AiMT Advances in Military Technology
Vol. 7, No. 2, December 2012

Up-to-Date Tribo-Fatigue Test Possibilities and Methods

J. Stodola*

[1] *Department of Combat and Transport Vehicles, University of Defence Brno, Czech Republic*

The manuscript was received on 5 March 2012 and was accepted after revision for publication on 4 October 2012.

Abstract:

This article deals with tribo-fatigue which is phenomena, situations, difficulties, and regularities related to the damage of fracture of tribo systems. Very often they could not be observed, comprehended, and described analytically, hence they could not expect proceeding from traditional views of solid mechanics, mechanics of fatigue damage and fracture, tribology, theory of dependability of mechanical systems and other disciplines of the mechanical and physical cycle. Tribo-fatigue involves special methods for wear-fatigue test used to estimate experimentally the mutual and joint influence of the processes of friction and mechanical fatigue on the performance of materials and models of tribo-fatigue system under complex loading conditions.

Keywords:

Tribology, fatigue, testing, mechanical systems, damage, modelling, deterioration, dependability.

1. Introduction

Fatigue is the branch of science concerned with the study of wear fatigue damages and fracture of the active systems of machines and its parts. The active system is a mechanical system that reacts to and transmits the alternating load with simultaneous occurrence of the friction process at any of its modes: sliding, rolling, fretting, impact, etc [1, 2]. The term fatigue is usually used for a process of damage evolution of material due to cyclic loading. Fatigue is a dangerous phenomenon, because no obvious signs of the damage process can be observed throughout the majority of the loading cycles [6, 7] etc.

Contacts between better surface and rough surface accompanied by local stress are repeated a large number of times mainly in the course of sliding or rolling, and

---

* *Corresponding author: Department of Combat and Transport Vehicles, University of Defence Brno, Kounicova Str. 65, 662 10 Brno, Czech Republic, tel. +420 973 442 278, fax +420 973 443 384, E-mail jiri.stodola@unob.cz*

wear particles are generated by fatigue propagated cracks, hence the term fatigue wear. Wear under these conditions is determined by the mechanism of crack initiation, crack grown/propagation, and final fracture, see Fig. 1 [3]; in repeated contact stress cycle dominance. Stress conditions are assumed to be either elastic or elasto plastic. The critical number N_c of rolling cycles for surface spalling by high-cycle fatigue in a steel ball bearing is experimentally given by the following equation

$$N_C = bW^{-n}, \tag{1}$$

where W is the load, b and n are experimental constants.

If the contact stress is at a level sufficiently high for plastic deformation to occur and repeated contact cycles are required to produce wear particles through crack initiation and propagation, a Coffin Manson type relation [4] of the fatigue fracture can be used to model the low cycle fatigue wear.

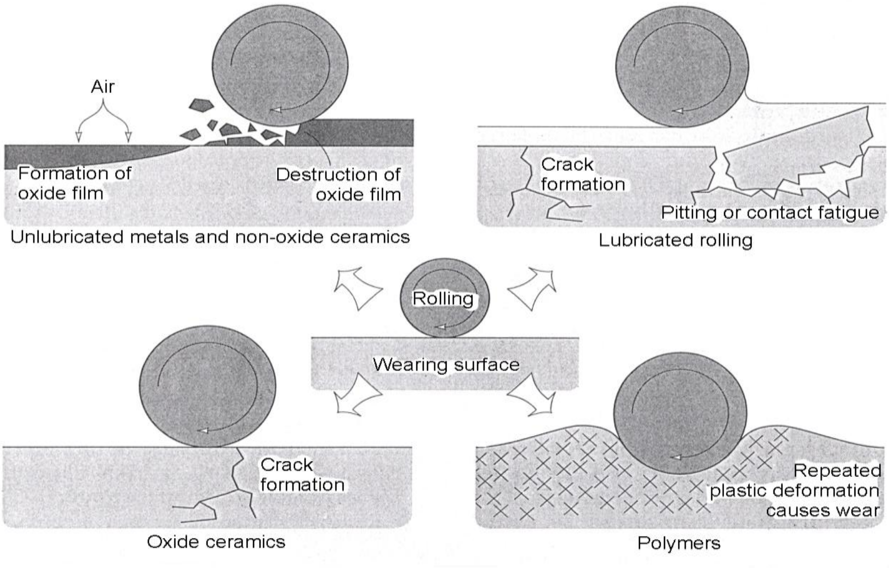


Fig. 1 Mechanisms of fatigue wear occurring during rolling

The wear rate for this mode is theoretically introduced by creating a two-dimensional abrasive wear model of the plastic wave formation. The wear coefficient K is given as follows

$$K = \frac{9x\sqrt{3}r\mu}{C^D \gamma_t^{1-D}}, \tag{2}$$

where r, μ and γ are constants that all are determined from the wave model as a function of the attack angle and the normalized shear strength of the contact interference, C is the monotonic effective shear strain and D is an experimental constant used as the power in the low-cycle fatigue.

The results obtained from both equations (1) and (2) are based on the experimental power of fatigue fracture. The mechanism of fatigue damage can be analysed through linear fracture mechanics approach to a certain extent. Similarly, the fatigue wear mechanism may be understood by analysing the process of the crack initiation and propagation in forming a wear particle. The crack propagation rate was theoretically calculated from a model of a subsurface crack, parallel to the surface, through linear fracture mechanics approach for elasto plastic solids, and following equation [7] has been proposed

$$\frac{\mathrm{d}a}{\mathrm{d}N} = c(\Delta K)^m , \tag{3}$$

where a is a crack length, N is the number of friction cycles, c and m are experimental constants and ΔK (MPa√m) is the range of the stress intensity factor.

Using standard fatigue test of steel, it was confirmed that the crack nucleation period is much longer (> 70 % of the total life) than the period for the crack propagation to cause a failure. However, in cases of steel sliding in air, with a high friction coefficient ($\mu = 0.5$), the number of critical friction cycles needed for the generation of a void around a hard inclusion in the substrate was theoretically calculated as about 3. This means that further theoretical modelling of low-cycle fatigue could be developed through the crack propagation (Eq. (3)). On the other hand, it is well-established that the void nucleation and crack initiation are the rate-controlling processes in high-cycle fatigue wear. By now experimental mechanics has become a basis for any calculations for strength and durability. It also plays one more important role, i.e. it serves to perceive regularities and specific features of the behaviour of materials under loads applied in various conditions including alternating loading, friction, etc. Tribo fatigue test involves special methods for wear fatigue test used to estimate experimentally the mutual and joint influence of the friction damage and mechanical fatigue on the materials performance and models of tribo-fatigue systems under complex loading conditions.

2. Formation of methods and models for wear-fatigue test

The development and progress of tribology has motivated the designing of a special class of testing equipment, such as the machines for friction (wear) tests. The first systematic fatigue tests were performed by A. Wöhler around the year 1850. It was fatigue tests at rotation bending at constant stress amplitude. Since this time we have usually used in practice other test and machines, for example fatigue test at a constant plastic strain amplitude and fatigue tests at constant total strain amplitude, and electrohydraulic, resonant, and ultrasonic machines, etc. [6]. The progress of tribo fatigue has required the development of a new class of testing equipment, such as the machines for wear fatigue tests. Fig. 2 shows the principle of formation of methods for wear fatigue tests in the case when rotational bending is taken as the basic method of fatigue tests.

Rotary motion is most common in present-day machinery; hence, the methods presented in Fig. 2 [2, 7] are of practical significance. At the beginning of the nineties of the last century a universal machine was created on the basis of a number of inventions; it was intended for wear-fatigue tests of materials and models of tribo-fatigue systems. Some technical characteristics are listed in Table 1. The machine has become the real representative of a new class of testing equipment [2]. The innovation decisions used when creating the SI testing machine allowed for obtaining new fundamental test results. Figs. 3 [1] and 4 [2] show some of these experimental results obtained at the universal SI machine. Fig. 3 [1] represents the first and convincing proof of the hypothesis on the possibility of plotting the total curve of friction fatigue. These are the results of a unique experiment embracing two years of continuous tests since the base durability was taken 80 million cycles. Now, when the total friction fatigue curve has been obtained, one may write the corresponding condition of wear resistance using, for example, one of its portions, i.e. the high-cycle fatigue curve.

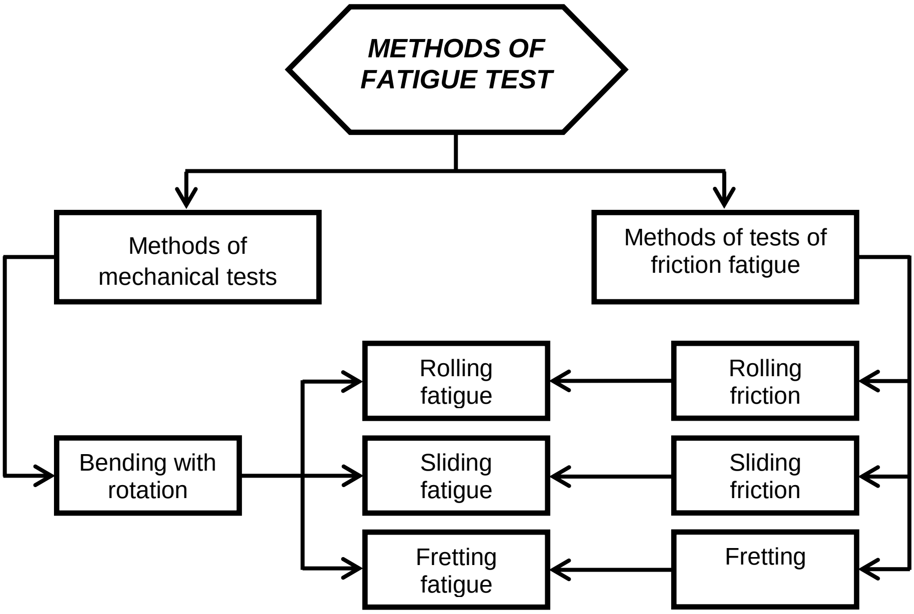


Fig. 2 Methods of wear-fatigue tests

Tab. 1 Technical characteristics of testing machine

Index	Unit	Magnitude
Specimen working part diameter in tests of fatigue and wear-fatigue	mm	10
Overall dimensions of counter specimen: block roller	mm	10 × 10 × 11.5 80
Range of rotation speeds of specimen	r.p.m.	50 – 5 500
Limiting permissible errors of maintaining rotation speed of specimen; bending and contact loads	%	3
Range of specified values of slip factor	%	0 – 85
Range of bending loads	N	55 – 1 600
Range of contact loads	N	15 – 5 500
Range of measurement of total wear of specimen and counter specimen	μm	5 – 1 000
Limiting permissible errors of measuring total wear of specimen and counter specimen	%	3
Range of measurement of friction torque	Nm	0.6 – 25
Limiting permissible errors of measuring friction torque	%	3

Remark:
The condition of correspondence of a testing machine to the world level [2] is the factor of technical level $K_{tl} \geq 1$. For the SI machine $K_{tl} = 2.39$.

Fig. 4 [2] shows the results of the first experiments on the study of the back effect (the influence of cyclic stresses on changes in friction and wear processes) at rolling fatigue using the method of multi-step loading. Comparative studies of the damage of a deformed system (the approach of the axes σ_c was measured) at rolling friction (the amplitude of cyclic stress was $\sigma_a = 0$) and mechano-rolling fatigue (at $\sigma_a = 0.8\,\sigma_{-1}$, and $\sigma_a = 1.0\,\sigma_{-1}$, where σ_{-1} is the fatigue limit) were carried out.

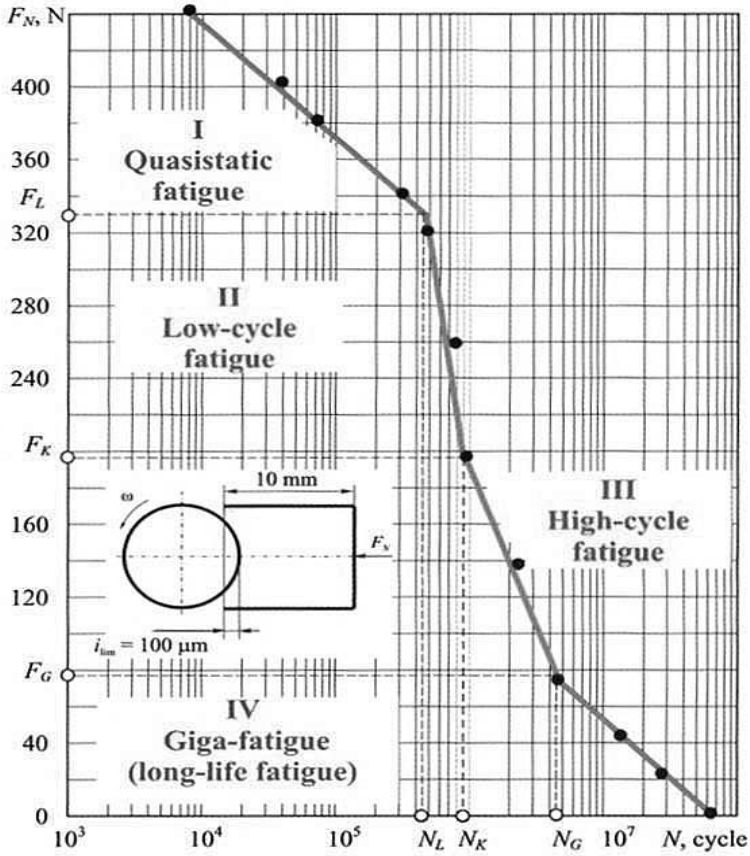


Fig. 3 Total friction fatigue curve [1]

It follows from the data obtained that cyclic stresses retard considerably the process of accumulation of wear fatigue damage (compared with the process of damage at rolling friction). In this case the range of the contact stress within which normal friction occurs widens by approximately 15 %.

The main and the most important feature of the methods of wear-fatigue test is that all of them are based on the common unified object, i.e. a shaft of 10 mm in diameter used in arbitrary loading schemes, see Fig. 5 [2]. This provides the compatibility of data obtained when testing structural elements, friction pairs, and tribo-fatigue systems. Until now researchers were lacking for such possibility. Suffice it to say that, for example, the traditional methods of rolling contact and sliding friction tests yielded non-comparable results at least because the dimensions of the objects being tested differed, as a rule, several times. New project has been implemented based on a new class of testing machines, i.e. module machines of SI series suitable for performing wear-fatigue tests using any of the accepted test schemes.

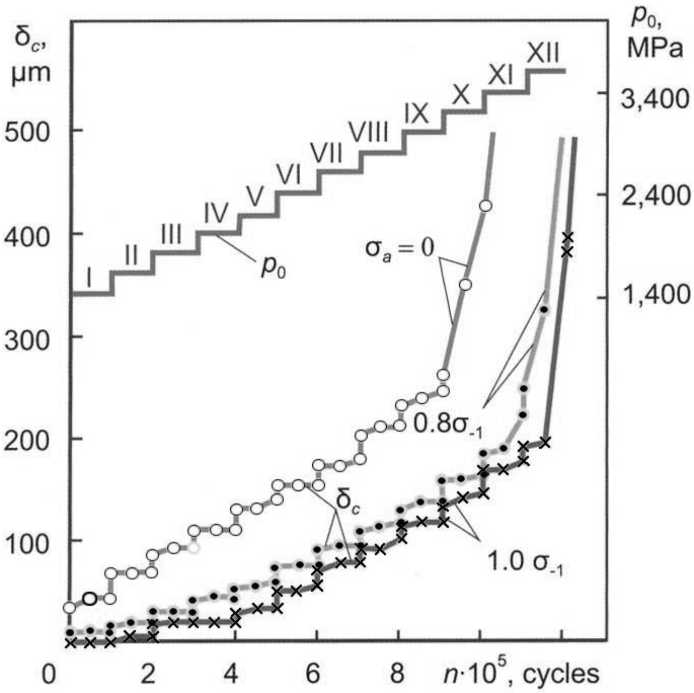


Fig. 4 Study of back effect at multistep loading

These methods and machines are also suitable for performing fretting fatigue tests. Figs 6 and 7 show the innovative test results obtained at module machines of SI series. For the first time four fatigue curves, see Fig. 6, were plotted [1, 2, 7]. The limit state criterion during tests for mechanical fatigue is disintegration/fracture of a specimen into pieces and that of tests for rolling fatigue is the critical density of pits on the rolling surface. The limit state during tests for rolling fatigue is determined by the criteria of damage and fracture typical for tests [12]. The fatigue limits (σ_{-1}, p_f, σ_{-1p}, $p_{f\sigma}$), the parameters of slope of the left branch of the fatigue curves (m_σ, m_p, $m_{\sigma p}$, $m_{p\sigma}$) and the abscissas of the breakpoints on the fatigue curves ($N_{\sigma G}$, N_{pG}, $N_{\sigma pG}$, $N_{p\sigma G}$) are determined in all four cases. Note that the fatigue limits at mechanical (σ_{-1}) and rolling (p_f) fatigue are unambiguous and unique characteristics if the test basis is specified, while the fatigue limits at rolling fatigue (σ_{-1p}, $p_{f\sigma}$) are not unambiguous and unique characteristics of the corresponding objects. Similar fatigue curves can be plotted for arbitrary value of the parameters p_0 = const or σ_a = const.

The comparison of the fatigue curves $N(\sigma_a)$ and $N(\sigma_a,\ p_0 = \text{const})$ makes it possible to characterize the influence of friction and wear on changes in the characteristics of resistance to mechanical fatigue under the given test conditions. This influence is called direct effect. The direct effect coefficient is determined as follows:

$$K_D = \frac{\sigma}{\sigma_P} \,. \tag{4}$$

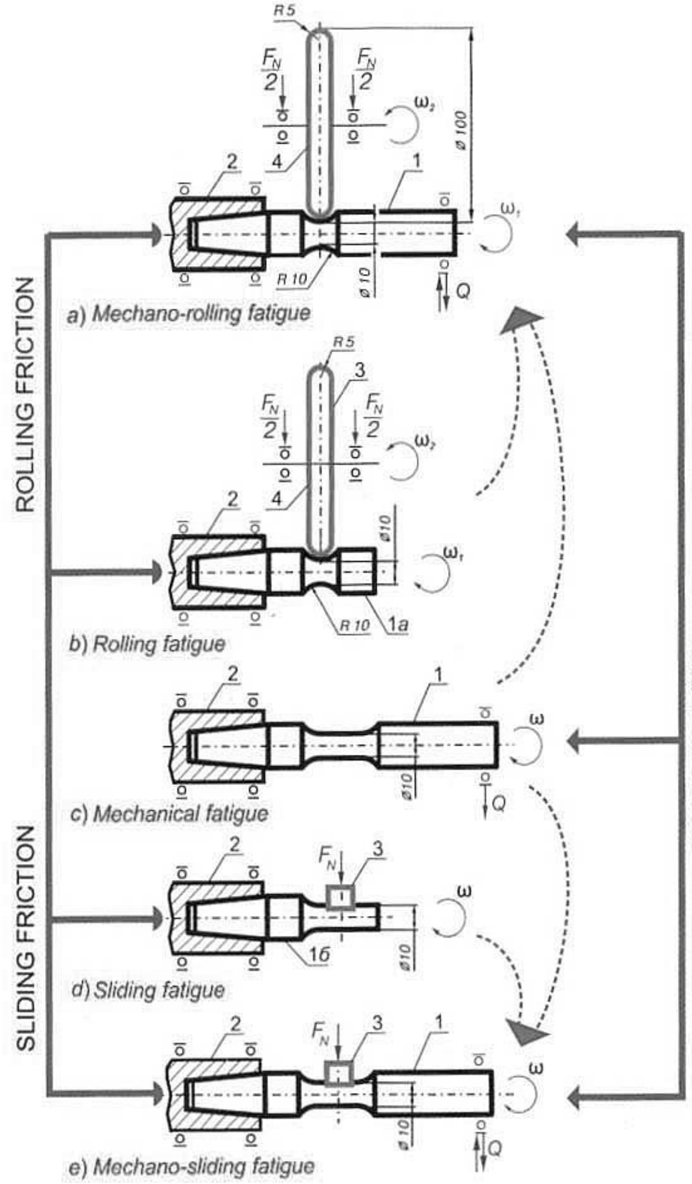


Fig. 5 Unified system of methods for wear-fatigue tests

In fact, the coefficient K_D is strength characteristic. Under conditions of the tests that yielded the results presented in Fig. 6 we obtain $K_D = 265/165 = 1.55$. The comparison of the fatigue curves $N(p_0)$ and $N(p_0,\ \sigma_a = \text{const})$ makes it possible to characterize the influence of mechanical fatigue on changes in the characteristics of friction and wear under the given test conditions. This influence is called back effect [5]. The back effect coefficient is determined as follows:

$$K_B = \frac{p_{f\sigma}}{p_f}\,. \tag{5}$$

In fact, the coefficient K_B is a tribological characteristic. Under conditions of the tests that yielded the results presented in Fig. 6, we obtain $K_B = 2\,200/1\,760 = 1.25$. Coefficients (4) and (5) characterize the direct and back effects in terms of the carrying capacity of a system, while the similar coefficients

$$K_D = \frac{m_{\sigma p}}{m_\sigma} \tag{6}$$

and

$$K_B = \frac{m_{p\sigma}}{m_p} \tag{7}$$

characterize these effects in terms of damage intensity since the parameters of slope of the fatigue curves describe, in essence, the rate of change of the fatigue resistance as the number of loading cycles required to reach the limit state [13]. In Table 2 nomenclature and numerical values of basic characteristics are presented, being determined on the fatigue curves presented in Fig. 6.

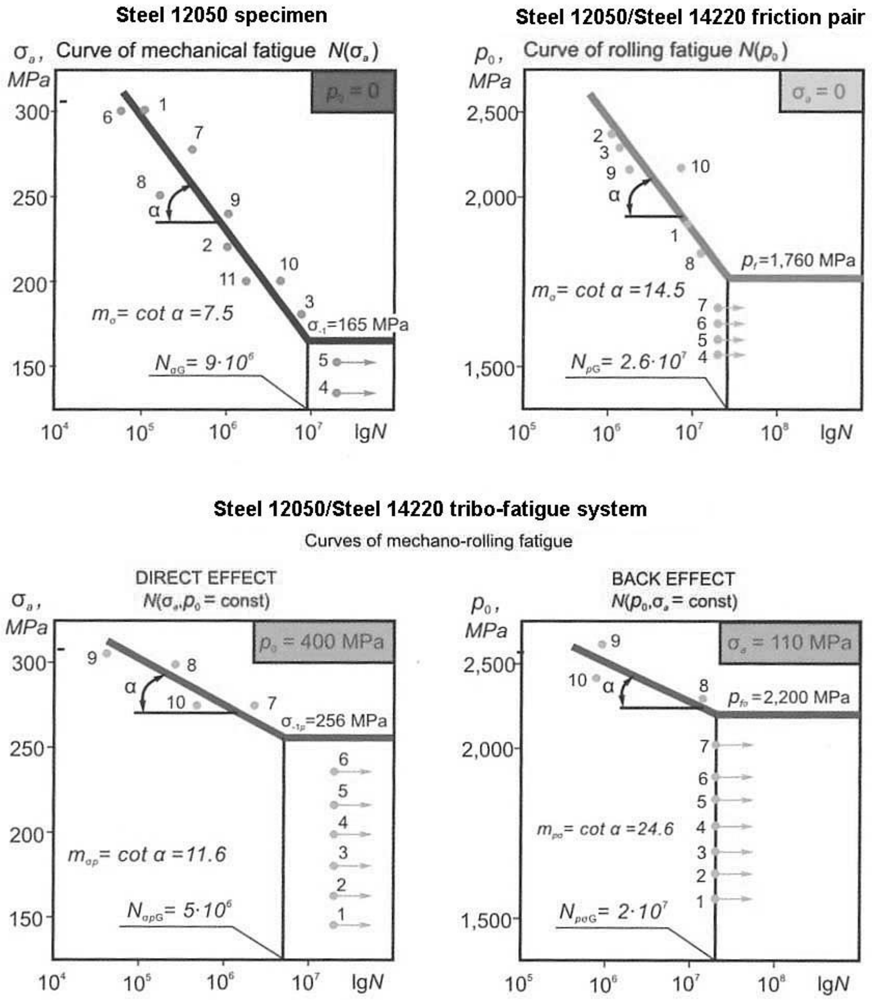
Tab. 2 Nomenclature and numerical values of basic characteristics

Characteristic of properties	Mechanical fatigue curve	Rolling fatigue curve	Mechanical-rolling fatigue curve	
	$N(\sigma_a)$	$N(p_0)$	$N(\sigma_a, p_0 = const)$	$N(p_0, \sigma_a = const)$
Fatigue limit [MPa]	$\sigma_{-1} = 165$	$p_f = 1\,760$	$\sigma_{-1p} = 256$	$p_{f_\sigma} = 2\,200$
Coordinate of the breakpoint	$N_{G_\sigma} = 9 \times 10^6$	$N_{G_p} = 2.5 \times 10^7$	$N_{G_{\sigma p}} = 5 \times 10^6$	$N_{G_{p\sigma}} = 2 \times 10^7$
Fatigue curve slope parameter	$m_\sigma = 7.5$	$m_p = 14.5$	$m_{\sigma p} = 11.7$	$m_{p\sigma} = 24.5$

Fig. 7 [2, 10, 11] shows the first multi-criteria diagram of the limit states for the tribo-fatigue system at rolling fatigue.

3. Conclusion

This article describes in brief a part of the most important and most frequent problem of up-to-date mechanical tests, especially fatigue test. In order to measure the properties of material (yield stress, ultimate tensile stress, ductility, hardness, fatigue, toughness, etc.), it is necessary to perform precise tests [6, 9, 14]. The tests are standardised so that the results can be used by designers, researchers, etc. all over the world. In our case, if we analyze Fig. 7, the diagram *ABCD* we make the following general conclusions:


Steel 12050 specimen

Curve of mechanical fatigue $N(\sigma_a)$

Steel 12050/Steel 14220 friction pair

Curve of rolling fatigue $N(p_0)$

Steel 12050/Steel 14220 tribo-fatigue system

Curves of mechano-rolling fatigue

DIRECT EFFECT $N(\sigma_a, p_0 = \text{const})$

BACK EFFECT $N(p_0, \sigma_a = \text{const})$

Fig. 6 Experimental fatigue curves of unified objects

- the fatigue limit of the specimen increases approximately up to 1.55 times provided that rolling occurs simultaneously (the direct effect – the portion *AB*),
- the critical (limit) stress at rolling increases approximately up to 1.225 times if cyclic stresses are simultaneously excited in the specimen (the back effect – the portion *DC*),
- within the range of optimal contact stress (p_0 = 400 – 1 300 MPa) wear at rolling leads to a significant rise of the reliability of the system in terms of the fatigue resistance; for this reason striving for warless friction is wrongful in this case,
- at cyclic loading under the optimal conditions ($\sigma_a \approx$ 50 – 100 MPa), tensile stresses are favourable since they promote considerable rise of the reliability of the system in terms of rolling friction resistance.

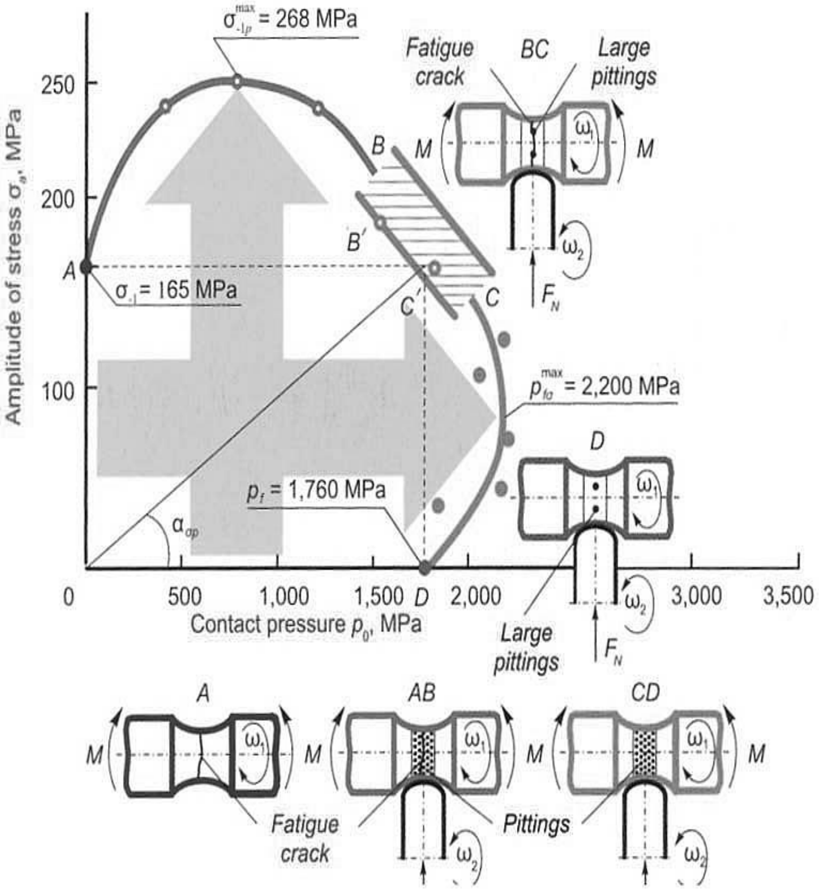


Fig. 7 Multi-criteria diagram of limit states for tribo-fatigue system at rolling fatigue

Improvement of the characteristics σ_{-1p} and $p_{f\sigma}$ of the limit state during wear-fatigue tests compared with these characteristics at rolling friction (p_f) and mechanical fatigue (σ_{-1}) can be explained from the viewpoint of mechanics by the following basic reasons:

- summation of the stresses having the opposite signs (the contact and bending stresses) that shifts the average stress of the cycle towards negative values, hence, reduces the maximal stress of the cycle;
- hardening of the specimen working part by surface plastic deformation;
- appearance of favourable compressive residual stresses;
- healing of initial fatigue cracks during the elastic-plastic deformation at rolling friction.

Issues connected with tribo-fatigue testing are prepared to be published in some of further editions of AiMT journal.

References

[1] SOSNOVSKIJ, AL. and SHERBAKOV, SS. *Surprises of Tribo-Fatigue*. Minsk: Magic Book, 2009. 197 p.

[2] SOSNOVSKIJ, AL., SHERBAKOV, SS. et al. *SI-Series Machines for Wear-Fatigue Tests*. Minsk: S & P Group TRIBOFATIGUE, 2009. 55 p.

[3] STACHOWIAK, GW. and BATCHELOR, AW. *Engineering Tribology*. 3rd edition. Oxford: Butterworth-Heinemann**,** 2005. 832 p.

[4] STACHOWIAK, WG. *Wear: Materials, Mechanisms and Practice*. Wiley, 2005. 458 p.

[5] TOTTEN, EG. *Handbook of Lubrication and Tribology. Volume I Application and Maintenance*. 2nd edition. Boca Raton: Taylor & Francis, 2006.

[6] KRUML, T. and MICHEL, J-P. *Mechanical Testing of Materials*. [cited 2012-02-06]. Available from: <http://ime.fme.vutbr.cz/images/umvi/vyuka/dislokace_a_plasticka_deformace/skripta/zkouseni_materialu-skripta.pdf>.

[7] STODOLA, J. *Advances in Special Technique*. Brno: University of Defence, 2010. 202 p. ISBN 978-80-7231-716-5.

[8] FLEMING, JR. and SUH, NP. The relationship between crack propagation rates and wear rates. *Wear,* 1977, vol. 44, no. 1, p. 57-64.

[9] SOSNOVSKIY, LA. *Tribo-Fatigue. Wear-Fatigue Damage and Its Prediction*. Heidelberg: Springer, 2011. 373 p.

[10] SOSNOVSKIY, LA. and SOSNOVSKIY, LA. jr. *Tribo-Fatigue. Wear-Fatigue Damage and Its Prediction*. Heidelberg: Springer, 2004. 373 p.

[11] SOSNOVSKIY, LA. *Fundamentals of Tribo-fatigue*. Gomel: BelGUT, 2003. Part 1 – 246 p.; Part 2 – 235 p.

[12] FROLOV, KV., SOSNOVSKIY, LA., MAKHUTOV, NA. and DROZDOV, YN. *Tribo-Fatigue: New Ideas in Promising Direction*. Gomel: Belarus Institute of Railway Transport Engineers, 1990. 7 p.

[13] KUKHAREV, AV. Some stages of progress of tribo-fatigue. *ISTF 2000 (Proc. of the III International Symposium on Tribo-Fatigue*. Beijing: Hunan University Press, 2000, p. 179-182.

[14] WANG, Y. and HADFIELD, M. A Study of Line Defect Fatigue Failure of Ceramic Rolling Elements in Rolling Contact. *Wear*, 2002, vol. 253, no. 9-10, p. 975-985.

Acknowledgement

This article has been sponsored by the Ministry of Defence of the Czech Republic in work on the Project of Research Establishment Development.