Yuriy SHALAPKO[*], **Norbert RADEK**[**]

ANALYSIS OF PHENOMENA IN REAL CONTACT SPOTS DUE TO DYNAMIC FORCING UNDER TANGENTIAL MICROMOTION

ANALIZA ZJAWISK W PUNKTACH STYKU RZECZYWISTEGO WYNIKAJĄCYCH Z DYNAMIKI MIKRORUCHU STYCZNEGO

Key words:

fretting-process, contact damage, partial slip, stick-slip, Hertzian contact

Słowa kluczowe

fretting-proces, uszkodzenie kontaktu, poślizg częściowy, stick-slip, kontakt Hertza

Summary

Currently, there are two basic concepts concerning surface damage processes: one connected with surface activation, which involves an increase in free energy in a tribological system, and the other connected with surface passivation, when free energy decreases. In oscillating tribocontacts, we observe intensive

---

[*] Khmielnytskyi National University, Instytutska 11, 29016, Ukraine,
e-mail: shalapko@yahoo.com.

[**] Kielce University of Technology, Al. 1000-Lecia P.P. 7, 25-314 Kielce, Poland,
e-mail: norrad@tu.kielce.pl.

formation of secondary structures of type I (Fe_2O_3, Fe_3O_4) and type II (FeO). Experimental and theoretical studies were conducted to determine the contact between a sphere and a plane, which is the most suitable system for simulating small-amplitude fretting (~ 0–3 microns). In a single point contact, we can observe all types of local surface damage in the radial direction depending on the relative slip amplitude (practically, from ~ 0), from absolutely elastic interaction in the central contact zone to the slip amplitude at the margin of the contact area in micrometers. It is very important to implement numerical and continuous integration of the stick-slip zones and calculate the contact stress and strain of the surface layer. Analyzing the influence of thermal fluctuation on the strength of materials, we can determine the parameters of activation of the surface damage at small-amplitude fretting.

INTRODUCTION

Fretting processes are determined by a complex set of mechanical, physical and chemical processes that occur in the contact zone between two surfaces in the presence of alternating tangential contact stresses. Partial slip contacts and the subsequent development of fretting damage occur in machine components under condition $F < \mu \cdot P$, where F and P are the tangential and normal forces applied to the contact pair. Partial slip is defined by the existence of stick and slip zones within the contact area. The effects of slip in the contact pairs were studied by Galin, Goryacheva, Pytko, Wierzcholski **[L. 1–4]**, as well as the phenomenon of fretting in the works of Szolwinski, Farris, Neyman, Rabinowicz, Nowell, and Hill **[L. 5–9]**.

In recent years, increasing attention of researchers is paid to quasi-static contact under dynamic loading **[L. 10–12]**. It can be argued that the state of the contact is typical for most real nominally fixed joints, where there are no obvious signs of relative displacement. The last statement requires a detailed discussion to determine the parameters of small-amplitude fretting.

The difficulty lies in the fact that, at certain loading of the surface layer, the amplitude-frequency response of small oscillations for the two bodies are practically the same, which excludes a priori, the relative displacement of the surfaces. However, during the investigation of the interface, the surfaces have obvious injuries typical for fretting. We can assume that an elastic interaction of two bodies in the tangential direction is enough to initialise fretting. The creation of a relationship between the surface characteristic of relative motion with dynamic microdisplacement and the following mechanism of the cracking of the surface is a very complex problem. The small amplitude fretting is characterised by the absence of global slip and multiple mechanisms of damage within the contact spot borders.

This paper attempts a first approximation to answer the question: Why do such small amplitudes of the slip, moderate loads, and the small number of cycles observed intense destruction of the surface? Is there a defining factor in the phenomenon of fretting that is not only the parameters of loading but also the presence of dynamic phenomena? Can structural dynamics effects play a role in interface behaviour?

EXPERIMENTAL TEST

The experiments were carried out on a fretting rig under dry conditions using the ball-on-flat configuration presented in **Fig. 1**. The material balls are bearing steel 100Cr6, diameter ϕ12.7 mm, HRC 62/66. A flat surface was represented by a specimen of steel 45 (HRC 40/43).

Fretting tests were carried out under a 50 N normal loading leading to a maximum Hertzian pressure around 1170 MPa. A reciprocating motion with a 20 Hz frequency and a number of fretting cycles from 5000 to 25000 was applied. Tests were conducted under constant relative humidity fixed at 50% and 20°C.

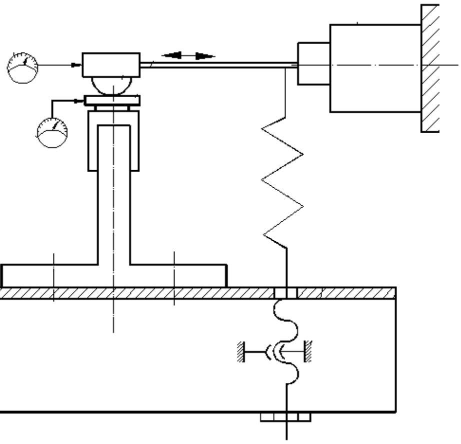


Fig. 1. Schematic drawing of the fretting rig
Rys. 1. Schemat instalacji do frettingu

Tangential force for contact is given directly by the vibrator. The regime of loading does not allow contact pair switches to global slip. Therefore, the relative displacements of the surfaces were determined using the Johnson method **[L. 6]** and the only for of the slip zone. In the stick zone, relative displacement is missing. This technique allows you to create the condition of fretting by controlled with amplitudes of a few microns or less. Achieving complete control over the sliding surfaces with this amplitude and frequency is possible only at sufficiently low normal loads. In this case, it may be neutralised of elastic deformations of the holders of specimens. Moreover, it is necessary to use a special driver with high precision.

Characteristics of wear and roughness parameters 3D of the contact zone were measured using a Talymap 3D – Talyscan 150 profilometer **(Fig. 5)**. It is a dedicated topography system that is fast, flexible and easy to use. Scanning a surface is done with a laser probe in 30-minute steps of 10 μm. Wear volume is calculated using profilograms. The surfaces were cleaned of oxides by means of deep ultrasonic treatment in a weak solution of nitric acid.

EXPERIMENTAL RESULTS

After cyclic loading of the contact area, geometric zones of stick and slip were measured. The amount of material that was destroyed in the slip zone was also determined. **Figure 2** shows the long-term evolution of the contact spots with partial slip. We note that at such small amplitudes (slip close to 1 ... 3 μm) there is a significant activation of the surface to fracture and oxidation. **Figure 3** shows the degree of destruction in inert material (glass) in the slip zone. In this case, when surface oxidation is limited, there is considerable destruction of the surface. We can assume a significant influence of the mechanical factor in combination with dynamic effects, which are obviously not sufficiently investigated.

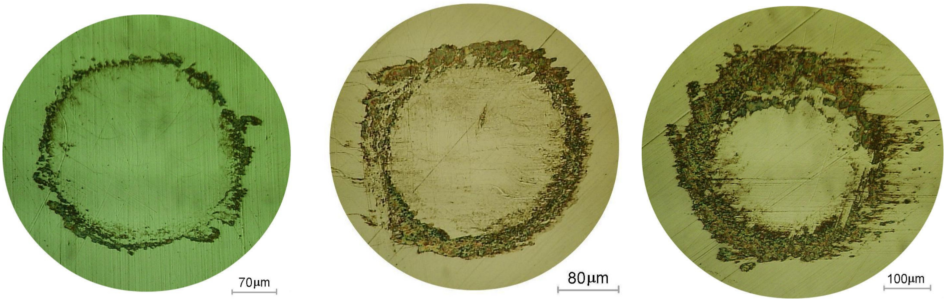


Fig. 2. The small amplitude fretting with partial slip regime for contact ball and the flat – $5 \cdot 10^3$, 10^4, $5 \cdot 10^5$ cycles respectively

Rys. 2. Niewielka amplituda frettingu przy częściowym poślizgu dla układu kula – powierzchnia płaska, odpowiednio przy $5 \cdot 10^3$, 10^4, $5 \cdot 10^5$ cyklach

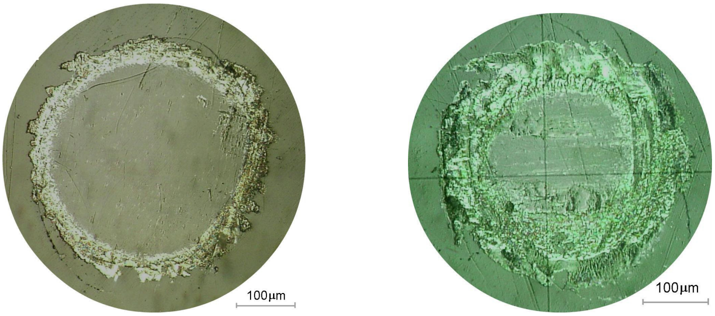


Fig. 3. Catastrophic damage to the marginal zone of contact for the glass surface in contact with steel ball – 7.5 · 10^3, 3 · 10^6 cycles respectively

Rys. 3. Uszkodzenie niszczące w strefie brzegowej kontaktu dla powierzchni szklanej będącej w kontakcie ze stalową kulą – odpowiednio 7,5 · 10^3, 3 · 10^6 cykli

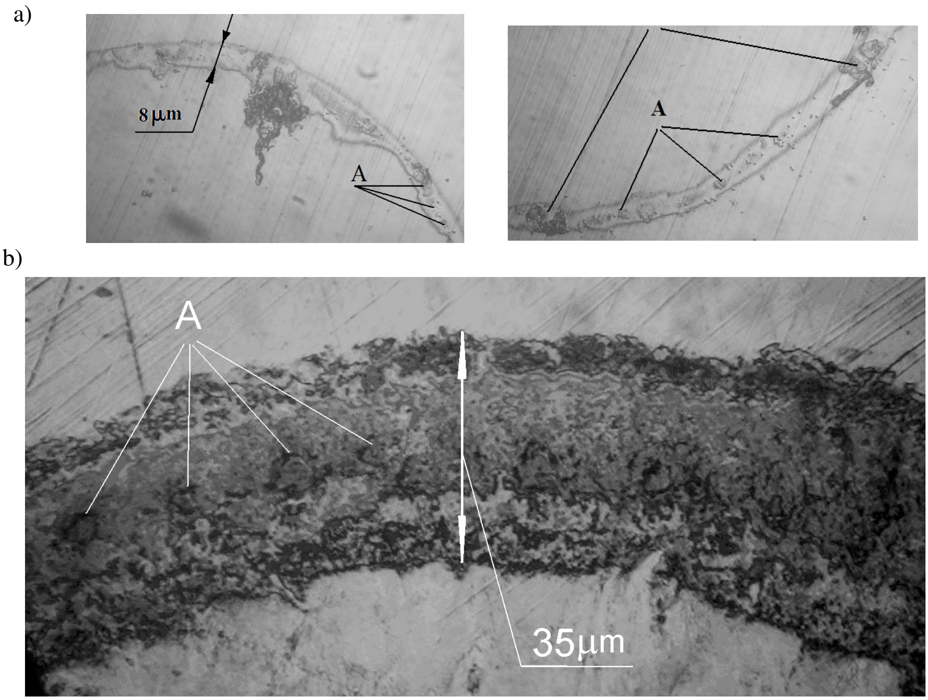


Fig. 4. Appearance of centres activation by generated into the slip zone (a) at 100 cyclic of loading steel surface. The structure of slip zone for steel C45 (b) at 10^4 cyclic of loading. The letter "A" shows the centres of activation in the middle of the slip zone, which correspond to the maximum work of friction forces (Fig. 7)

Rys. 4. Pojawienie się aktywnych centrów w strefie poślizgu (a) przy 100 cyklach przy obciążaniu powierzchni stalowej. Struktura strefy poślizgu dla stali C45 (b) przy 10^4 cyklach obciążenia. Litera „A" pokazuje aktywne centra w środku strefy poślizgu, co odpowiada maksymalnej pracy sił tarcia **(Rys. 7)**

Fig. 4 (a) represents the initial phase of the development of the fretting-process of the zone of slip with a width of 8 ...12 μm. The relative micro displacements of the surface, according to theoretical calculations, are very small and can be located within 0005 ... 0.5 microns. Apparently, in terms of energy, it is enough to have several cycles of oscillation for the start of the active destruction of an unstable form from the thermodynamic point of view of local areas of actual contact. The feature of the behaviour of individual point contacts is that the high normal pressure at these points and shear in the tangential direction leads to the formation of metallic bonds, which are destroyed and restored within a few cycles. The natural evolution of the contact seeks to reduce the tangential stress. The latter has the opportunity to take place because of the effects of cyclic micro-slip and subsequent deterioration. This surface activation of the centres of origin and further intensive destruction occur in the central slip zone and will be further theoretically justified by determining the maximum force of friction.

ANALYTIC SOLUTION

According to the thermofluctuational concept the thermal motion of atoms, molecules and other structural units is regarded as a decisive factor in the process of mechanical failure, and the process is the accumulation of breaks the basic chemical (atomic) and physical (intermolecular, intercrystalline, hydrogen) bonds in the bulk of the material as a result of fluctuations in thermal energy.

The kinetic approach to the evaluation of the long-term strength of materials, taking into account the thermal motion of atoms in the destruction of solids, was first proposed by S. Zhurkov **[L. 13, 14]**. He has confirmed that the external load itself does not lead to the rupture of atomic bonds but only intensifies the process of destruction. The stress concentration near defects and irregularities in this theory is presented as a reason for the localisation of the discontinuity of atomic bonds, leading to the birth and development of cracks. To characterise this temporal process in any critical stress is impossible. The most determining parameters reflecting the kinetic nature of fracture may be an indicator of strength, which can be determined by the following formula **[L. 13]**:

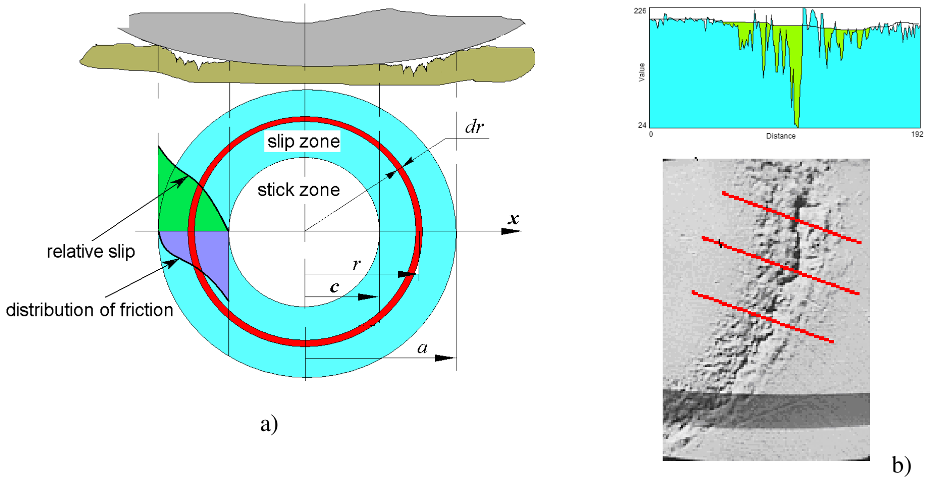
$$t = t_0 \exp \frac{(U_0 - \gamma\sigma)}{\kappa T} \qquad (1)$$

where t_0 is a constant equal to the period of oscillation of atoms, 10^{-13} s, U_0 is the initial energy of activation processes of destruction and creep for unloaded material, kJ/mol, γ is the structural-sensitive constant of material; it represents the activation volume, kJ/(mol·MPa); T is the absolute temperature of the material, K; σ is the equivalent stress due to loading, and κ is the Boltzmann constant.

We are interested in the following expression for the activation energy as a result of friction:

$$U(\sigma) = U_0 - \gamma\sigma \tag{2}$$

Here $\gamma\sigma$ expresses the direct work of the external load, and the remaining part $U(\sigma)$ expresses the thermal fluctuations. One can define energy and activation parameters of destruction in the ring zone of low-amplitude fretting according to the scheme presented in **Fig. 5**.



a)

b)

Fig. 5. Scheme of stick-slip zones and mixed oscillating contact with the distribution of the friction forces and relative displacement in the slip zone (a). Profilograms of slip zone (b)

Rys. 5. Schemat stref stick-slip i mieszanego kontaktu oscylacyjnego z rozkładem sił tarcia i względnym przemieszczeniem w strefie poślizgu (a). Profilogramy strefy poślizgu (b)

The slip rate for the point with radius *r* is defined by Johnson **[L. 6]** as follows:

$$\Delta S = \frac{3 \cdot \mu \cdot P_n}{16 \cdot G \cdot a}(2-\gamma) \cdot \left[1 - \frac{2}{\pi}\arcsin\frac{c}{r}\right]\left(1 - 2 \cdot \frac{c^2}{r^2}\right) + \frac{2c}{\pi r}\left(1 - \frac{c^2}{r^2}\right)^{\frac{1}{2}} \tag{3}$$

Distribution of friction forces $F(r)$ in the slip area $c \le r \le a$ from the condition of general equilibrium is determined, N, using the following formula:

$$F(r) = \int \tau(r) \cdot 2\pi r dr \tag{4}$$

where $\tau(r)=\frac{3}{2}\frac{\mu P}{\pi a^2}\left(1-\frac{r^2}{a^2}\right)^{\frac{1}{2}}$ is the distribution of tangential stress for the slip zone by acting parallel to the axis for entire the contact area and expresses by the Amonton's Law, N/m^2.

Then the work due frictional forces (J) at any point in the slip zone is defined by the following formula:

$$A_i(r)=F_i(r)\ \cdot\Delta S_i(r) \tag{5}$$

The energy density (J/mm^2) in the slip area is determined using the following:

$$\rho = \int_{s(c)}^{s(a)} \tau(x)\,dx \tag{6}$$

Figure 6 shows the distribution of a normal, tangential stress and the magnitude of relative slip. The distribution of friction forces in the field of circular spots $\left(\frac{F}{\mu \cdot P}=1\right)$ on the moment of transition to global slip is obtained from Formula (4). The area of sticking disappears $c=0$, and the friction of force in the centre increases to maximum force for static friction. In the conditions of partial slip ($\frac{F}{\mu \cdot P}<1$), the work of friction forces in the area of fretting are distributed according to parabolic law, which becomes significantly asymmetric and approaches the value μP **(Fig. 7)**. At $\frac{F}{\mu \cdot P}=1$, the work of friction and the friction is distributed. Since the relevant values of the friction and microslip meet one and the same parameter $r = x$, the function of friction work is found through parametric $F = f(x)$ and $S = s(x)$ **(Figs. 7, 8)**.

Thus, the work of friction for the regime of mixed contact in the middle of the microslip zone is a maximum and indicates the location of the initiation of micro cracks, which is a prerequisite for the destruction of the details to the mechanism of fretting-fatigue **(Fig. 7)**. Cumulated energy from friction is equal to the square shaped, bounded curve, $F = f(x)$, or determined using Formula (5) **(Fig. 9)**.

Thus, for the regime of mixed contact, the maximum friction works in the middle of the microslip zone and indicates the location of the initiation of micro cracks, which is a prerequisite for the destruction of the details to mechanism of fretting-fatigue **(Fig. 7)**. Cumulated energy from friction is equal the square shaped, bounded curve, $F = f(x)$ or by Formula (5) **(Fig. 9)**.

The kinetics of the accumulation of energy on the slip area is defined by (4). Given that the transition to a global sliding rarely occurs in excess $c/a = 0.5...0.6$ **[L. 16]**, it can be argued that the density of accumulation and dissipation energy in the zone with contour spots of contact is of the order 10^{-6} $\ldots 10^{-7}$ J/mm^2.

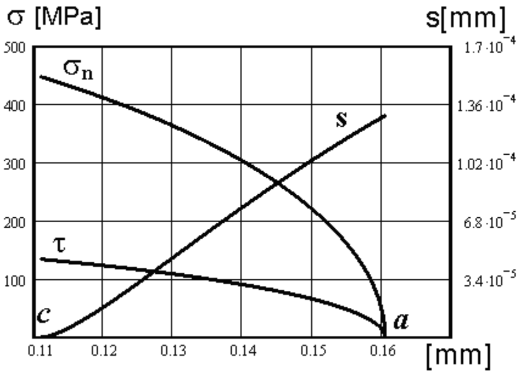


Fig. 6. Distributions of the relative slip s, normal σ and tangential stress τ for the field of sliding into the contact steel sphere on flat. The normal load P = 50 N, the tangential *F* = 10 *N*, the static friction coefficient is 0.3

Rys. 6. Rozkłady względnego poślizgu s, normalnych σ i stycznych τ naprężeń dla obszaru poślizgu styku stalowej kuli i powierzchni płaskiej. Normalne obciążenie P = 50 N, styczne F = 10 N, współczynnik tarcia statycznego 0,3

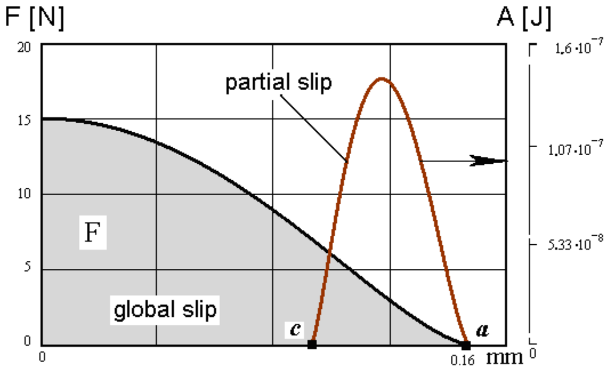


Fig. 7. The distribution of friction force in the contact spot at the moment of transition to global slip $F = \mu \cdot P = 50$ N ($c = 0$) and the work of friction for partial slip $F < \mu \cdot P = 10\ N$

Rys. 7. Rozkład siły tarcia w punkcie kontaktu w momencie przejścia do globalnego poślizgu $F = \mu \cdot P = 50$ N ($c = 0$) i pracy tarcia przy częściowym poślizgu $F < \mu \cdot P = 10\ N$

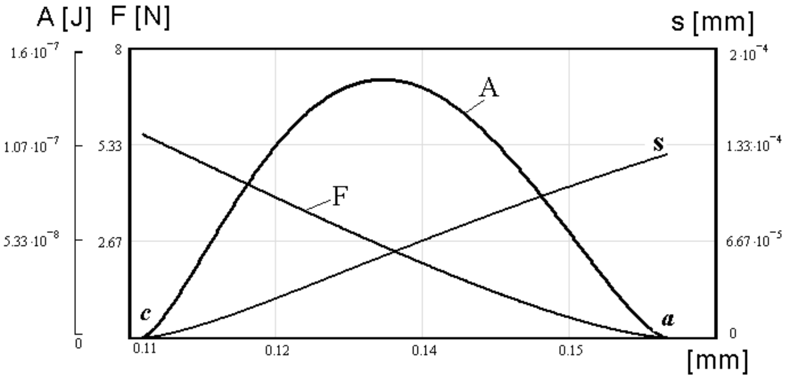


Fig. 8. Distribution of the relative slip s, work A and friction force F for the slip zone. The normal load $F = \mu \cdot P = 50$ *N*, the tangential $F < \mu \cdot P = 10$ *N*, the static friction coefficient is 0.3

Rys. 8. Rozkład względnego poślizgu s, pracy A i siły tarcia F w strefie poślizgu. Normalne obciążenie $F = \mu \cdot P = 50$ *N*, styczne $F < \mu \cdot P = 10$ *N*, współczynnik tarcia statycznego 0,3

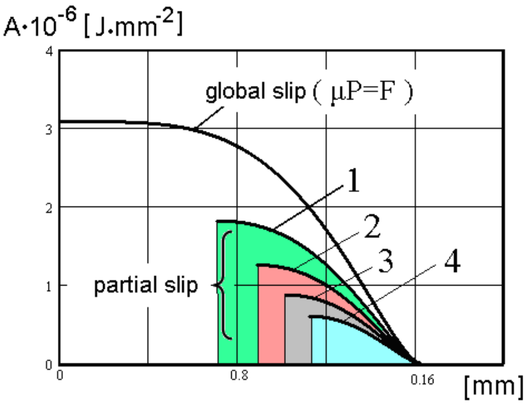


Fig. 9. The process of accumulation of frictional energy into contact from partial slip regime (1, 2, 3, 4) to global slip

Rys. 9. Proces akumulacji energii tarcia w kontakcie od częściowego poślizgu (1, 2, 3, 4) do globalnego poślizgu

ACTIVATION ENERGY OF THE SUBMICRON FRETTING-PROCESS

Let us return to the kinetic dependence of the fracture process of the material under stress (1). We have measured the wear as a molar loss of steel surfaces in the zone of slip under normal load 50 N, with an oscillating tangential 10 N

(Fig. 5). An experimental calculation of the activation energy of fracture U (σ) and structural-sensitive coefficient γ is presented in **Table 1**. We take into account the equality of the distribution of energy between two surfaces, as well as the fact that 10 ... 16% of the total frictional energy must be spent for destruction of the surface layer **[L. 17]**.

Table 1. Determination of activation energy in process of fracture and activation volume in the elementary act of destruction at small amplitude fretting

Tabela 1. Wyznaczanie energii aktywacji w procesie pękania i objętości aktywacji w elementarnym procesie uszkodzenia przy małej amplitudzie frettingu

Physical quantity	Experiment	Calculation	Constant	Results
J, mm^3/cycle, wear	+		10^5 cycles	$331\cdot10^{-11}$
υ, mm^3/mol, molar volume of steel	–	–	7093	
η, мм^2, activation area	+	$\pi(a^2-c^2)$		0.042 мм^2
ρ, J/(mm^2·cycle), energy density in contact		+		$1.5\cdot10^{-6}$
E, J/cycle, mechanical energy of the fracture		+		$32.5\cdot10^{-10}$
M, mol/cycle, amount of substance was destroyed in the slip zone	+	$M=\frac{J}{\upsilon}$		$4.67\cdot10^{-13}$
$U(\sigma)$, кJ/mol, activation energy of process of fracture		$U(\sigma)=\frac{E}{M}$		6.95
U_0, kJ/mol, activation energy of fracture of steel	+	From different sources	75 **[L. 9]** 200 **[L. 10]** 400 **[L. 11]**	
σ, MPa, equivalent stress in the slip zone according to von Mises **[L. 1]**		$\sigma=\sqrt{\sigma^2{}_n+3\tau^2}$		36
γ, кJ·mm^2/(mol·N), activation volume in the elementary act of destruction		$U(\sigma)=U_0-\gamma\sigma$ Accordingly U_0, from different sources		1.9 5.36 10.9
Avogadro constant			$6.02\cdot10^{23}$	
γ, nm^3		Accordingly U_0		3 8.46 17.2
γ, (cm)^3		Accordingly U_0		$300\cdot10^{-23}$ $846\cdot10^{-23}$ $1720\cdot10^{-23}$

DISCUSSION AND CONCLUSIONS

The magnitude of structure-sensitive coefficient γ for the activation energy of the fracture of metals from 75 to 400 kJ/mol according to the different sources **[L. 18–20]** shows a significant activation of the surface at low-amplitude fretting, compared to one direction of friction. In **[L. 18]**, we can see a scatter factor of 1 to 10. In our case, the possible values of the activation volume of the elementary act of destruction can be from 3 to 17.

It is clear that there are significant influences of dynamics on contact, which are superimposed on the thermal fluctuation vibrations of atoms in the crystal lattice of iron. These dynamic phenomena require several other approaches to describe them. We can affirm that the dynamic contact interaction and the phenomenon of cyclic microslip take place at a much lower threshold energy of the surface activation. It is important that, for the first time, a quantitative evaluation of the surface activity of metals under small-amplitude fretting has been obtained. The above results were obtained with 100000 load cycles. For further cyclic loading, with the condition of saving the configuration of spot contacts, the surface energy of activation is increased significantly. It eventually leads to the "freezing" zones of stick and slip. The fracture surface is actively growing after the transition of the contact to the regime of global slip. The energy of frictional sliding is also growing. However, in this case, the coefficient does not reach such high values as in the zone of microslip. Thus, we can make the following conclusions:

1. The energy of surface damage in the zone of partial slip contact has been calculated.
2. The volume of activation γ of the steel surface for the elementary act of destruction at submicron amplitudes of fretting-process has been defined.
3. Dynamic phenomena in the contact leads to a decrease in the surface of the threshold activation energy and is 2–4 times higher as compared to reciprocate friction and 4–7 times higher as compared with the destruction of steel under uniaxial tension

REFERENCES

1. Galin L.A., Goryacheva I.G., 1977: Axisymmetric Contact Problem of the Theory of Elasticity in the Presence of Wear, J. Appl. Math. Mech., 41, No. 5, pp. 826–831.
2. Goryacheva I.G., 1998: Contact Mechanics in Tribology, Kluwer Academic, Boston, MA.
3. Pytko S., Wierzcholski K.: The influence of variable friction coefficient on stress distribution in the contact zone of two rollers loaded with tangent forces (in Polish). Exploitation Problems of Machines, Polish Academy of Sci. 1, 25, 1976, pp. 32–44.

4. Pytko S., Wierzcholski K.: Elastohydrodynamic contact between two rollers in unsteady motion. International Journal of Friction Lubrication and Wear, vol. 55, 1979, pp. 245–260.
5. Szolwinski M.P., Farris T.N.: Mechanics of fretting fatigue crack nucleation. Wear, 198:93–107, 1996.
6. Szolwinski M.P., Farris T.N.: Observation, analysis and prediction of fretting fatigue in 2024-t351 aluminum alloy. Wear, 221:24–36, 1998.
7. Neyman A.: Fretting w elementach maszyn. Wydawnictwo Politechniki Gdańskiej, Gdańsk 2003.
8. Stowers I.F., Rabinowicz E., 1973: The Mechanism of Fretting Wear, ASME J. of Tribol., 95, pp. 65–70.
9. Hills D.A., Nowell D.: Mechanics of Fretting Fatigue. Kluwer 1994.
10. Fouvry S., Kapsa Ph.: An Energy Description of Hard Coatings Wear Mechanisms", Surface & Coating Technology, 138 (2001), p. 141–148.
11. Liskiewicz T., Fouvry S., Wendler B., (2003): Impact of variable loading conditions on fretting wear. Surface and Coatings Technology, 163–164, pp. 465–471.
12. Shalapko J., Gonchar V.: Modeling and real-time simulation for evolution of fretting-process // Proc. of 10-th International Carpathian Control Conference, Poland 2009, p. 483–486.
13. Zhurkov S.N.: On the basis of physical strength // Solid State Physics. T. 22, vol. 11, 1980, c. 3344–3349.
14. Zhurkov S.N., Narzullaev B.N.: Vremennaya zavisimost prochnosti tverdogo tela // "Zhurnal tehnicheskoi fiziki". T. 23, vol. 10, 1953, c. 1677–1689.
15. Johnson K.L. Contact Mechanics, Cambridge: Cambridge University Press; 1985
16. Shalapko Y.: Stick-slip regime of fretting for nominally – fixed joints / / Bulletin of Khmelnitsky National University (2007). № 5, s. 62–66.
17. Kragelski I.V., Dobyczin M.N., Kambolov V.S.: The basis of calculations on friction and wear. Moscow: Mashinostroenie 1977, 526 c.
18. Regel V.R., Slutsker A.I., Tomashsky A.E.: Kineticheskaya priroda prochnosti tverdyh tel // Uspehi fizicheskih nauk (1972),Vol. 106, № 2, c.193–223.
19. Jauhari I., Rozali S., Masdek N.R.N., Hiroyuki O.: Surface properties and activation energy analysis for superplastic carburizing of duplex stainless steel /Materials Chemistry and Physics, Vol. 122, Issues 2–3, (2010), p. 454–458.
20. Ibatullin I.D.: The kinetics of fatigue damage and fracture of surface layers // Samara: Samarskiy. gos. techn. univer., 2008, 387 c.

Streszczenie

Obecnie istnieją dwa podstawowe pojęcia dotyczące procesów uszkodzenia powierzchni: jedno związane z aktywacją powierzchni, które łączy się ze wzrostem energii swobodnej w układzie tribologicznym, a drugie związane z pasywacją powierzchni, gdy energia swobodna spada. W tribokontaktach oscylacyjnych obserwuje się intensywne powstawanie struktur wtór-

nych typu I (Fe_2O_3, Fe_3O_4) i typu II (FeO). Przeprowadzono badania eksperymentalne i teoretyczne, które miały na celu określenie kontaktu między kulą a powierzchnią płaską. Układ ten jest najbardziej odpowiedni do prowadzenia badań symulacyjnych frettingu o małej amplitudzie (0...3 mikrony). W styku punktowym obserwujemy wszystkie rodzaje miejscowych uszkodzeń powierzchni w kierunku radialnym zależne od względnej amplitudy poślizgu (praktycznie od 0), np. całkowicie sprężyste oddziaływania w centralnej strefie styku czy amplituda poślizgu na brzegu powierzchni kontaktu w mikrometrach. Należy zastosować całkowanie numeryczne i ciągłe w strefach stick-slip i obliczyć naprężenie i odkształcenie warstwy wierzchniej w miejscu styku. Analizując wpływ fluktuacji cieplnych na wytrzymałość materiałów, możemy określić parametry aktywacji zniszczenia powierzchni przy frettingu o małej amplitudzie.