ISSN 1068-3666, Journal of Friction and Wear, 2012, Vol. 33, No. 3, pp. 203–207. © Allerton Press, Inc., 2012.
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Comparative Experimental Study of Friction Parameters in a Tribopair and a Force System

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Received April 18, 2011

Abstract—The paper presents the results of experimental study of the effect of stresses resulting from off-contact load on variations in the friction torque and the coefficient of resistance to rolling in a force system compared to a similar tribopair. The results are compared with the theoretical data obtained on the basis of the deformation approach to the analysis of friction. It is shown that the calculation estimates agree well with the experimental results both qualitatively (the regularities) and quantitatively (the numerical values). The error of the determination of the coefficient of resistance to rolling does not exceed 7%. The study results make it possible to formulate and solve the problem of the effective control over the friction force (coefficient) by varying cyclic (bending) stresses.

Keywords: force (tribo-fatigue) system, tribopair, friction, law of friction, coefficient of resistance to rolling, contact load, contact area.

DOI: 10.3103/S1068366612030105

INTRODUCTION

In tribology the friction force, which arises during the friction of macroscopic objects, is assumed to depend on only one force factor, namely, the normal contact load [1–3]. In force or tribo-fatigue systems, in which the stress-strain state is caused by the effect of both the contact and volume loads excited in the same zone, the stresses and strains resulting from an off-contact load form additional boundary conditions on the contact surface. This varies considerably the tribological characteristics. Theoretical studies [4–6] have shown that in a tribo-fatigue system the resulting rolling friction force (coefficient) in the tension zone declines compared to the pure rolling force (coefficient) under the simultaneous action of contact and off-contact loads and, conversely, this force increases in the compression zone.

The aim of the study is to study experimentally the effect of the stresses resulting from off-contact load on variations in the coefficient of resistance to rolling in a force system and a similar tribopair and to compare the data with the results of the theoretical solutions.

PROBLEM FORMULATION

The traditional approach to the determination of the friction coefficient is that the friction force and coefficient in the tribopair are assumed to depend only on the contact load F_N (contact pressure p):

$$f(p) = \frac{F_S}{F_N} = \frac{\tau_W}{p}, \tag{1}$$

where F_S is the friction force, τ_W is the specific friction force, F_N is the contact load, and p is the contact pressure.

From the viewpoint of tribo-fatigue, the friction coefficient in force systems is determined as a function of the contact pressure p and the cyclic stresses σ resulting from the off-contact load:

$$f(p,\sigma) = \frac{F_S(p,\sigma)}{F_N}. \tag{2}$$

According to the data of [4–6], depending on the conditions of friction or testing it can be

$$f(p,\sigma) \gtreqless f(p), \tag{3}$$

i.e., the cyclic stresses can either increase or reduce the friction coefficient.

In this work, we carried out the systematic comparative analysis of relations (1)–(3) based on the experimental results; all tests were performed under rolling friction conditions so that $f(p) = f_r$ is the coefficient of resistance to rolling in the friction pair and $f(p,\sigma) = f_\sigma$ is the coefficient of resistance to rolling in the force system.

A modification of the roller/shaft force system (steel 18KhGT/steel 18KhGT) was tested (Fig. 1); the test method was published earlier [7].

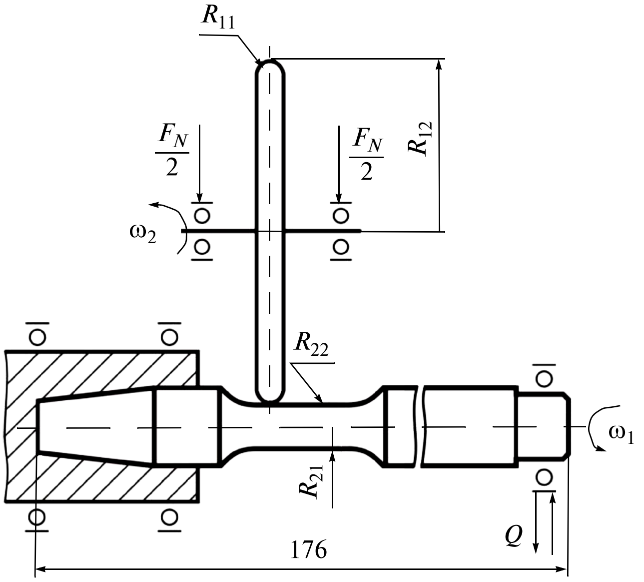

Fig. 1. Model for mechano-roling fatigue tests.

RESULTS OF TESTING THE STEEL 18KhGT/STEEL 18KhGT FORCE SYSTEM

This force system was tested using the developed method at three values of the contact stresses (p_0 = 2000 MPa, p_0 = 3200 MPa, and p_0 = 5600 MPa), which correspond to the range of elastic and elastoplastic deformations (see the dependence of the maximum contact pressure p_0 on the approach of the axes δ_c—insert in Fig. 2). The bending load Q was assigned stepwise 5 min after the beginning of the tests. The initial bending load was $Q = 160$ N (the bending stresses were $\sigma_a = 160$ MPa). The increment of the bending stresses at each loading step was $\Delta\sigma_i = 40$ MPa = const; the duration of the step was $n_i = 30000$ cycles. The bending load was directed downwards to produce tensile stresses in the contact zone and upwards to produce compressive stresses (see Fig. 1). The degree of slippage was constant during the tests and amounted to $\lambda = 3\%$.

The test results are presented as the graphs of the dependence of the average coefficient of resistance to rolling $\overline{f_\sigma}$ (under various values of the contact stresses p_0) on the cycle stress amplitude σ_a at the given loading step (Fig. 2). Sixty values of f_σ obtained during the test at one loading step (10 min) correspond to each point on the graph at σ_a = const; this provides a sufficient accuracy of the results. The data presented in Fig. 2 allow us to draw the following conclusions.

(1) During the contact fatigue tests (in all figures RF means rolling friction) the values of the coefficient of resistance to rolling $\overline{f_r}$ remain unchanged if F_N = const; this agrees with the numerous known data. Depending on the contact stresses, the values of $\overline{f_r}$ are 0.0626 at p_0 = 2000 MPa (elastic contact) as well as 0.0830 at p_0 = 3200 MPa and 0.0887 at p_0 = 5600 MPa (elastoplastic contact); i.e., the transition from elastic contact to elastoplastic results in a higher coefficient of resistance to rolling (by ~41.6% under the test conditions).

(2) During the mechano-rolling fatigue tests (rolling friction + cyclic bending) the values of the coefficient of resistance to rolling $\overline{f_\sigma}$ in the compression zone diminish, as a rule. The increase in the bending stresses σ_a to 640 MPa leads to the reduction of $\overline{f_\sigma}$ by 5.1% at p_0 = 2000 MPa, by 6.0% at p_0 = 3200 MPa, and by 0.9% at p_0 = 5600 MPa.

(3) Conversely, during the mechano-rolling fatigue tests with friction occurring in the compression zone, the values of the coefficient of resistance to rolling $\overline{f_\sigma}$ grow. The increase in the bending stresses σ_a to 640 MPa results in the rise of the coefficient $\overline{f_\sigma}$ by 11.7% at p_0 = 2000 MPa, by 5.6% at p_0 = 3200 MPa, and by 0.13% at p_0 = 5600 MPa.

(4) The most pronounced effect of the cyclic stresses on the coefficient of resistance to rolling occurs in the elasticity range (p_0 = 2000 MPa). In transition to plastic contact, this effect weakens and the effect is weaker the greater the plastic strain.

ANALYSYS OF THE TEST RESULTS

It is shown in work [5] that the friction process in a force system is characterized by the parameter $f_F = \pm\sigma_a/\tau_W$, which is called the friction index. The following dependence of $\overline{f_\sigma}$ on the ratio σ_a/τ_W is proposed for sliding friction [6]:

$$f_\sigma = f_S\left(1 \pm \mu_p \frac{\sigma_a}{\tau_W}\right) = f_S\left(1 \pm \mu_p f_F\right), \tag{4}$$

where μ_p is the dimensionless parameter of the interaction of the damages caused by the contact and off-contact loads (the frictional and mechanical stresses).

In the case of rolling friction, we replot the dependences presented in Fig. 2 using the parameter σ_a/p_0 (Fig. 3). It is easy to see that all of the graphs shown in Fig. 3 can be approximated by the following linear equation of one type

$$\overline{f_\sigma} = \overline{f_r} \pm a_r \frac{\sigma_a}{p_0}, \tag{5}$$

where a_r is the parameter characterizing the angle of the slope of the straight lines $f_\sigma(\pm\sigma_a/p_0)$ to the abscissa axis.

Analysis of the experimental data in accordance with equation () is presented in Table 1.

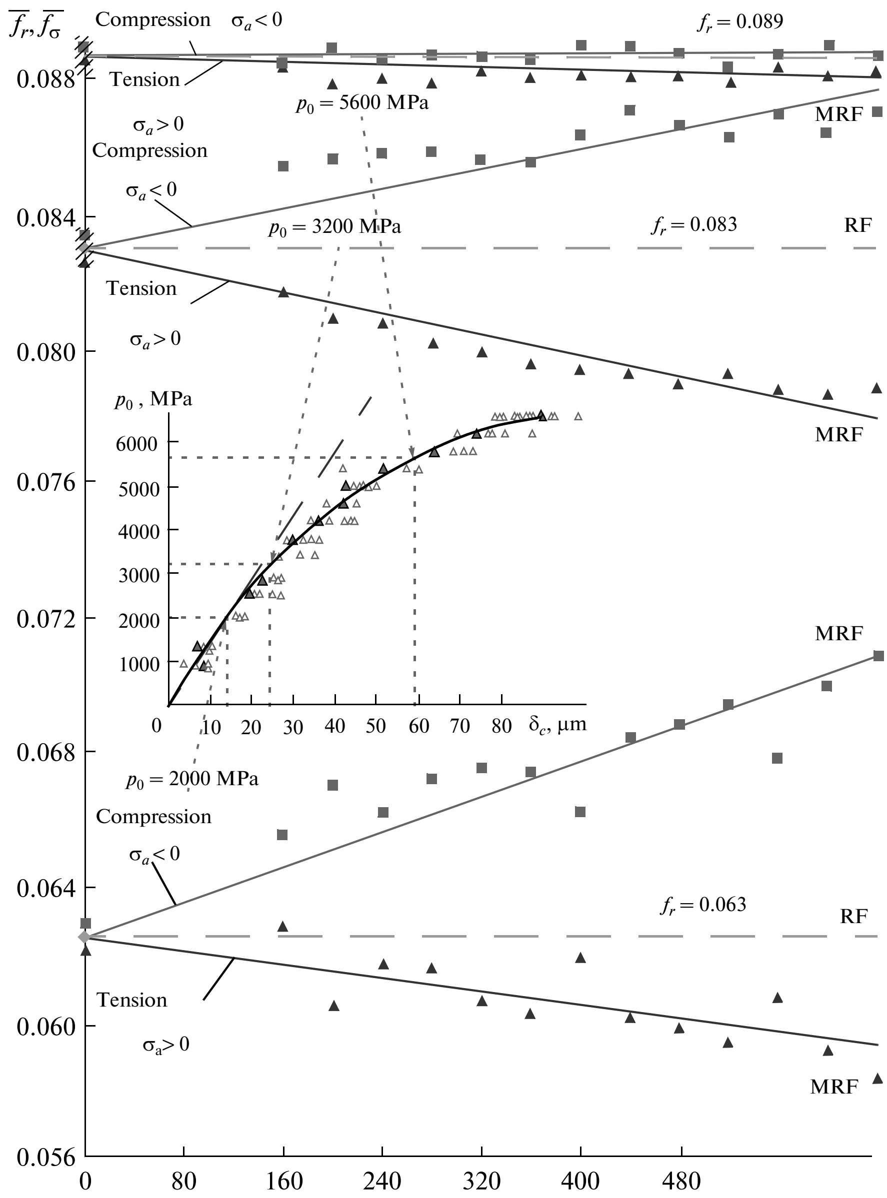

Fig. 2. Force system steel 18KhGT/steel 18KhGT: dependence of average coefficient of resistance to rolling $\overline{f}_r$ on amplitude of stresses σ_a (the dashed line corresponds to the value of $\overline{f}_r$ in the tribopair).

It is easy to show that equations (4) and (5) are almost identical, since

$$f_\sigma = f_r \pm a_r \frac{\sigma_a}{p_0} = f_r\left(1 \pm \frac{a_r}{f_r}\frac{\sigma_a}{p_0}\right) = f_r\left(1 \pm \mu_r \frac{\sigma_a}{p_0}\right) = f_r\left(1 \pm a_r f_F\right), \tag{6}$$

where $\mu_r = a_r/f_r$ is the dimensionless parameter of the interaction of the damages caused by the contact and off-contact loads (the frictional and mechanical stresses). By analogy, we can obtain $\mu_p = a_S/f_S$.

The values of the parameter μ_r calculated from the experimental data are given in Table 1.

The methods of the mechanics of deformable solids were applied in work [4] to determine the friction coefficient (the coefficient of resistance to rolling) in the force system:

$$f = f^{(s)}\left[1 \pm k_{\sigma/p}\left(\frac{\sigma_{yy}^{(b)}}{p_0}\right)\right], \tag{7}$$

where $f^{(s)}$ is the pure rolling friction coefficient and $k_{\sigma/p}$ is the function, which possesses the following values depending on the method of its determination: $k_{\sigma/p}^{(1)} = 0.225$ and $k_{\sigma/p}^{(2)} = 0.787$.

It is seen that formulae () and (4) are almost identical.

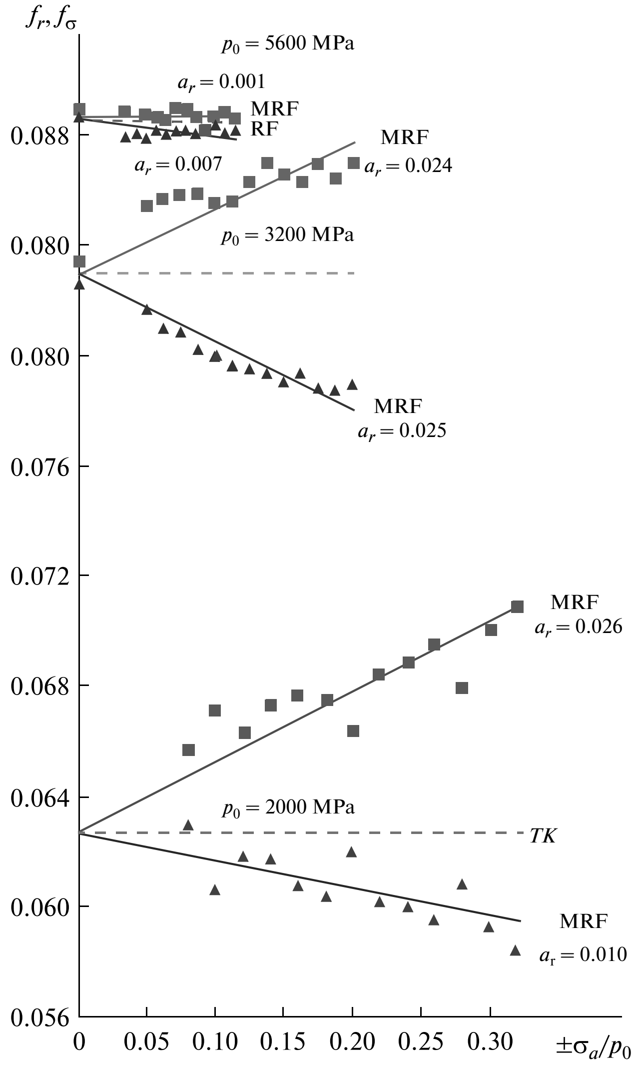

Fig. 3. Force system steel 18KhGT/steel 18KhGT: dependence of average coefficient of resistance to rolling $\bar{f}_r$ on ratio σ_a/p_0 (the dashed line corresponds to the value of $\bar{f}_r$ in the tribopair).

The results of the comparison of the experimental and theoretical values of the coefficient of resistance to rolling in the force system at $k^{(1)}_{\sigma/p} = 0.225$ and $\sigma_a/p_0 = 0.3$ are presented in Table 2.

It can be seen that in this case the calculation estimates agree satisfactorily with the experimental data both qualitatively (the regularities) and quantitatively (the numerical values).

CONCLUSIONS

The following basic regularities of the effect of the cyclic stresses σ_a on variations in the coefficient of resistance to rolling f_r (the force F_R) are established: (a) greater σ_a, and therefore higher ratio σ_a/p_0, entails a more significant variation of the coefficient of resistance to rolling; this regularity is observed in both elastic and elastoplastic contact; (b) the change of the coefficient of resistance to rolling f_r with varying cyclic stresses σ_a reaches 12.5% in elastic contact and up to 4% in elastoplastic contact. The cycle stress amplitude in the experiments σ_a does not exceed the endurance limit $\sigma_{-1} = 640$ MPa and the ratio σ_a/p_0 varies within the 0–0.33 range.

It is shown that the calculated estimates agree satisfactorily with the experimental data both qualitatively (the regularities) and quantitatively (the numerical values). The error of the experimental and theoretical results of determining the coefficient of resistance to rolling does not exceed 7%.

The presented data are of great practical importance since they open the way to control the friction processes by varying off-contact loads as effectively as by varying contact loads.

Table 1. Analysis of experimental results

Maximum contact pressure p_0, MPa	Conditions of friction	Parameters			Equation $f_\sigma = f_r \pm a_r(\sigma_a/p_0)$	Range of σ_a, MPa
		a_r	μ_p	μ_p/a_r		
Force system steel 18KhGT (shaft)/steel 18KhGT (roller) ($\sigma_{-1} = 640$ MPa, $p_f = 1272$ MPa)						
2000	In tension zone	0.010	0.160	16.00	$0.063 - 0.010(\sigma_a/p_0)$	σ_a 640
	In compression zone	0.026	0.415	15.96	$0.063 + 0.056(\sigma_a/p_0)$	
3200	In tension zone	0.025	0.301	12.04	$0.083 - 0.025(\sigma_a/p_0)$	
	In compression zone	0.024	0.289	12.04	$0.083 + 0.024(\sigma_a/p_0)$	
5600	In tension zone	0.007	0.079	11.29	$0.089 - 0.007(\sigma_a/p_0)$	
	In compression zone	0.001	0.011	11.00	$0.089 + 0.001(\sigma_a/p_0)$	

Table 2. Determination of calculation of error of coefficient of resistance to rolling based on experimental results and theoretical states

Force system	p_0, MPa	Parameter of interaction, a_r		Friction coefficient in force system f_σ				Error, %	
				experimental results		calculations by (4)			
		$\sigma > 0$	$\sigma < 0$	$\sigma > 0$	$\sigma < 0$	$\sigma > 0$	$\sigma < 0$	$\sigma > 0$	$\sigma < 0$
Steel 18KhGT/Steel 18KhGT	2000	0.010	0.026	0.060	0.070	0.058	0.067	2.06	5.08
	3200	0.025	0.024	0.076	0.090	0.077	0.089	2.51	1.77
	5600	0.007	0.001	0.087	0.089	0.083	0.095	4.49	6.39

DESIGNATONS

F_N—contact load; F_S—sliding friction force; F_R—rolling friction force; $f(p) = f_r$—coefficient of resistance to rolling in tribopair; τ_W—frictional stress (specific friction force); p—contact pressure; $\sigma(\sigma_a)$—cyclic stresses (cycle stress amplitude); $f(p,\sigma) = f_\sigma$—coefficient of resistance to rolling in force system; p_0—maximum contact stress in center of contact zone; δ_c—approach of axes (in tribopair); μ_S—dimensionless parameter of interaction of damages caused by contact and off-contact load (frictional and mechanical stresses); f_F—complex indicator of friction in force system (friction index); a_r—parameter characterizing angle of slope of straight lines $f_\sigma(\pm\sigma_a/p_0)$ to abscissa axis; μ_p—dimensionless parameter of interaction of damages caused by contact and off-contact load (frictional and mechanical stresses); $f^{(s)}$—friction coefficient during pure rolling; $k_{\sigma/p}$—function taking into account effect of ratio $\sigma_{yy}^{(b)}/p_0$ on friction coefficient variations.

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