Determining the functional and material properties needed for abrasive wear prediction

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Abstract. Abrassive wear is a complex mechanical process with specific characteristics, dependent on the bodies velocities and load, the quality of contact surfaces, the mechanical properties of the superficial layers, lubrication etc. During the friction of the bodies in contact, the mechanical properties and the micro-topography of superficial layers change, most of the time irrecoverable, leading to the shut-down of the technical system they are part of. The present paper proposes a theoretical and experimental analysis of the abrasive wear behaviour of a coupling made of steel/cast iron as well as the detection of the wear trace dependent on the inclination angle of the harder material asperities (penetrator).

1. Introduction

Dependent on the nature and properties of the materials in contact, load and relative velocity, environmental characteristics, material behaviour under the action of some conic penetrators may be different. A surface crossed by such a penetrator with different inclination angles under a certain normal force may be deformed as a wave. It may result a ductile splintering and the breaking of the distorted material which is called micro splintering.

For the theoretical and experimental analysis of the surfaces deformation under the action of a conic or stacked penetrator (with different angles) the starting point was the following set of simplifying hypothesis [1, 2, 3, 4]:
- it is considered that in small loadings, the total number of microareas of some surfaces in contact tends to one, and in large loadings the microareas get united so that the nominal area tends to be equal to the real area;
- to evaluate the wear resulted, a parameter of the microgeometry (inclination angle of asperity $\alpha$) and the critical shear stress of the deformable material ($\tau_f$) are considered;
- it is considered that micro-splintering with detachment of wear particles occurs when the attack angle ($\alpha$ of the asperity or of the penetrator)is higher than a critical value ($\alpha_{cr}$).

To achieve the experimental researches a sliding motion stand was built where the cast iron sample is fixed and the mobile sample slides on it. The mobile sample is the knife-shaped penetrator with different angles ($\alpha = 3^\circ, 10^\circ, 20^\circ, 40^\circ, 60^\circ, 90^\circ$). The displacement of the mobile sample on the fixed one is $80mm$. The normal testing force that acts upon the mobile sample is $F_n = 17N$ for all tryings. The wear was measured for all cases in the central part of the displacement, on a lenght of $10mm$. 

2. Theoretical model

In order to characterize the abrasive resistance, the Archard wear coefficient is proposed, where the resistance parameter is the resistance to flow, rated on Vickers hardness. The geometry of Vickers penetrator leads to the 8% specific deformation which is considered more representative for contact phenomenon than the standard test value of the resistance to flow (2%).

So, the Archard wear coefficient is:

\[ k_A = \frac{U_V \cdot \sigma_{CV}}{F_n \cdot L_f} = \frac{h_u \cdot \sigma_{CV}}{F_n}, \]  

(1)

where \( U_V \) is the wear volume got after a friction length \( L_f \) and \( h_u \) is the wear trace depth.

The wear volume \( U_V \) evaluation may be conducted by computing the sectional area of the wear trace which appears after a number of friction cycles \( 40, 80, 160 \). It has been noticed that the Archard wear coefficient depends on the penetrator angle and the removal of the material volume as a wave occurs – according to Manson-Coffin theory – after a certain number of strain cycles. Figure 1 presents the Archard wear coefficient for plastic deformations dependent on the inclination angle of the asperity.

\[ \alpha \Rightarrow k_A(\alpha) \]

**Figure 1.** Variation of the Archard wear coefficient for plastic deformations dependent on the inclination angle of the asperity.

In order to know the moment of the wear particle occurrence it is necessary to define the state of deformation of the material layer located under the knife sample which is considered rigid.

The model Yang-Torrance [5, 6, 7, 8] is considered. According to the model, the material is submitted to deformations on axial and tangential directions under the penetrator action.

The shape of plastic deformation wave is dependent on the viscosity properties of the material and the size of axial and tangential deformation [7, 8, 9].

The Manson – Coffin cyclical degradation model defines a specific value \( C \) where the fracture is caused by deformation. Experimentally [4] this deformation is:

\[ C = \exp(a \varepsilon_f + b), \]  

(2)

where \( a, b \) are constant \( a = 1.62; b = 2.15 \) and \( \varepsilon_f \) is the deformation generated by the reduction of the section of a sample submitted to the pull fracture test.

When specific deformation \( C \) is greater than a critical value \( C_{cr} \) defined by Yang-Torrance, the wear leads to the occurrence of some deformation waves:
where \( \varepsilon_{ra}, \varepsilon_{rt} \) are the axial respectively, tangential relative deformation of the material.

The wear trace is considered uniform for a deformation smaller than the critical deformation \( (C < C_{cr}) \). It is considered that the micro-splintering wear occurs when the asperity or penetrator angle exceeds a critical value \( (\alpha_{cr}) \) for which the plane of the splinter’s angle of shear is positive [5, 6].

The entire wear process is dependent on the lubrication of the surfaces in contact, which is defined by the adhesion coefficient \( (f) \) and by the cold-tempering characteristic of the plastically-deformed/warped material, experimentally determined \( (C_n \simeq 0.8,...,1.2) \).

The adhesion coefficient is dependent on the following: the critical shear stress of the adhesion layer, the critical shear stress of the material and the lubrication of the surfaces in contact. For unlubricated materials, the adhesion coefficient is considered equal to one \( (f_n = 1) \), and for lubricated materials, with a consistent lubricate film, the adhesion coefficient tends to zero \( (f_f \approx 0) \).

Figure 2 presents the dependence of critical specific deformation function on the penetrator inclination (asperity) for different values of adhesion coefficient \( (f) \) and material \( (C_n = f) \).

Figure 3 presents the effect of lubrication upon the critical specific deformation for different inclination angles of the knife sample.

The number of strain cycles when deformation wear occurs is determined based on Manson-Coffin criteria.

\[
N_{fr} = \frac{C}{\varepsilon_{rt}}
\]  \hspace{1cm} (4)

and for micro-splitterng deformation \( (C > C_r) \):

\[
N_{for} = \left( \frac{C}{2\varepsilon_{ra}} \right)^2.
\]  \hspace{1cm} (5)
Figure 3. Critical specific deformation dependent on the penetrator angle.

3. **Experimental model**

The theoretical wear model in the process of slippage assumes to know the adhesion coefficient between the layer of the squeezed material and the rigid penetrator. In order to evaluate this characteristic, the experimental determination of friction coefficient by measuring the normal and tangential forces is conducted.

It is experimentally and theoretically known that the size of friction coefficient depends on the inclination angle of the penetrator and on the adherence given by the lubrication of the deformable material.

The friction coefficient between the two materials (steel/cast) is measured for a pressure $F_n = 17N$ in three cases of lubrication – fluid ($f$), limit ($l$) and dry ($u$) and using guide oil. Figure 4 presents the experimental values of friction coefficient for the coupling made of steel/cast iron, for all three lubrication cases, where the indicated values represent the average of five identical tries.

**Figure 4.** Experimental values of friction coefficient.
Depending on the measured values of the friction coefficients for the three lubrication conditions, the statistical mediums of the adhesion coefficient are established.

The geometry of the layer for specific experimental conditions are determined by measurements. The critical specific deformation of cast iron, function on the penetrator angle and lubrication in experimental conditions, is presented in figure 5.

The differences between theoretical and experimental values are given by the number of strain cycles the measurements were submitted to and, the eventual inaccuracy of measurement.

**Figure 5.** Critical specific deformation under experimental conditions

The wear rate (figure 6) may be defined taking into account both the Archard wear coefficient in the concept of deformation wear \( I_{\mu_d} \) and micro-splintering wear \( I_{\mu_{za}} \) for the three lubrication conditions, and the fact that the wear particle occurs after a number of strain cycles.

**Figure 6.** Evolution of wear intensity dependent on the penetrator angle.
4. Conclusions
The wear particle occurrence is dependent on lubrication, strain cycles and surface deformation. Thus, for deformation wear at the same angle $\alpha < \alpha_{cr}$, the number of strain cycles is higher for dry friction than for limit and fluid lubrication. In case of micro-splintering wear the situation is opposite thus, for the same angle $\alpha < \alpha_{cr}$, the number of cycles is higher for limit and fluid lubrication than for dry friction.

The theoretical results are valid for small numbers of cycles. If the cumulative effect were considered, than the theoretical results would be extrapolated for greater numbers of cycles.

A considerable agreement is noticed from theoretical and experimental analysis.

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