A MODEL OF FRICTIONAL CONTACT IN MINIATURE POLYMER-ON-POLYMER JOURNAL BEARINGS

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SUMMARY

A model of contact between two rubbing surfaces of the journal and the bearing bush in polymer-on-polymer miniature bearings is presented and discussed. The prediction of frictional behaviour of such bearings is possible in particular during the transition from standstill to sliding.

Keywords: miniature journal bearings, polymer-on-polymer contact, modelling of friction

1 INTRODUCTION

Polymer-on-polymer miniature bearings are often embodied in small mechanisms of various applications. The frictional behaviour of such bearings is rarely investigated [1-4]. It relates in particular to the static friction i.e. the transition from standstill to movement in small mechanisms. The start-stop motion is often typical (e.g. in quartz watches or clocks). The time of standstill before movement plays also very important role in the operation of the discussed bearings. Such problems are very important also in MEMS (Micro Electro Mechanical Systems) devices since their elements are sometimes manufactured using polymeric materials [5-7].

To understand the frictional behaviour of miniature, journal polymer-on-polymer bearings a model of frictional contact for optimisation of the bearing design and the prediction of the frictional behaviour of such bearings was elaborated.

2 MODEL

The model is based on the assumption that it is possible to sum the adhesion and mechanical components of friction in the analysed polymer-on-polymer contact. Since the realistic area of contact (RAC) defines these two components of friction a model of RAC formation on nano-scale is elaborated. The load applied, roughness and rheological processes in the contact were taken into consideration. The Atomic Force Microscope (AFM) 3D images of the surfaces of polymeric journal and the bearing bush have been used in computer simulation.

A Winkler’s approach in modelling of the contact of the realistic surfaces on the elementary areas was applied and the deformation of the equivalent surface was defined (Figs 1 and 2). The nominal force of contact on the elementary discrete area of the AFM image \( S = \Delta x \Delta y \) (where \( \Delta x, \Delta y \) - distance between scanning lines) was calculated under consideration of compression when \( P(d) = (E/\kappa h) (S(d-z)) \), where

- \( E \) - reduced elasticity modulus,
- \( d \) - distance between surfaces,
- \( \kappa = (1+2v_1)/(1-v_1^2) \),
- \( h \) - normalized parameter which has physical meaning as the thickness of deformed layer and
- \( v_1, v_2 \) - Poisson’s ratios of the contacting materials.

The deformation is realized also by tensile in contact points in these areas where the distance between the surfaces is lower than the range of Van der Waals forces; the adhesion force was taken into consideration in this analysis.

By summarizing on all elementary contacts the total adhesive force \( F(d) \) and total deformation force \( P(d) \) acting on the considered part of the surface (adequate to the scanning area) were calculated for the selected approach of the surfaces \( d \).

If the applied load \( N \) is known, so by the solution of the equation \( F(d) + P(d) + N = 0 \) is possible to find the approach \( d = d_0 \) at which the load applied to the considered area \( F(d_0) + P(d) + N = 0 \) will be balanced with the reaction force \( P(d_0) \) acting against the compression of the deformed material.

The supporting contact area on the level \( d_0 \) determines the real area of contact (RAC) i.e. \( A_0 = \sum S_j \), or for the topography with uniform netting \( A_0 = \Delta x \Delta y n \) where: \( j \) - number of points when \( z_j > d_0 \), \( n \) - general number of points for which \( z_j > d_0 \). It is possible to find distribution of elongation and compressive forces \( F(d_0) \) and \( P(d_0) \) in the contact area.

As the result of the application of the viscoelastic contact it is possible to predict that during the process of contact of the rough surfaces under load (in the stress state) a creep of the polymeric material occurs. According the laws of the relaxation processes the elasticity modulus decreases i.e. \( E_{(p-1)} < E_{(p+1)} \).
As the result of the decrease of the elasticity modulus of the polymeric material the balancing deformation (at the constant load) of the polymer will occur which leads to the increase of RAC. The process of RAC formation in the polymer-on-polymer contact is continuous process as a function of time. After discretization and the elaboration of the algorithm it was possible computer modelling of RAC as a function of time.

For the determination of the rheological variation of the elasticity modulus it was assumed following time dependence of the elasticity modulus versus time:

\[ E(t) = E_0 - \delta E_0 (1-e^{-t/\tau}) \]  

where:
- \( E_0 \) - initial elasticity modulus,
- \( \tau \) - characteristic time of relaxation,
- \( \delta = (E_0 - E_\infty)/E_0 \) - coefficient determining the grade of rheological changes and, 
- \( t \) - time.

The Boltzmann’s superposition principle and viscoelastic functions according to Voight’ model were used to obtain this formula.

### 3 COMPUTER SIMULATION

In the computer simulation of the friction process it was assumed that during the relative motion of the rubbing surfaces during the initial phase of sliding it occurs the shearing in the elastic regime on the whole RAC. The initial RAC and the approach \( d=d_0 \) (adequate to the known external load \( N \)) can be determined for any combination of materials with known topography (by the use of AFM) and known physicomechanical properties (\( E, \nu, \gamma \) -surface free energy) by the application of computer modelling described above. For the determination of the friction force \( T \), adequate to minimum shearing force \( Q \) necessary to initiation of the relative sliding between the contacting surfaces on the area adequate to AFM images it was separately analysed the phenomena occurring during contact of:

* elementary areas of surfaces \( S_i = \Delta x \Delta y \) of RAC for which do not occur direct contact (Fig.1) but the distance \( l_i \) is in the range of molecular distance,
* elementary areas of surfaces \( S_i + \Delta x \Delta y \) of RAC for which occurs direct contact e.i. \( z_i > d_0 \) (see Fig.1).

In the first case the adhesive (non-contact) component of friction force \( T_{ad} \) was computed.

As the condition for sliding it was assumed that the value of the work of the shearing force must be higher than the energy of molecular interaction of contacting polymeric materials (the destruction of adhesive bonds will occur in such situation). The energy needed for the breaking of the adhesion bridge was calculated as the work of Van der Waals forces on the sliding distance from \( l_{ia} \) to \( \infty \) (where \( l_{ia} = d_0 - z_i \)). The condition relating to such situation is as follows:

\[ Q^2 > \frac{1}{z_{io}^2} \cdot 4CGS \cdot \frac{7}{3} \Delta \gamma \left( \frac{\nu}{l_i} \right)^2 \left( \frac{E}{l_i} \right)^{\nu+1} \int_{l_{ia}}^{\infty} dl_i \]  

where:
- \( C = \frac{\tan \alpha}{\tan^2 \alpha + 1} \), \( \tan \alpha = \frac{z_i^\prime}{\Delta x} \),
- \( G = \frac{E}{(1+\nu)} \), \( S_i = \Delta x \cdot \Delta y \),
- \( \Delta \gamma = (\gamma_i \cdot \gamma_j)^{1/2} \),
- \( l_{ia} = d_0 - z_i^\prime \),
- \( z_i^\prime \) - height of deformed Winkler’s layer,
- \( \Delta x \) - scanning step in AFM image in direction of sliding,
- \( G \) - reduced modulus of rigidity,
- \( E \) - reduced modulus of elasticity (Young’s modulus),
- \( \nu \) - reduced Poisson’s ratio,
- \( S_i \) - area of the base of one Winkler’s layer
- \( \Delta y \) - step of scanning perpendicular to the slide direction,
- \( \Delta \gamma \) - interfacial adhesive energy and \( \epsilon \) - reduced intermolecular distance.

Summarising of determined in such manner forces \( Q_i \) for the all Winkler’s layers for which it is fulfilled the condition of non-contact when the distance \( l_i \) is of the scale of intermolecular distances (\( l_i \sim \epsilon, \ l_i \geq \epsilon \)) gives, as the result, the non-contact (adhesive) component of friction force \( T_{ad} \) (being the result of adhesive interactions of the polymeric surfaces) was found i.e.:
\[ T_{ad} = \sum Q_i \quad \text{for Winkler’s layers at which} \]
\[ l_i = d_0 - z_i' \geq \varepsilon \]

In the second case the contact (mechanical) component of friction \( T_{mech} \) was computed. As the condition of sliding it was assumed that the value of work of the shearing force must be higher than the energy of the molecular interactions of the contacting polymeric materials being under contact load of known force \( P_i \) (it will occur the breaking of the permanent contact). The energy needed for the breaking of the permanent contact was computed as the work of Van der Waals forces for the sliding on the distance from \( l_{in} \) to \( \infty \), where \( l_{in} \) was determined from the formula:

\[
P_i = \frac{8}{3} \Delta \gamma \left[ \left( \frac{\varepsilon}{l_{in}} \right)^3 - \left( \frac{\varepsilon}{l_{in}} \right)^9 \right] \tag{3}
\]

For the determination of minimum value of the shearing force needed for the breaking the contact bridge on the area of one Winkler’s layer the aforementioned formula for \( Q_i \) can be used in which the lower limit of integration should be introduced as \( l_{in} \).

Summarizing of the determined by this way all forces \( Q_i \), for all Winkler’s layers for which is fulfilled the condition of direct contact i.e. \( z_i' < d_0 \) gives a the result the value of contact (mechanical) component of friction force \( T_{mech} \) (being the result of the mechanical interactions of contacting polymeric surfaces) i.e.:

\[ T_{mech} = \sum Q_i \quad \text{for the Winkler’s layers for which} \]
\[ z_i' < d_0 \]

For the estimation of the total friction force \( T \) needed for the relative displacement (sliding) of the contacting surfaces on the area adequate to the scanning area for obtaining AFM images it is necessary to sum two components of friction force (adhesive component \( T_{ad} \) and mechanical component \( T_{mech} \)) i.e. \( T = T_{ad} + T_{mech} \).

4 SUMMARY AND CONCLUSIONS

The experiments carried-out have shown that the increase of the friction coefficient and the time needed to transition from standstill to sliding (two parameters connected strongly with the process of increase of friction force) increase significantly during this transition phase as a function of the time of the standstill of the micro bearing under the load. It was found that about such behaviour decides the process of formation of RAC under the applied load. The model of viscoelastic contact in the analysed micro bearings with the use of AFM images was elaborated and the friction force was computed. The application of the 3D AFM images of the topography of the tested surfaces of polymeric elements enables to investigate adhesive and frictional processes of the formation and destruction of contacts in molecular scale. The results of the computer simulation of such contacts are in good agreement with the results of experimental measurements of the increase and decrease of the friction force as a function of sliding time during the transition from the standstill to sliding in the analysed polymer-on-polymer miniature journal bearings.

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6 REFERENCES