear Plastic flow of materials	
Biological wear		

WEAR, LUBRICATION AND OPPORTUNITIES OF REDUCING DAMAGE DUE TO WEAR

Basic tribological models include different types of intensity and wear /3/, caused by application of lubricants with influence to compounded problems (a complex consideration focused in finding opportunities to reduce material damage of surfaces).

Crack nucleation and propagation

It is evident that the first tiny cracks occur on the surface or just below it. Most often it is in places of different irregularities in the crystal structure of materials and intergranular bonds (dislocation). Micro and macro unevenness (result of mechanical or thermal surface treatment) will be also conductive to the formation of primary cracks due to local stress concentrations which create preconditions for the continual progress of this type of damage. Primary cracks are extended obliquely at an angle relative to the surface in the direction of deformation, caused by shear stress (i.e. it creates a new form; distortion).

In the case of the gear tooth, these are the slopes from the centre line to the root and top of the drive gear, and obliquely in the direction of the centre line of the driven gear /3/. The cracks and dislocations in the crystal lattice create a place of concentration for new alternating stresses in the material, which leads to plastic deformation of the surface cracks as well as their branched propagation and spreading, /3/.

The spread of cracks, especially the chipping and removal of isolated pieces of material, contributes to the lubricant (pressure in the lubricant).

Pitting appears as an initial surface defect in process, and particularly is evident in skating in the direction opposite to the rolling surface (a common occurrence in the running of the gears, especially if they are made of unhardened steel). If it continues with the formation of new craters, then adapting surfaces come into contact, as offset micro unevenness. All this leads to the complete elimination of local overload, and thus to the disappearance of pitting. The resulting damage to the surface will be soon levelled due to normal wear surfaces or plastic flow of material surfaces.

Pitting as a process goes with the formation of new craters and expanding existing ones, which leads to progressive and destructive pitting with severe disabilities of the surface (thus leads to the weakening of the material between adjacent holes and their separation from the surface in the form of chipboard-spalling).

The process, as a rule, is combined with more or less abrasive wear surfaces. In the cases of severe shock loads, the cracks are expanding at depth, encompassing broad areas of the material, which results with the fracture of the element (the most severe form of failure). The occurrence of pitting, for example in gears, depends largely on:
- type of material,
- material structure,
- mechanical properties (hardness),
- the method of surface treatment (mechanical, thermal or chemical treatment).

Progressive pitting occurs more often in dynamic conditions with a higher level of load and greater frequency of load change, and generally speaking, working conditions. So, it is about:
- higher load and more levels of variable loads,
- increased stresses in the material,
- higher revs,
- higher frequency cycle load changes,
- higher sliding speeds,
- higher thermal stresses in the material.

Pitting is a more common problem in the drive gear (heavier forms at root surfaces of teeth). Initial pitting can therefore be significantly reduced by adjusting the coupling and accurate production of gears. When we have progressive pitting, the hole is constantly growing, so the effective surface of contact decreases (some of the sockets-holes, at the same time, are increasing). In doing so, contact stresses grow and reach critical value with plastic deformation and intensive wear. Pitting most often occurs in cylindrical gears with genuine and obliquely gear teeth, on the tooth surface, but on helical teeth (conical teeth) it is less frequent due to different conditions of sliding on the tooth surface. Pitting does not occur in open systems (notebooks, conveyors) which work without lubricants or are lubricated by consistent grease, /3/.

TYPES OF DAMAGE (WEAR, EROSION, CORROSION)

Fluid erosion

Erosive wear and fluid erosion refer to the flow of lubricating fluid with high relative speed with respect to the solid surface in contact. It can induce a certain kinetic effect of estrangement material of contact surfaces. Figures in the content of this work are given according to /2, 3/.

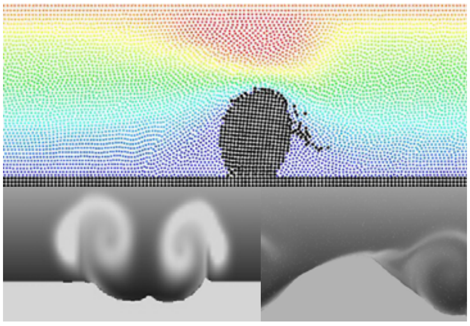


Figure 1. Fluid erosion.

In fact, erosion wear is the result of influence of very small solid particles (and sub-micro sizes) suspended in the lubricating fluid. These are very small particles suspended in oil (sizes below 5 μm are difficult to remove; there are particles below 1 μm that cannot be practically removed by conventional technical means for purifying lubricating fluid). This is important to note because it is difficult to set a clear border line between abrasive and erosive wear, /2/.

Impact erosion

This type of erosion is a special type of abrasive wear with the destruction of the surface due to repeated impact of solid particles on the surface (the material is removed from the surface according to the kinetic effect of particles in motion). It is evident, the impactors of the erosion can be dust or sand from collisions at high speed on the surface of solid objects (blades and casing of pumps, blowers and valves in hydraulic and pneumatic installations, etc.). The corresponding data regarding the relative speed of particles, particle size and angle of attack to the surface, precisely define the kinetic energy of the erosive power and intensity of the corresponding damage.

Erosivity increases with increased content of quartz in natural materials and appropriate size and shape of striking particles. Sharp edges of particles cause more wear than round edges, with the inclination angle of attack defined between the surface of the object and trajectory of the impacting particle. The influence of the angle of impact depends on the type of material. Elastic and soft materials suffer the greatest damage at angles of 20° to 30°, while brittle materials suffer at a right angle, /2/.

Brittle material with particle impact causes cracks in the form of shells with bright trace in the surface at the point of impact. For elastic materials, surface defects are maximal at low angles of impact. Damage created by separating the material from the surface is similar to the cutting process.

Material of the attacked surface is the most important factor influencing the reduced damage of surface erosion.

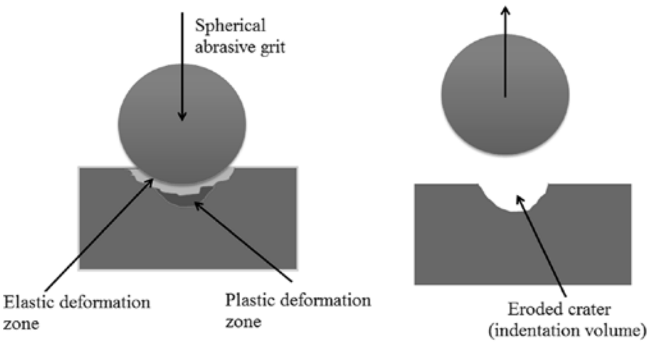
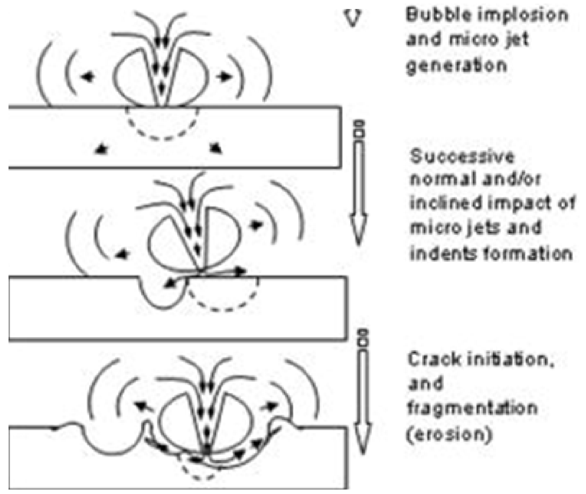


Figure 2. Impact erosion.

Cavitation erosion

Cavitation erosion occurs if steam or other gas bubbles appear in the liquid flow of lubricant when the pressure in the liquid falls below the pressure of liquid vapour at operating temperature. When the liquid streams back into the area of high pressure, the breaking of bubbles is logical (bubble collapse). For emerging steam or gas bubbles in the fluid (this is not about bubbles of air dissolved in oil) it is needed to spend considerable energy for bubbles to collapse when the energy is released in the form of a hydraulic wave /2/. The collapse of gas bubbles occurs gradually, without a sharp shock, and normally does not damage the surface, but may possibly only reduce the payload. The collapse of vapour cavitation performance with a rapid and sharp blast is locally concentrated with high frequency, which leads to fatigue of the surface material and surface damage.



Source: A. Sahaya Grinspan and R. Gnanamoorthy: *J Fluids Eng* 131(6) (May, 2009)

Figure 3. Principle of cavitation erosion.

In addition, local sudden increase of pressure leads to significant increase in local temperature, which helps to accelerate certain chemical reactions. Lubricated by water, emulsions or suspensions, or rather, the presence of water as a contaminant in the lubrication system, contributes to significant accompanying chemical reactions and can be very conspicuous.

Mechanical impacts caused by cavitation remove a significant oxide layer, thereby facilitating further chemical processes in depth. Due to a combination of mechanical and chemical effects, some authors call this type of erosion - cavitation erosion, /2/.

Cavitation is most common in diesel engines with low and medium speeds. Cavitation surface wear depends on the hardness of the material. Cavitation wear rarely extends into the depth of the material.

The occurrence of cavitation depends on the vapour pressure of lubricating fluid, of course, at conditions of high temperature and a significant vacuum in places where it occurs, as a rule the local lubricant layer, /2/. Cavitation wear must be avoided to the maximum extent possible, so that it sometimes can be largely eliminated by using lubricants of higher viscosity.

Occurrence of cavitation wear can be regarded as a first problem of design which needs to be solved by:
– reducing the clearance between the sleeve and bearings,
– increasing oil pressure in the circulation.

It is obvious that reducing the clearance decreases to a certain limit, the radial movement of the sleeve in the bearing and during increased oil pressure it reduces possibilities of the appearance of cavitation bubbles. One of the options for reducing cavitation wear is use of harder materials for bearings applications.

Damage due to fatigue

Fatigue is one of the most important mechanisms to be analysed in order to prevent loss of mechanical properties of materials and structural damage. In this sense, it can be noted that lubricants have a beneficial effect on reducing damage to the surface by fatigue and increasing the lifetime of mechanisms (e.g. rolling mechanism). A layer of lubricant amortizes the impact of variable loads and reduces other types of surface wear, primarily reducing the possibility of initial surface cracks.

Corrosion acids

Acids (particularly strong acids) and acidic compounds are very aggressive towards metals and other materials in a variety of structural systems. Acids can come from the environment or from the technological process. A special type of corrosion of this type occurs in the internal combustion engine (IC) in which aggressive substances originating from the fuel combustion process exist. In the process sulphur burns to SO_2 and SO_3 in a small part of the combustion chamber, reaching to the area of piston rings, and partly in the form of a solution in the oil and lubricating system. Sulphur oxides with condensed water from combustion products, for example, result in sulphurous acid and very aggressive sulphuric acid.

It is known that the cylinder liner, piston rings and valve seats, as well as other parts of the engine-specific bearings are mostly exposed to acid caused corrosion.

In the case of large low-speed engines with heavy diesel fuel with greatest danger from this type of corrosion, the oil will be added with special very alkaline and dissolved supplements. For high-speed diesel engines and Otto engines, this improvement contains detergent additives with excess alkalinity. Reducing this type of wear is a major problem of metallurgical and structural nature.

Resistance of steel toward corrosion by strong acids depends on their composition and TMP treatment (very beneficial effect of phosphorus addition). Coating of metal resistant to corrosion, especially chrome, gives excellent results in terms of the respective resistance.

Thermal wear

Here is a group of processes of wear and destruction of surfaces at extremely high temperatures (reactors, furnaces of all kinds). There are very complex processes of oxidation and conversion of structure, which have resulted in the erosion surfaces and plastic flow.

Biological wear

Under the biological decomposition, any undesirable change in properties or quantity of material under the activities of bacteria and living organisms is meant, or indirectly with its dead weight and metabolism products, /2/. In the area of cooling and lubricating systems, an aqueous emulsion, oil or aqueous suspensions of solid lubricants are highly susceptible to the effects of many bacteria and fungi. The fact is not only a reflection in the degradation of such lubricants and danger to the health of workers, but also the possibilities of substantial corrosion of metal in contact with polluted and degraded fluids.

Certain bacteria (thiobacillus) act oxidative to some sulphur compounds, which leads to the presence of a highly corrosive acid, as in case of the devices in coal mines and iron (pyrite), according to /2/. Against such corrosion usually in mechanical devices and their systems of lubrication and cooling, a successful solution can be by adding effective bactericides and fungicides in an appropriate system.

Important terms of tribological vocabulary, /1/

For an easy understanding of these considerations, some of the terms and definitions that more closely determine and support the analysed models are indicated. Abrasive wear /1, p.5/, for example, is defined as a result of the application of lean lubrication or contaminated lubricants (from ore flotation containing Si or B). Further are given the following complementary terms and definitions.

Abrasives. Crystal granular materials with high hardness and prismatic shape, able to carry-out cutting other materials;

Abrasive particles. Hard particles in zones of solid bodies contact are causing wear of contact surfaces leaving clues as burrs, nicks and fissures.

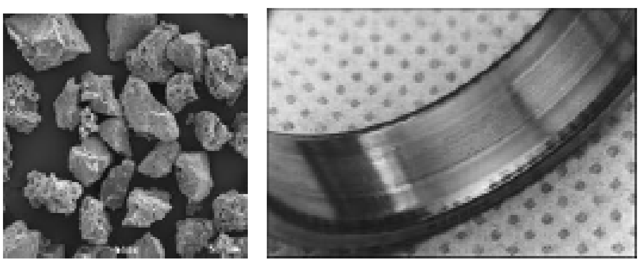


Figure 4. (a) Hard particles; (b) traces of wear of hard particles.

Abrasive wear. Type of wear that occurs when hard particles or hard tops move on the surface of solids.

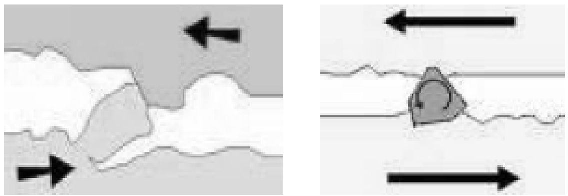


Figure 5. The process of abrasive wear.

Abrasion corrosion. A synergistic process in which abrasive wear and corrosion due to their mutual influence are rapidly developing.

Abrasively. The ability of materials or substances to cause abrasion resistance (ASTM).

Abrasive tribometer. Device for measuring the resistance of a material to abrasive wear.

Adhesive wear /1, p.7/. Wear that occurs due to the termination of friction connections in the contact zone of solids and transfer material from one area to another and the environment.

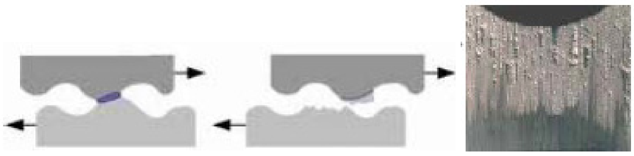


Figure 6. Process of adhesive wear and consequences on contact surfaces.

Factor wear (wear factor). The relationship between the intensity of wear and pressure in the contact zone (zone of the normal load):

$$k = \frac{I_h}{p} \left[\frac{\text{m}^2}{\text{N}}\right],$$

where: I_h - intensity of wear measured by volume of worn material per meter of slide; p - pressure in the contact zone in N/m^2.

FEA-Failure Effects Analysis (Analysis of consequences of failure). It is used in analysing consequences of failure in mechanical systems /1, p.33/.

Abrasive wear

Abrasive wear involves processes related to the terms: interference, cutting and grooving /2/. It is a predominantly permanent plastic deformation of the surface (i.e. the material on the surface or just below it). Abrasive wear is the loss of material from the surface in contact with the relative motion relating to:

– interference of harder surface with roughness on the surface of the softer material, or
– action of particles of different origin on different surfaces or between these surfaces.

Abrasive wear together with adhesive wear represents a basic form of mechanical wear in machines and equipment /2/. Abrasive wear, i.e. occurs in gear drives and is the characteristic of open mechanisms, although to a lesser extent, it occurs in closed mechanisms. Abrasive wear in bearings represents a specific type of tear. IC engines have also expressed abrasive wear, since large amounts of air are sucked in directly from the atmosphere in the work process, or combustion. Contaminants are hard particles of atmospheric origin (the dominant component is SiO_2). Frequent contaminants in oxides are K, Mg, Fe, Al, C, etc.

Particle sizes of atmospheric impurities vary within wide limits from 0.1-1 μm (smoke particles) and 1-150 microns (grains of sand), atmospheric dust, where grain size and distribution of grain impurities in atmospheric dust vary similarly to the composition of atmospheric dust /2, p.174/.

In the case of hydrostatic or hydrodynamic lubrication, the layer thickness of lubricant (oil film thickness is within the limits permitted or defined) permits particles of foreign matter in the fluid to pass freely through gaps of elements which may cause only minor damage to the surface.

For all cases, it is necessary to perform specific analysis of the intensity of abrasive wear, depending on the ratio of hardness of abrasive bodies or particles (abrasives) and the hardness of the material surface on which the abrasive works, /1/.

WEAR AND DAMAGE OF SURFACE CAUSED BY FATIGUE

A broader context of respecting models and mechanisms of fatigue is needed to understand adhesive and abrasive wear of surface materials in contact with the corresponding relative motion. Fatigue and its consequences today are usually the main causes and life limits of technical structures, machinery, equipment and systems, their parts or elements, which more intensively lose their performance rather than machines, and they are being replaced with new parts or even sets, so revitalized machines continue to operate normally with sustainable performance; these are interchangeable parts and spare parts. For loaded contact surfaces it is important to examine the conditions in which the contact is achieved, as well as lubrication conditions. In such contacts, as is known, the stress in the material appears as: pressure or stretching; shear.

Due to possible complex effects (with aforementioned and other facts as heat) the material is exposed to complex stresses at the level of the structure where the intensity and direction of stress is not always possible to determine. All loads are below limits of material resistance with the appropriate safety factor or according to the strength and stiffness (safety factor is basically of random quantity).

For very variable cyclic loads after a specified number of cycles damage is also possible, or complete failure occurs (fatigue). The phenomena of fatigue, related wear and material damage of machine elements can be very complex.

The micromechanical character of damage is deeply related to the molecular structure of the material itself, representing not quite researched material properties. Basically, only external manifestations of these phenomena and their external causes are known closer. Cyclic changes in stresses in the material are a precondition for the occurrence of fatigue. Fatigue does not occur in sleeve bearings or other mechanical components with relatively few permanent or variable loading (bearings in rotating machines), except in cases where parts are exposed to severe vibration of high frequency.

Fatigue usually appears in the case of sliding bearing piston machine (especially for internal combustion engines, crusher machine, punching machine etc.). Fatigue is common here. Damage due to surface fatigue usually occurs in the upper layer. Damage in the depth of structure is also possible with the breaking off of significant material parts.

Fatigue wear

Fatigue wear refers to the mechanism of wear that occurs during load and load shedding of the surface layer of structural elements /1, p.110/.

Fatigue cracks in the surface layer of structure (Fig. 7) are formed according to /3/ as a result of:
(a) tensile stress on the back side of contact,
(b) tangential stress,
(c) initial stages of delamination elongation voids in the surface layer and their combination.

The zone of structure in which there are solutions with stress concentration and favouring of the occurrence of fatigue should therefore be avoided.

It is evident that materials may have a certain level of stress (static) or are burdened with low frequency loading and unloading, but at high frequency the load changes to a completely different condition and level of stress (much lower stress level according to fatigue strength, defined as required in accordance with the number of cycles), see /5, 6/.

The occurrence of fatigue is affected by the intensity and type of stress or considerably more influenced by time of loading and the range of varying loads (difference between maximal and minimal stress) the structure is exposed to.

Definition of changing stresses and fatigue strength of the structure (material) are contained in the S-N diagram (Wöhler curve).

For example, in ship structures the fatigue /5/ is due to:
– influence of waves, particularly ship bending by waves (for 20 years life operation of ships, it is estimated that the number of cycles is 10^8);
– changing the state of cargo (ballast, full boat, etc.);
– operating influence of mechanical facilities, such as engine, drive or screw.

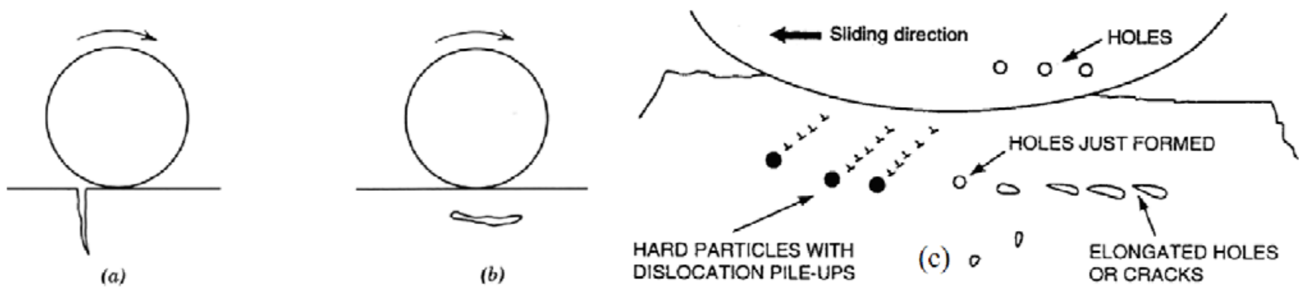


Figure 7. Fatigue cracks in the surface layer of structure.

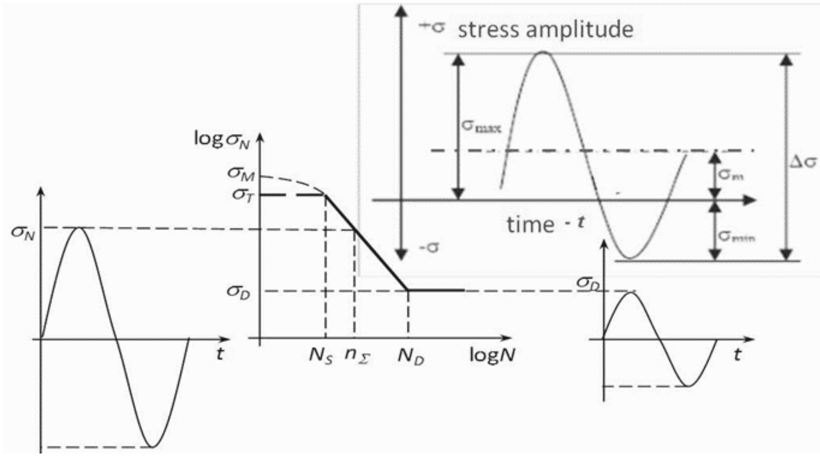


Figure 8. Definition of stress variables (fatigue strength).

Preventing damage due to fatigue is usually a problem that can be solved at the local level of ship structures. Fractures due to fatigue are prevented by reducing the amplitude of the stress, optimal design and dimensioning with rational solutions that reduce stress concentration. Increase in size only is not always suitable to achieve a higher level of safety. Stress by bending moments from waves is proportional to the hull moment of resistance and slightly depend on the local elements of the structure.

Fatigue loads at significantly frequency can be prevented by keeping stress below the fatigue limit. A typical welded joints of ship structures has a fatigue limit below 50 N/mm^2. Therefore, it should provide solutions to achieve sufficiently low working stresses to avoid fatigue in any part of the primary structure.

For continuous variable stress amplitude $\Delta\sigma$, number of cycles is obtained by experiments as a determined number of cycles to failure N (life-time of detail) for each type of ship structural element which undergoes fatigue /5/. Results are typically shown in S-N diagrams (Wöhler curve), generally at the level of a logarithmic scale as a function:

$$(\Delta\sigma)^m N = C$$

where: m and C - constants that determine the gradient (slope) and curve step.

Analysis of fatigue life is calculated taking into account the following stresses: σ_n nominal stress; σ_k critical stress; σ_s hot-spot stress.

Hot-spot stress occurs in structures with exposed fatigue at the focal point where cracks can occur. This stress includes stress concentration due to structural discontinuities and the presence of addition parts (welded or riveted joints). Stresses at the focal point are local stresses with average values in the local zone close to the source (e.g. welded joint) and can be considered as ‘nominal’ levels of stress in the location of welded structures.

Design based on fatigue /6, 9, 12/

The central issue regarding the determination of the fatigue threshold (critical number of cycles and subcritical crack propagation) is just as important as the issue of fatigue. In calculating fatigue, two cases are important:

– fatigue with a small number of cycles (< 10000 cycles, fatigue is caused by plastic deformation), and
– fatigue with large number of cycles (plastic deformations can occur in a small zone around the crack tip).

In both cases the solutions are defined based on empirical - phenomenological nature and on the analysis of numerous carefully designed experiments.

Regarding the first case, according to the Coffin-Manson law, in accordance with /9/:

$$\sigma_a = \sigma_u N^e + \frac{1}{2} E \varepsilon_f N^{-b}$$

where: $2\sigma_a = \sigma_{\max} - \sigma_{\min}$ (alternate stress); σ_u - tensile strength; ε_f - fracture strain in the direction of the load; N- number of cycles when fatigue cracks occur; c, b - material constants that depend on temperature, grain size, initial size of defects (surface treatment); for metals, the constants usually are $c = -0.008$, and $b = 0.5$.

In another case the fatigue fracture in an appropriate manner depends on the stress intensity factor, /9/. From the experiments, it has been found that crack growth in each cycle does not depend just on crack length.

Fatigue is a phenomenon that can cause microcracks and their subcritical growth while at one point fracture occurs. The number of cycles - N_f at which fracture occurs can be calculated, /9/, from:

$$N_f = \frac{2}{(m-2) C C_1^m \Delta\sigma^m} \left(a_0^{-\frac{m-2}{m}} - a_{cr}^{-\frac{m-2}{m}} \right); \quad m = 2$$

where: a_0, a_{cr} - initial and critical rate of the crack at $\sigma = \sigma_{\max}$; C, m - material constants (sometimes differ by type of experiment).

Based on the above, it is possible to establish equivalence from which it is seen that the number of cycles to failure (N_f) is equal to the sum of the number of cycles required for the formation of cracks (N_o) and the number of cycles required for the formed cracks to extend to critical size (N_c):

$$N_f = N_0 + N_c\,.$$

Fatigue usually comes from surface defects (close to the defects, stress state is flat). In such cases, $N_0 = 0$, $N_c = N_f$.

According to American standards AISC (Appendix B), the structural analysis of elements exposed to fatigue is defined, /9/, which uses the reference value of strength parameters for the load case with the number of cycle categories of loading and other parameters.

For brittle materials, it often leads to fracture if the material is subjected to static loading after a long period of time, whereby the refraction is a result of chemical reactions within the aggressive environment, moisture or other influence, or from a cause that leads to a reduction in surface energy of the body. The problem of calculation impact of aggressive environment on the extension of cracks is solved by introducing the stress intensity factor - K_{Ic}, that has to be treated as a constant in material/environment systems. Reducing toughness depends on the adsorbed chemical substance is a function of the concentration and period of time in which the crack is exposed to aggressive fluid. Relevant data, regarding the factors as K_{Ic} for certain materials, type of fluid and exposure time for material/fluid impact can be seen in /9/.

These data are extremely important in the selection of materials for structures operating in salty environments. Fatigue can also occur due to temperature changes (principally different in the field of low and high temperature). At low temperatures, materials retain a relatively stable composition and structure (increasing service life) and at high temperatures at different phase transformations (aging, creep and recrystallization), as a rule, there is a decrease of tensile strength and fatigue strength.

Those aspects of crack propagation, due to cyclic loading and environmental impact to materials, are intended to highlight the significance of fatigue in the design. Safety factors need to be significantly increased in order to avoid unintended consequences for structures in analysed operating conditions, as specified in various complex problems of stochastic nature, with no adequate general verification (experimental) database.

The consequences of fatigue wear

The type and wear mechanisms cause the consequences that arise in the areas of contact element tribosystems, i.e. represented effects of fatigue under variable dynamic loads over a longer period. As a result of fatigue wear, separation of large particles (flakes) can occur, with a diameter 1 to 2 mm (pitting), followed by rapid destruction of the surface (Fig. 9a), /3/. If sliding on the surface goes with triaxial pressure, cracks come out only after their previous extension parallel to the surface, so that they create larger delaminated surfaces (Fig. 9b), according to /3/. Two types of wear are usually encountered, although both are wear fatigue:
(a) abrasion due to rolling - tedious (fatigue) wear;
(b) sliding wear - delamination wear.

The consequence of fatigue damage reflects in the material surface and directly below it, with the break off of bits (small parts) of material from the surface, creating a characteristic relief in the form of small or large holes - pitting (pit-hole), Fig. 10.

For new gears, the pitting occurs as running or initial pitting (a phenomenon that eventually reduces and disappears), according to /3/. It is a very dangerous, destructive or progressive pitting, where the process can rapidly advance to the final cancellation of the refractive element.

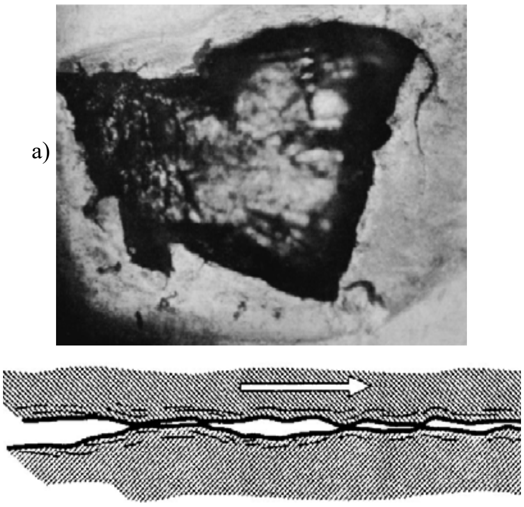


Figure 9. a) Fatigue fracture of steel balls (pitting); b) delamination wear: type of fatigue wear at slipping where cracks that spread a larger delaminated surface parallel to the created surface.

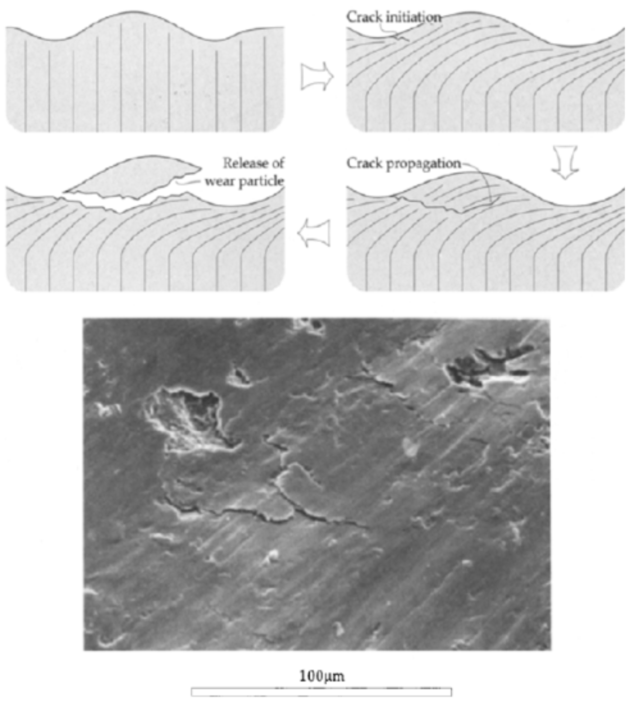


Figure 10. Schematic representation of the fatigue wear mechanism and example of cast iron surface damage due to fatigue wear.

Extremely high cyclic stress exists in:
(a) materials of roller bearings (for balls or rollers and especially in the outer and inner rings);
(b) materials of teeth of various gears;
(c) material in camshafts and tappets of internal combustion engines;
(d) other elements of machines.

The necessity for different views and creating suitable models for new designs exist. In this work, a contribution with the wider view as precisely focused in terms of understanding the problems and consequences according to the necessities for appropriate research, design and measures considering problems with different materials. Significant contribution to the overall performances of structures and technical assets (containing lubricants and oils in installations) and high performance tribology systems (that may have a high expenses and damage of the environment) need to be treated with due care.

Presented considerations should contribute to the improvement of system development for establishing programs and gaining solutions (research and innovation projects with applications for real future benefit).

This paper gives referenced useful ideas and examples from practice based on these claims. Also is given an expansion of database with objective and reliable content directed to researchers in order to accept the subject matter, researching parameters and feasible optimisation with different objective functions (processes, technologies, materials, stress, deformation, energy, economy, etc).

Analysis of parameters in these models (regarding the configuration and material characteristics of the structure, as well as in joints and loads) shows that for these elements one cannot always expect the creation of the elasto-hydrodynamic layer of thicker lubricant and thus one needs to calculate with considerable forces of sliding friction or rolling, and considerable normal and shear stress in materials, with maximum tension just below the point of contact. Hence, surface fatigue in materials often appears.

CONCLUSION

Many works have treated the problems of structural integrity and life /7-10/ and fracture mechanics and micromechanics of different materials and structures exposed to variable loading and stress. There are many examples of analyses of real structures in fatigue /9, 11, 12/. Many authors believe that this approach to the issue of fatigue and structures could be of benefit to researchers as an integrated design-technological-exploitation basis for further research. Without tribological dimensions and the presence of oil and lubricants in technical systems it is not possible to analyse all types of impacts on structural material degradation and corresponding real structures that work in real dynamic conditions when required to execute lubrication (in more cases, oils and lubricants; in a number of cases, lubrication between structural materials in tribology conjunction).

Hence the problem becomes more complex than what can be treated by basic mechanics or theory of elasticity and plasticity. Now it is necessary to access and correct the conception of the lubricating system and rational environmental protection at resolving problems brought by the use of oils and lubricants in technical systems and machines.

Future work can be directed to performing calculations and analysis of integrity and life of real structures whose initial material/structure degradation sets new conditions to different materials of basic structural elements coupled in real terms (conditions dictated by humidity, temperature, salty atmospheres, gases and impurities).

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