Validation of a micro-contact model to evaluate the mean friction factor at high sliding speed

G. LISTa, G. SUTTERb, J.J. ARNOUXa

a. LEM3, UMR 7239, Université de Lorraine - Ile du Saulcy 57045 Metz Cedex 1 France

Abstract:
Mechanical phenomena of dry friction are analyzed under conditions of high sliding speeds. Modeling the contact at the scale of asperities is conducted to understand the phenomena controlling the friction force. The friction factor is obtained by using an experimental device based on a compressed air launcher. To explain the evolution of the amplitude and friction forces, a numerical model based on the finite element method is proposed. This allows taking into account the different mechanisms of interaction when the asperities successively enter into collision. As the asperities shearing occurs at high strain rate and large deformation, a thermo-viscoplastic behavior coupled with damage law is introduced to better estimate the stress levels. The results of numerical simulations are coupled with experimental observations obtained by white light profilometer. The considered parameters are the sliding speed, the actual surface of contact and the overlaps of asperities. Different pairs of materials were explored (steel, titanium and tantalum) to validate the approach and propose a general method to find the mean value of the friction factors.

Key words: dynamic friction, micro-contacts, asperities, FEM.

1 Introduction
The interaction between solid surfaces is generally investigated through the friction factor such as described by the Coulomb’s model. When the sliding speeds tend toward extreme conditions the evaluation of friction factors become crucial to correctly represent the physical phenomena for a wide range of problems including metal forming and machining. The tribological contact with two loaded surfaces in relative motion is nevertheless very complex. The combination of high pressures and high sliding speeds increases the difficulty of the determination of the friction factor. In one hand, the experimental tests should reproduce the local conditions of high pressure and high speeds of the studied processes with the capability of the force measurement. These conditions were achieved in the present study with simple geometries of specimen mounted on a specific ballistic device [1–3]. In the other hand, the contact modeling must take into account the entire physical phenomenon susceptible to occur during the sliding [1,4]. Shearing of asperities is believed as one of the most important parameter controlling the force opposing to the sliding. A model at the level of micro-contacts of asperities is thus considered. The Finite element method, which is used to model the interaction, has the advantage to take into account most of physical parameters such as complex material behavior or damage consideration [5–7]. Understanding the processes that occur at the asperities level when two rough surfaces are brought into contact has the main objective to evaluate the magnitude of shearing stress occurring during the junction growth. The contact force can be determined by summing the mean shear stress taking place at each asperity in contact. The knowledge of the real surface in contact during the friction process remains very important to predict the values of the friction forces and friction factors. Correlation with experimental observations of the surfaces in contact is then necessary in order to explain the evolution of the amplitude of the friction forces in the different studied cases.

2 Experimental set-up
The surfaces of the bodies in contact were subjected to high sliding velocities by using a specific set-up; see Fig. 1 [2]. As shown in the figure, two plates labeled A are fixed on a dynamometer ring which imposes a normal pressure between the plates and the specimen. The tests were carried out at the velocity $V$ of 20 m/s with an apparent pressure $P_a$ of 50 MPa:
where \( S_a \) is the apparent surface corresponding to the area of a plate \( A \) in contact during the test (120 mm\(^2\)). The pressure magnitude is calibrated by adjusting the dimensions of the specimens leading to the normal force \( F_N \). Compressed air of the gas gun is used to propel a projectile through a launch tube on the specimen \( B \) with a rectilinear displacement. A set of strain gauges glued on a thin tube (the load sensor) supporting the ring records the axial component of the tangential forces \( F_T \). No running-in phase is present in this study since the aim of this work being the understanding and analysis of the initial phase of the dry friction process at room temperature. Two pairs of materials were selected, the first is a couple consisting in the same mild steel C22/C22 and the second is a couple of titanium alloy/tantalum. The friction factor \( \mu \) is then defined through the tangential and normal forces by:

\[
\mu = \frac{F_T}{F_N}
\]

FIG. 1 – Ballistic set-up for friction tests (a) device principle (b) schema of the specimen and plates.

3 Micro-contact model

Whereas the experimental set-up provides the friction force at macroscopic scale, the mechanism of the friction was simulated at the level of junction asperities by means of the finite element software ABAQUS in version 6.11 [8]. The explicit method was used to perform all the simulations. The modeling consists in collision of two asperities as illustrated in FIG. 2. The model combines a thermo-viscoplastic approach with damage consideration and fully thermo-mechanical coupling. The Lagrangian model in plane-strain assumption considers two deformable asperities with mixed triangular and quadrilateral elements. One of the asperities, representing the plates \( A \) in FIG. 1, is animated by a motion controlled by the imposed velocity \( V \) (20 m/s) whereas the second one, representing the specimen \( B \), is fixed at its basis. The asperities have a geometrical shape of an isosceles trapezium. This choice has the advantage to allow the geometry to be very various by changing the dimensions such as the height, the width of the bottom basis, and the approach angle.

FIG. 2 – Meshing of asperities for the collision process
In the present study, the height of the asperities is fixed at 5 μm. The overlaps of the two asperities can be changed and it is controlled by the parameter δ which represents a proportion of the height (0 ≤ δ ≤ 1). An asperity is also dependent of a bulk part in a rectangular form on which the boundary conditions were applied. For the couple C22/C22 the two asperities have the same mechanical properties, for the couple titanium alloy/tantalum the specimen in tantalum is fixed whereas the specimen in titanium alloy (Ta6V) is moving such as in the experiments. Physical parameters of the three considered materials are listed in Table 1, where ρ represents the material density, E and ν the Young’s modulus and Poisson’s ratio, k is the thermal conductivity, Cₚ the heat capacity and Tₘ the melting temperature.

<table>
<thead>
<tr>
<th></th>
<th>E (GPa)</th>
<th>ν</th>
<th>ρ (kg/m³)</th>
<th>k (W/m°C)</th>
<th>Cₚ (J/kg°C)</th>
<th>Tₘ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C22</td>
<td>210</td>
<td>0.3</td>
<td>7800</td>
<td>45</td>
<td>400</td>
<td>1530</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>114</td>
<td>0.34</td>
<td>4430</td>
<td>6.6</td>
<td>611</td>
<td>1600</td>
</tr>
<tr>
<td>Ta</td>
<td>186</td>
<td>0.35</td>
<td>16 650</td>
<td>54</td>
<td>153</td>
<td>2977</td>
</tr>
</tbody>
</table>

Table 1. Physical parameters of the considered materials

Metallic materials are also known for their strain rate dependence on the mechanical behavior. At the considered high velocity acting on a weak material volume represented by the asperity overlap δ, the effect of the high strain rate cannot be neglected. The thermo-mechanical response of the work material is modeled by the Johnson–Cook relation [9]:

$$\bar{\sigma} = \left( A + B \left( \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right)^n \right) \left( 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \left( 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^{C_2} \right)$$

(3)

where $\bar{\sigma}$ is the effective Von Mises stress, $\dot{\varepsilon}^p$ is the accumulated plastic strain and $\dot{\varepsilon}$ the equivalent plastic strain rate in the sense of Von Mises which are defined from the components of the strain tensor. The constant $A$ is the initial yield stress determined at the room temperature $T_r$ and at the reference plastic strain rate $\dot{\varepsilon}_0$. The parameters $B$ and $n$ are respectively the strain hardening modulus and exponent while $C$ is the strain-rate sensitivity coefficient. The parameter $m$ controls the thermal softening taking into account $T_m$ the melting temperature of the sample. The values for the Johnson–Cook’s parameters used in simulations are given in Table 2. In order to perform the material separation leading to a prospective material transfer, a computational failure model based on the Johnson–Cook’s damage law [10] was also considered. Failure of one element is done when damage parameter $\omega$ exceeds the critical value of 1. The damage parameter follows a cumulative damage law:

$$\omega = \sum \left( \Delta \bar{\varepsilon}^p / \bar{\varepsilon}^f \right)$$

(4)

where $\Delta \bar{\varepsilon}^p$ is the increment of the effective plastic strain that occurs during an integration cycle and $\bar{\varepsilon}^f$ the equivalent strain to failure defined by:

$$\bar{\varepsilon}^f = \left( d_1 + d_2 \exp \left( d_3 / \bar{\sigma}_m / \bar{\sigma} \right) \right) \left[ 1 + d_4 \ln (\dot{\varepsilon} / \dot{\varepsilon}_d) \right] \left[ 1 + d_5 \left( (T - T_r) / (T_m - T_r) \right) \right]$$

(5)

where $\sigma_m$ is the hydrostatic pressure $d1$, $d2$, $d3$, $d4$, $d5$ are the damage failure material constants and $\dot{\varepsilon}_d$ the strain rate reference, see Table 3. At high friction velocity, flash temperature and material thermal softening might be attributed to enhanced plastic yielding at elevated temperature from plastic deformation of asperities. The temperature rise due to the plastic deformation is estimated by assuming the conversion of plastic work into heat through the Taylor-Quinney factor which is currently chosen at 0.9 [11]:

<table>
<thead>
<tr>
<th>A(MPa)</th>
<th>B(MPa)</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>$T_r$</th>
<th>$\dot{\varepsilon}_0$</th>
<th>d1</th>
<th>d2</th>
<th>d3</th>
<th>d4</th>
<th>d5</th>
<th>$\dot{\varepsilon}_d$ (μm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C22</td>
<td>520</td>
<td>269</td>
<td>0.282</td>
<td>0.0473</td>
<td>0.53</td>
<td>25</td>
<td>1</td>
<td>0.24</td>
<td>1.1</td>
<td>-1.5</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Ta6V</td>
<td>862.5</td>
<td>312</td>
<td>0.34</td>
<td>0.012</td>
<td>0.8</td>
<td>25</td>
<td>1</td>
<td>0.27</td>
<td>0.48</td>
<td>0.014</td>
<td>3.87</td>
<td>1</td>
</tr>
<tr>
<td>Ta</td>
<td>684.5</td>
<td>205.3</td>
<td>0.78</td>
<td>0.1</td>
<td>0.425</td>
<td>25</td>
<td>3500</td>
<td>0.7</td>
<td>0.32</td>
<td>-1.5</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Parameters of the material constitutive equations for the mild steel [12,13] titanium alloy [14,15] and tantalum[16,17].
4 Results and discussion

The normal force $F_N$ is imposed during the test by Equation (1) while the tangential force $F_T$ may be estimated by the contribution of shearing stress $\tau$ for each asperity in contact.

$$F_T = \tau \alpha_{eff} S_a$$  \(6\)

The factor $\alpha_{eff}$ ($0 \leq \alpha_{eff} \leq 1$) represents the fraction of the contact area which actually contributes to shear. Both the values of $\tau$ and $\alpha_{eff}$ must be known in order to predict the friction factor $\mu$ [18]. The shear stress $\tau$ was evaluated by the mechanisms of junction growth simulated by the proposed micro-contact model. In the simulations, strong junctions were considered, i.e. the junctions were modelled by a rough contact and slipping between the surfaces cannot exist. Since the shearing volume influences the magnitude of the strain rate and damage phenomena, two values for the overlaps $\delta$ were also considered as illustrated in FIG. 3 and FIG. 4. Note that failure occurs in the part consisting of titanium alloy as experimentally observed in the mechanism of material transfer [19]. The tangential stress for an asperity can vary according to the time $t$ from the beginning to the end of the contact. The value of the tangential shear can be evaluated by the mean of the average shear stress component $\sigma_{xy}$ determined along the upper basis of length $w$, see FIG. 2.

$$\bar{\tau}_a(t) = \frac{1}{w_0} \int_{w_0}^{w} \sigma_{xy}(x) dx$$  \(7\)

where $x$ is the distance along the upper basis of an asperity. The maximum is generally reached before the damage initiation. Thus the possible values for the shear stress may be estimated in a certain range. The magnitude of mean shear stress was estimated ranging between 220 MPa and 590 MPa in the case of the steel and between 280 and 690 MPa for the tribo-pair Ta6V/Ta. These values result of a competition between the strain hardening, strain rate hardening, temperature softening and failure process.

![FIG. 3 – Shear stress for the pair C22/C22. (a) with an overlap of 0.25 (b) with an overlap of 0.5.](image)

![FIG. 4 –Shear stress for the pair Ta/Ta6V. (a) with an overlap of 0.25 (b) with an overlap of 0.5.](image)

A possible way to estimate the factor $\alpha_{eff}$ is to compare the surface profiles in contact before and after the friction test, as illustrated in schematic principle in FIG. 5. The mean value the factor $\alpha_{eff}$ may be estimated from the optical observation by:

$$\alpha_{eff} \approx (\sum L_i)/L_0$$  \(8\)

It is suitable to study the profiles on the specimen $B$, since the contact takes less time than for the plates $A$. 

4
Illustrations in FIG. 6 show the evolution of the sliding surface on the specimen B for the case of the pair C22/C22. The profile was obtained by white light interferometry. The measurement was realized for a very short duration time of friction which limits the successive interactions and allows the definition of $\alpha_{\text{eff}}$ from the formula in equation (8). It was found that the factor $\alpha_{\text{eff}}$ has a relatively weak value ranging between 0.03 and 0.05. In the case of the pair Ta6V/Ta, the results give similar values although slightly higher reaching sometimes 0.07 due to the mechanisms of material transfer and micro-welding [19].

FIG. 6 – Evolution of the sliding surface measured on the mild steel specimen.

FIG. 7 presents the comparisons between the experimental results ($F_{\text{exp}}$) and the estimation of $F_T$ obtained with the formula in Equation 6. To obtain the frame values presented in FIG. 7, the minimal and maximal forces $F_{\text{min}}$ and $F_{\text{max}}$ were given considering the minimal and maximal shear stress estimated by the numerical simulations. The mean value of 0.04 for the factor $\alpha_{\text{eff}}$ was here selected. The results must be considered to validate the approach mainly for the beginning of the friction process, where the estimation of the shear stress by simulation and the value of $\alpha_{\text{eff}}$ are more representative. The average value $F_{\text{av}}$ from the predicted friction forces $F_{\text{min}}$ and $F_{\text{max}}$ gives finally a good estimation of the friction force $F_T$.

FIG. 7 – Evolution of the friction force and the possible values predicted by the model for different tribo-pairs. (a) mild steel/mild steel (b) titanium alloy/tantalum.

5 Conclusion

In order to evaluate the friction force and friction factor, a model based on the interaction of single pair of asperities was used to calculate the mean shear stress during the junction growth. The results were coupled
with optical observations of surface profiles. The knowledge of the effective real surface contributing to the shearing process coupled with the estimation of the magnitude of shear stress given a range of possible value for the friction forces. The variation of the friction forces observed in experimental were well estimated both the case of the mild steel and titanium/tantalum samples. This suggests that the proposed method could be used to predict the value of the friction coefficient for a wide range of conditions and materials. Future investigations regarding the evolution of the contact surface and the temperature effect with the sliding distance and contact time should be conducted in order to better estimate the mean friction factor at high sliding velocities. The consideration of other types of junctions such as weak contact, where asperities slide on each other, would present another way to better estimate the friction stress among the whole population of asperities in contact.

References