# ANALYSIS OF DIRECT AND BACK EFFECTS UNDER WEAR-FATIGUE DAMAGES

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## ABSTRACT

The main results of the investigation of effect of friction and wear processes upon the changing of fatigue resistance characteristics and effect of cyclic stresses upon intensification of wear are described. The analysis of the diagram of limiting states of load-bearing systems for which wear-fatigue damage is typical in operative conditions is given.

## KEYWORDS

Direct effect, back effect, life, stress intensity factor, fatigue limit, fretting fatigue, contact - mechanical fatigue, friction-mechanical fatigue, wear-fatigue damage, load-bearing system.

## INTRODUCTION

From available information more than 80-90% of failures in operation of modern machinery is due to inadmissible wear or fatigue damage of constructive elements. It is natural that tribology and mechanics of fatigue damage have been developing rapidly for the last thirty years.

In the second half of eighties it has been realized that in actual operative conditions both damaging phenomena - wear and fatigue - frequently develop together and in interaction. It gave an idea of complex-wear-fatigue damage of units termed as load-bearing systems. The typical examples of such systems are crankpin-connecting rod end with sliding bearing, wheel-rail, slined shaft-shaft-clutch, tooth gears, etc.

During the last five - seven years the methodological and theoretical fundamentals of tribo-fatigue (Fig. 1) - the science and technology of complex assesment and increasing reliability of nload-bearing systems based on the criteria of resistance to fatigue, erosion and wear strength have been worked out. (Sosnovskiy, 1986; Sosnovskiy, 1989; Sosnovskiy and Makhutov, 1991).

As a rasult of theoretical and experimental studies two effects have been determined which conditionally were termed direct and back effects. The influence of factors related to friction and wear processes on fatigue (mechanical) resistance of load-bearing system elements is termed direct effect. The effect of recurrent alternating stresses (under the conditions of tension - compression, bending, torsion or combined loading) on changing the wear processes of load-bearing system is termed back effect.

A brief analysis of both effects during fretting fatigue (FF), friction-mechanical fatigue (FMF) and contact-mechanical fatigue (CMF) is given below.

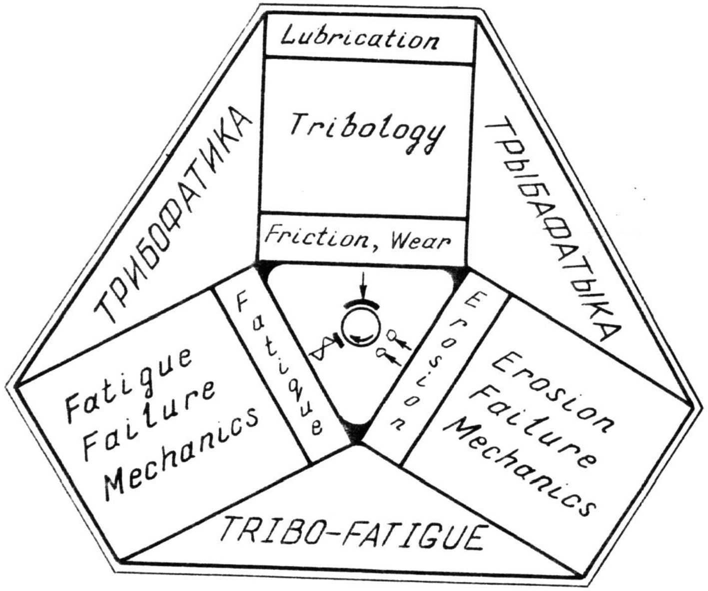


Fig. 1

## DIRECT EFFECT

Generalizing the well-known data the effect of contact pressure on the relative life of specimens $N_\sigma(q) / N_\sigma$ can be described in the way it is shown in Fig.2.

The service life during wear-fatigue tests $N_\sigma(q)$ can either be increased or decreased compared with life $N_\sigma$ during conventional fatigue (F). It depends on the value q and test conditions. Thus, during FF the life is always less than that during F. The increasing of the life during FMF as against that during F is observed only in the narrow range of the changing q while during CMF this range is rather wide. It is not difficult to explain the shape of the curves shown in Fig.2 due to the corresponding action of the processes of strain hardening-loosing of materials relative to test conditions.

According to the experimental data (Draygor and Valchuk, 1962) the increase of the life $N_\sigma(q)$ as compared with the life $N_\sigma$ may be achieved as much as 10 times depending on the value of q during CMF. The decrease of $N_\sigma(q)$ during FF compared with $N_\sigma$ may make up as much as 10 - 100 times and even more (Filimonov and Balatsky, 1973).



Up to the present time a number of works are known in which the theoretical analysis of direct effect is given. Thus, during FMF of the metal-to-polymer load-bearing system the life service $t_\sigma(q)$ expressed in time units can be calculated by a formula (Sosnovskiy and Makhutov, 1991).

$$t_\sigma(q) = [(U_0 / R_T^M) - a_T T_\Sigma] / [a_\sigma \sigma_a^{m+2} (1+K_W) R_\sigma^\tau / C_f b_f],$$

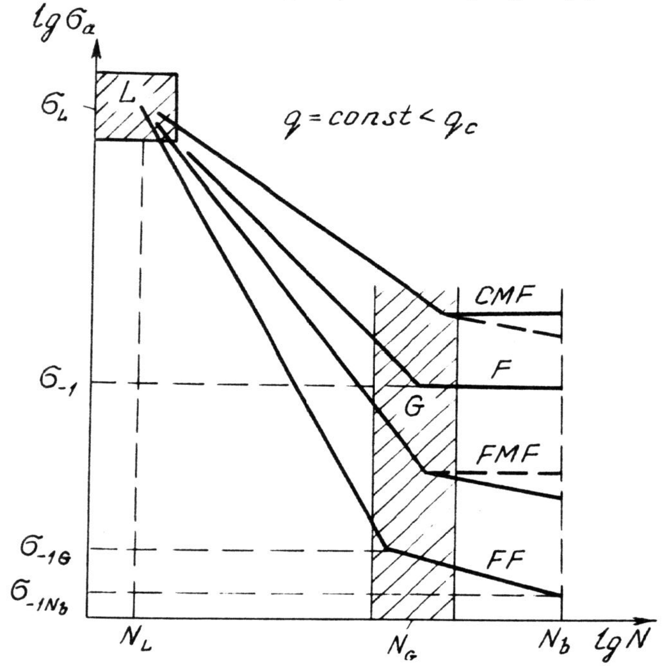


Fig.2

where $\sigma_a$ - stress cycle amplitude; $R_T^M$, $R_\sigma^\tau$, $C_f$, $b_f$, $a_\sigma$, $a_T$, m - parameters and coefficients, $U_0$- energy of rupture of interatomic binding, $T_\Sigma$ - temperature in the zone of contact caused by all the sources of heat, the coefficient $K_W$ is the function of main parameters describing the condition of friction and contact interaction of the elements of the system. Since $(1+K_W) > 1$, then the damaging effect of friction without lubrication is foreseen with the help of this formula.

The methods of failure mechanics are used to calculate the longevity or fatigue limit during FF (Dekhovich and Makhutov, 1984; Troshchenko, Tsybanev and Khotsjanovsky, 1988). In the latter work the process of FF is considered to be two-staged (Fig. 3).

For any position of the crack end in relation to normal Q and tangential F of loads the values of stress intensity factors $K_I$ and $K_{II}$ are calculated using the formula in the work (Rooke and Jones, 1979). In stage I the crack growth is controlled by means of tangential maximum stress intensity factor

$$K_{\tau max} = (\tau_{r\Theta})_{max} (2\pi r)^{1/2},$$

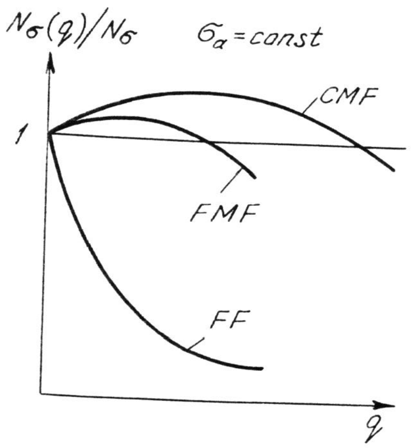


Fig.3

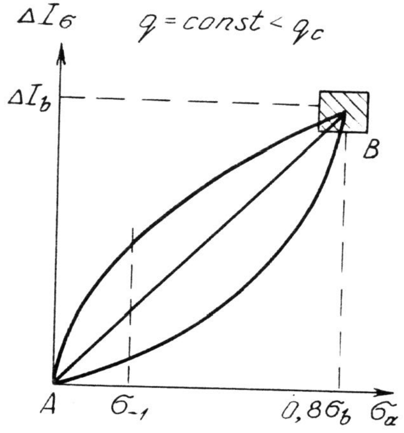


Fig.4

where $(\tau_{r\Theta})_{max}$ - maximum value of tangential stress determined as an extreme value of function $\tau_{r\Theta} = f(\Theta)$ known in the failure mechanics (Panasyuk, 1968) written in polar coordinates r, Θ.

The current value of crack angle Θ of inclination is determined with the help of the method of consecutive approximations from formula

$$tg(\Theta/2)\,[1+6/(1-2tg^2(\Theta/2))] = K_{II}/K_I,$$

which is obtained from the condition of maximum $K_\tau$.

The condition of crack growth during stage I is $K_\tau > K_{IIth}$, while $K_{IIth} = K_{Ith}/(3)^{1/2}$ (obtained using Mises' criterion).

Stage II of crack growth is governed by the maximum tensile stress intensity factor (Rooke and Jones, 1979; Otsuka, Mori and Miyata, 1983)

$$K_\sigma = \sigma_\Theta\,(2\pi r)^{1/2}.$$

Transition from stage I to stage II (see Fig. 3) takes place under condition that $K_\sigma > K_{Ith} = K_{th}$.

In case the value of $K_\tau$ reduces to its limit value $K_{th}/(3)^{1/2}$ while at this moment the value of $K_\sigma$ does not reach its limit value $K_{th}$ then the crack is non-growing. From this condition that the crack does not grow the fatigue limit during FF can be estimated (Edwards, 1981).

The current stressed condition in crack tip is determined by sum values $K_I$ and $K_{II}$ which are calculated for the tensile semicycle:

$$K_I^t = K_{I\sigma} + K_{IF} - K_{IQ},$$

$$K_{II}^t = -K_{II\sigma} - K_{IIF} + K_{IIQ}.$$

and for the compression semicycle



$$K_I^c = -K_{I\sigma} - K_{IF} - K_{IQ},$$

$$K_{II}^c = -K_{II\sigma} - K_{IIF} + K_{IIQ}.$$

The rate of crack growth is determined with the help of formula

$$dl/dn = C\{[(1-R)^{n_1}\Delta K]^{n_2} - \Delta K_{tho}{}^{n_2}\},$$

where $K_{tho}$ - the range of limit value of stress intensity factor at the stress ratio R = 0; C, $n_1$, $n_2$ - parameters determined experimentally.

Elastoplastic value of the range of stress intensity factor in order to use it in equation (4) is calculated with the help of formula (Tanaka, Mitoh, Sacoda and others, 1985)

$$\Delta K_p = \Delta K g^{0.5},$$

where the value ΔK is obtained during elastic solution and plasticity function

$$g = \begin{cases} 1 + 0.5(1-b)/(1+b) + g_1 E\varepsilon_p/\sigma_a, & \sigma_a \geq \sigma_*, \\ 1 + 0.5[(1-b)/(1+b)]\,(\sigma_a/\sigma_*)^2 + g_1 E\varepsilon_p/\sigma_a, & \sigma_a < \sigma_* \end{cases}$$

$$g_1 = b + 3.82\,(1-b)/(\pi(b)^{1/2}),$$

where E - Young's modulus, $\sigma_a$ - stress amplitude, $\sigma_*$ - cyclic yield point determined as stress level during non-elastic cyclic deformation $\varepsilon_p = 0.002$, b - degree indicator in the material cyclic hardening law

$$\sigma_a = \sigma_*\,(\varepsilon_p/0.002)^b.$$

The longevity is calculated with the help of a computer.

During stage II of the main crack growth fatigue life can be calculated with the help of the formula (Sosnovskiy, 1987).

$$N_{II} = (1-\omega_F)/[C_k(m_k+1)\Delta K_\omega{}^{m_k}],$$

where $\Delta K_\omega = \Delta K_I/(1-\omega_F)$; $\omega_F = A_1/A_0$ - initial damage extent by the crack (during stage I), $A_1$ -area of the specimen; $m_k$, $C_k$ - parameters, $A_o$ - cross sectional area of the specimen.

## BACK EFFECT

Generalizing the known experimental data one can state that the increment of wear rate $\Delta I_\sigma$ of elements of load-bearing system under the effect of the stress amplitude growth $\sigma_a$ reaches 200% (Sosnovskiy, 1986; Nosovsky, Tsybanev and Belas, 1990). Depending on the experimental conditions and nature of materials from which elements of load-bearing system are manufactured the change of $\Delta I_\sigma$ from $\sigma_a$ can be expressed with the help of the curves which are schematically shown on Fig.4. It may be, firstly, linear (direct line AB) or non-linear (curve AB). Secondly, the increment $\Delta I_\sigma$ can be accelerated (upper curve) or slowed down (lower curve). It is analogous to the accumulation of fatigue damage under random loading: its laws are connected with the metal behaviour under cyclic loading (Sosnovskiy, 1987)

Up to the present time some equations describing back effect have been obtained. Thus, during FMF of the metal-to-polymer system the formula is obtained when $q = const$ (Sosnovskiy, 1986)

$$I_\sigma = I / \{1-(b_V V_{0.5\gamma} / V_o)[(T_M / T_o)^{m_T}((\sigma_a - \sigma_{-1min}) / \sigma_W)]^{m_V}\},$$

where I - intensity of wear of the unit element during friction without cyclic loading ($\sigma_a = 0$); $b_V$, $m_T$, $m_V$, $\sigma_W$, $\sigma_{-1min}$ - parameters; $T_m / T_o$ - relative temperature of metal in the contact zone, $V_{0.5\gamma} / V_o$ - relative dangerous volume of the deformed element during the cycle. According to this formula during dry sliding friction $I_\sigma > I$.

During FF of the metal-to-polymer system the wear parameter $W_n$ is proportional to the slip amplitude $\alpha(\sigma_a)$ which depends on $\sigma_a$

$$W_n = n^k Q\,[((K_o / (F)^{1/2})\, f_d^{1/2} - K_1)(1 / \nu_\sigma) + K_2\, \alpha(\sigma_a)],$$

where n - number of loading cycles, Q and F - normal and tangential of loading in the zone of contact, $f_d$ - dynamic coefficient of friction, $\nu_\sigma$ - frequency, K, $K_o$, $K_1$, $K_2$ - coefficients. This formula is drawn by means of the modification of the known equation (Uhlig, 1954) to calculate the volume of the worn material during fretting corrosion.

## LIMITING STATES

The diagram of the limiting states of load-bearing system is shown on Fig. 5. It represents the generalization of a diagram which was suggested in the work (Sosnovskiy and Makhutov, 1991). Let us briefly describe a curve of limiting states during CMF.

Point A designates the fatigue limit when friction is absent (i.e. at $q = 0$). Under the conditions of wear-fatigue tests ($q > 0$) the fatigue limit $\sigma_{-1q}$ grows at first together with the contact pressure until it reaches the greatest value $\sigma_{-1q}^{max}$ and afterwords due to contact damage development it drops down to the initial value (point B). Therefore, curve AB represents function $\sigma_{-1}$ ($q$, $N_b$ = const) = $\sigma_{-1q}$, where $N_b$ - basic number of cycles for which the diagram of limiting states is plotted.

When tests are carried out for rolling fatigue (i.e. at $\sigma_a = 0$) then a rolling fatigue limit $q_c$ exists (point D) corresponding to the number of cycles $N_b$. During tests for CMF alongside with growing cyclic stresses $\sigma_a < \sigma_{-1}$ the rolling fatigue limit $q_c$ will also initially increase reaching a certain greatest value $q_{c\sigma}^{max}$ and then decline down to the initial value (point C).

Therefore, curve DC represents a function given on Fig. 5. Thus, within the portion AB of diagram the limiting state is determined in the final account by mechanical fatigue (initiation and



development of a main crack). However, it is substantially corrected quantitatively by the conditions of contact interaction between components of a load-bearing system (direct effect). The limiting state within the DC portion is governed mainly by the rolling fatigue (spalling, delamination wear). However, it is substantially corrected quantitatively by the level of cyclic stresses caused by mechanical alternating loading (back effect). The limiting state within the BC portion can be reached on the basis of both criteria simultaneously.

During FMF a curve of limiting states (see Fig. 5) should resemble in principle a curve during CMF. During FF no conditions were found for which the value of fatigue limit would increase in comparance with fatigue limit during conventional fatigue (F). Therefore a curve of limiting states during FF has no hunch which is characteristic for CMF and FMF.

The portion AC of limiting curves during CMF and FMF on Fig. 5 is described satisfactorily by means of the equation

$$\sigma_{-1q} / \sigma_{-1} = (1 + q / q_c)(1 - \mu_q q / q_c)^2, \qquad q \leq q_c$$

and the portion DC with the help of the equation

$$q_{c\sigma} / q_c = (1+\sigma_a / \sigma_{-1})(1 - \mu_\sigma \sigma_a / \sigma_{-1})^2, \qquad \sigma_a \leq \sigma_{-1},$$

where $\mu_\sigma$, $\mu_q$ - parameters.

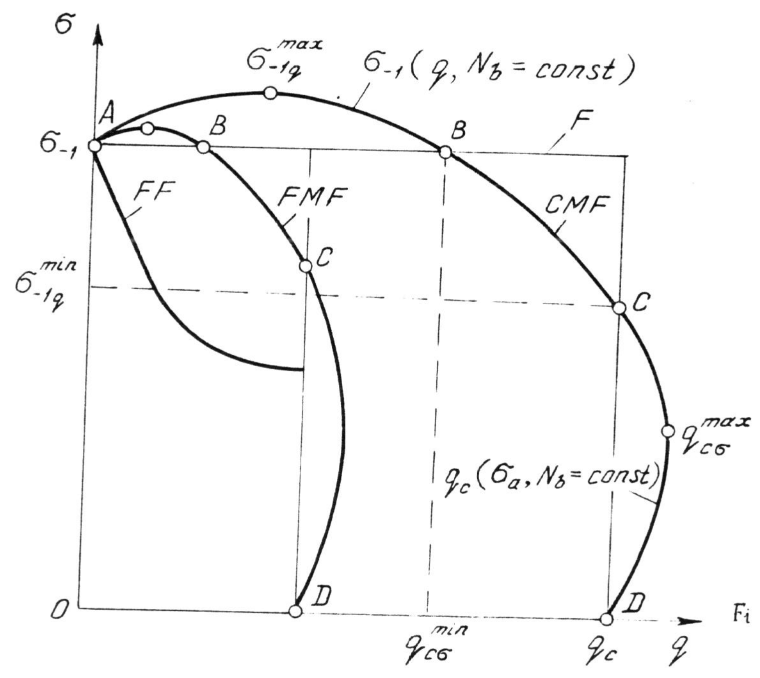


Fig. 5

Up to the present time some equations for calculation of the fatigue limit $\sigma_{-1q}$ during wear-fatigue tests have been obtained. Thus, during FMF for metal-to-polymer system (Sosnovskiy, 1986) the following relation is true.

$$\sigma_{-1q} = \sigma_{-1}[1-C_s (S_q / S_o)(q_{tf}^{(1)} T_p / (q_d - q))^{m_s}],$$

where $S_q / S_o$ - relative dangerous volume of polymer counterbody, $T_p$ - its temperature in the zone of contact; $q_d$ - destruction limit of the polymer, $m_s$, $C_s$, $q_{tf}^{(1)}$ - parameters.

## CONCLUSION

If theoretical and experimental studies during FF have been developing for a long time and successfully, then during FMF and CMF they are essentially in their initial stage. To solve the main problems of tribo-fatigue which are of significant importance for modern machine engineering the combining of efforts of specialists on tribology and mechanics of fatigue fracture is necessary. To accelerate the solving of main problems wide international cooperation would be useful. From the practical point of view it is important to create a unified complex of machines for wear-fatigue tests of models for load-bearing systems and work out standard methods of investigation.

## REFERENCES


1. **L.A.Dekhovich. and N.A.Makhutov** (1981), Physicochemical Mechanics of Materials, No.3, pp.86-90.

2. **D.A.Draygor and G.I.Valchuk** (1962), Influence of Wear upon Fatigue Strength of Steel with the Account of Size Effect, UkSSR Academy of Sciences Publ., Kiew, p.111.

3. **R.D.Edwards** (1981), Fretting Fatigue, Appl. Sci, pp. 67-97.

4. **G.N.Filimonov and L.T.Balatsky** (1973), Fretting in Joints of Ship Parts, Sudostrojenie, Leningrad, p.296.

5. **I.G.Nosovsky, G.V.Tsybanev and O.N.Belas** (1990), Problems of Strength, No.4, pp.31-34.

6. **A.Otsuka, K.Mori and T.Mija** (1983), Eng. Fract. Mech, vol.7, No.3, pp. 429-439.

7. **V.V.Panasyuk** (1968), Ultimate Equilirium of Fragile Bodies with Cracks, Naukowa Dumka, Kiev, p.248.

8. **D.Rooke and D.Jones** (1979), J.Strain Anal., vol.14, No.1, pp.1 - 6.

9. **L.A.Sosnovskiy** (1987), Statistic Mechanics of Fatigue Fracture, Science and Technology, Minsk, p.288.

10. **L.A.Sosnovskiy** (1988), Complex Assesment of Reliability of Load-Bearing Systems Using the Criteria of Resistance to Fatigue and Wear (Principles of Tribo-Fatigue), BIRE, Gomel, p.66.





11. **L.A.Sosnovskiy** (1989), Tribo-Fatigue: Problems and Prospects, Presentation at Subject Exhibition of the USSR Academy of Sciences "Mathematics and Mechanics for Public Economy", Gomel, p.65.

12. **L.A.Sosnovskiy and N.A.Makhutov** (1991), Industrial Laboratory, No.5,pp.27-40.

13. **K.Tanaka, Y.Mitoh, S.Sakoda et. al.** (1985), Fatigue Fract. Eng. Mater. Struct., vol.8, No.2, pp.129-142.

14. **V.T.Troshchenko, G.V.Tsybanev and A.O.Khotsjanovsky** (1988), Problems of Strength, No.6 pp.3-8.

15. **H.H.Uhlig** (1954), J. of Appl. Mech., vol.21, p.401.