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A new model for friction under shock conditions

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Abstract. This article is aimed at the developpement of a new model for friction under shock conditions. Thanks to a subgrid model and a specific Coulomb friction law, it takes into account the interface temperature and deformation but also the influence of asperities when the contact pressure is relatively low (≤3 GPa).

1 Introduction

Dry friction is a common phenomenon, that everybody can experiment during his every day life. It has been widely studied since Da Vinci, Amontons and Coulomb. However many dry friction situations are still unknown or misunderstood. For example, we may cite the recent experiment of Camara et al. [2008], which consists in peeling tape under vacuum. This action produces enough X-ray, a phenomenon called X-triboluminescence, to make a radiography of the physicist's finger.

Dry friction involves a wide range of physics and chemistry phenomena, as plastic deformation, melting, oxidation, adsorption, desorption, thermal conduction, acoustic emission, vibrations, light emission... which occur at various scales, from atoms to continents.Those particularities explain why this is a particularly complex matter and why there is almost no formalism to modelize it. Moreover, it occurs under various conditions of loading, from every day life friction to aircraft break systems with contact pressure up to few MPa and sliding velocity up to 10 m.s^{-1}.

In our case, we are interested in classical shock conditions: contact pressure ranging from 1 GPa to 50 GPa and sliding velocity up to 1000 m.s^{-1}.

Only few studies have been conducted under those very specific contact conditions. We can cite the works of Bowden and Freitag [1958], Bowden and Persson [1961], Montgomery [1976], which were dealing with very high speeds but relatively low contact pressure.

Rajagopalan et al. [1999], Irfan and Prakash [2000], Liou et al. [2003, 2004], Yuan et al. [2009] realized plate impact experiments under high sliding velocity and contact pressure up to 5 GPa. The fact that one of the plate remains fully elastic, allows the physicists to determine directly the stress at the contact interface from the measure of the velocities on the free surface of the plate. Thus the friction coefficient is determined without inverse analysis. However, the contact pressure is limited by the elastic domain of the plate. Another way of studying friction under shock loading is by the mean of NEMD (Non-Equilibrium Molecular Dynamics). The reader will refer to Hammerberg et al. [2007] for more information about it. However this kind of approach is limited by the small volume of material that the physicist is able to calculate.

In order to obtain high contact pressure (> 5 GPa), new experiments are necessary, such as those of Winter et al. [2006] or Juanicotena [2006]. This article, introduces a new model for friction between metallic materials under these very specific shock conditions. The results obtained numerically will be compared to experimental ones. The experimental setup introduced by Juanicotena [2006] is used here.

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2 A new model

2.1 Physic of friction under shock conditions

The extreme conditions existing in the core of contact, simplify the problem of friction. First of all, the loading time scale is about $1\,\mu$s which is sufficiently small to avoid formation and circulation of wear inside the contact. The thermal conduction cannot take place neither and this results in the existence of a very thin boundary layer (few μm) heated by the friction of the interface. As shown by Winter et al. [2006], the two competing phenomena that govern the behavior of the surface are the thermal softening, due to the strong heating of the boundary layer, and the hardening of the surface governed by the pressure, the strain and the strain rate. It is important to note that the heat generated can be such that the melt temperature is reached.

2.2 DLP model

The size of the boundary layer prevents classical hydrocodes to take it into account. That's why a 1D subgrid model, called DLP, has been developed [Dambakizi et al. 2009]. It accounts for frictional contact, elastoplastic yielding and work hardening, heating by friction and plastic work, thermal softening and melting, as well as dynamic effects. Its main purpose is to obtain the interface temperature due to frictional heating. For more details about the algorithm used, the reader is referred to Dambakizi et al. [2009]. We will focus hereafter on the description of the friction law. This last one is a Coulomb-Tresca like:

$$\tau = min(\mu P; Y(P, T_i)) \tag{1}$$

It is composed of a Coulomb part: μP where the friction coefficient is constant : $\mu = cst$. P is the contact pressure. The second part is Tresca like. The yield limit is described thanks to a Steinberg-Cochran-Guinan model Steinberg et al. [1980] which takes into account pressure hardening and thermal softening. The exponential term is here to take into account possible melting of the boundary layer:

$$\begin{aligned} &Y(P, T_i) = f\frac{Y_{max}}{\sqrt{3}}(1 + g\,P - \beta\,(T_i - 300))\,e^{\frac{-0.001*T_i}{T_F - T_i}} \\ &f \in [0; 1]. \end{aligned} \tag{2}$$

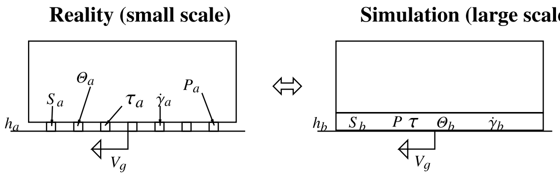
Here T_i is the flash interface temperature, T_F is the melt temperature, Y_{max} β and g are the pressure and temperature dependance parameters of the SCG model. With only two friction parameters μ and f, this friction law, coupled to the subgrid model, describes correctly the experimental curves obtained for high impact velocity. However for low impact velocity and in the low contact pressure range, it failed because of the lack of description of the friction phenomenon under this conditions. The hypothesis made hereafter is that at relatively low contact pressure the deformation of asperities and of surface irregularities may play an important role. In order to take into account their behavior, the Coulomb part of the DLP model is modified into a new one to obtain the T/P model.

2.3 T/P model

To develop this model we simplify the shape of asperities to rectangular ones as shown in Fig. 1. We suppose all asperities identical.

The asperities and the boundary layer are supposed to shear adiabatically. Thus we have for the asperities:

$$\begin{aligned} &\text{Plastic work} = \text{Heat generated} \\ &\sqrt{3}\tau_a\dot{\gamma}_a\,S_a\,h_a = \rho C_P\,S_a\,h_a\dot{\Theta}_a \end{aligned} \tag{3}$$



Reality		Simulation	
h_a :	asperities heigth ;	h_b :	heigth of the boundary layer
S_a :	asperity surface ;	S_b :	apparent surface ;
Θ_a :	température inside asperities ;	Θ_b :	interface temperature
τ_a :	shear stress inside asperities ;	τ :	friction stress ;
V_g :	sliding velocity ;	$\dot{\gamma}_b$:	shear rate inside the boundary layer;
$\dot{\gamma}_a$:	shear rate inside asperities ;	P :	contact pressure;
P_a :	pressure inside asperities ;	ρ :	density.
C_P :	specific heat capacity.		

Fig. 1. Multiscale approach.

and for the boundary layer:

$$\text{Plastic work} = \text{Heat generated}$$
$$\sqrt{3}\tau\dot{\gamma}_b S_b h_b = \rho C_P S_b h_b \dot{\Theta}_b \tag{4}$$

By assuming a number n of asperities, the equality of the power dissipated yields to:

$$n\rho C_P S_a h_a \dot{\Theta}_a = \rho C_P S_b h_b \dot{\Theta}_b \tag{5a}$$
$$n\tau_a \dot{\gamma}_a S_a h_a = \tau\dot{\gamma}_b S_b h_b \tag{5b}$$

Noting m the surface ratio defined by $m = \frac{nS_a}{S_b}$, we get:

$$(5a) \rightarrow \dot{\Theta}_a = \frac{1}{m}\frac{h_b}{h_a}\dot{\Theta}_b \tag{6a}$$
$$(5b) \rightarrow \tau\dot{\gamma}_b h_b = m\tau_a\dot{\gamma}_a h_a \tag{6b}$$

The shear rate of the asperity and the boundary layer are respectively approximated by $\dot{\gamma}_a = \frac{V_g}{h_a}$ and $\dot{\gamma}_b = \frac{V_g}{h_b}$. Then equation (6b) simplifies into:

$$\tau = m\tau_a \tag{7}$$

Because of the plastic deformation of the asperities, the shear stress inside them τ_a is equal to the yield stress of the material Y_a. Then:

$$\tau = m\frac{Y_a}{\sqrt{3}} \tag{8}$$

We retrieve, the Shaw's friction law used in metal forming simulation Shaw et al. [1960]. As for the DLP model, a Steinberg-Cochran-Guinan model Steinberg et al. [1980], is chosen to describe the evolution of the yield stress:

$$\tau = m\widetilde{Y}[1 + gP_a - \beta(\Theta_a - 300)] \tag{9}$$

Here $\widetilde{Y}$ is a constant whose value is between $\frac{Y_0}{\sqrt{3}}$ and $\frac{Y_{max}}{\sqrt{3}}$. The multi-scale approach, then leads to:

$$(\Theta_a - 300) = \frac{1}{m}\frac{h_b}{h_a}(\Theta_b - 300) \tag{10a}$$
$$\tau = m\widetilde{Y}[1 + gP_a - \beta(\Theta_a - 300)] \tag{10b}$$

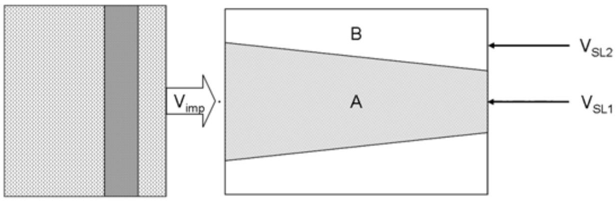


Fig. 2. Experimental setup.

where equation (10a) is obtained by integrating equation (6a). Here, we didn't take into account the variation of m, h_a, and h_b. This approximation allows a straigthforward integration. Inserting equation (10a) in equation (10b), we get:

$$\tau = m\widetilde{Y}\left[1 + g\frac{P}{m} - \beta\frac{1}{m}\frac{h_b}{h_a}(\Theta_b - 300)\right]. \tag{11}$$

where the $\frac{P}{m}$ term is due to force equilibrium:

$$n\,S_a\,P_a = S_b\,P_b \Rightarrow P_a = \frac{P}{m}$$

Greenwood and Williamson [1966] have shown, that the surface ratio m is proportional to the applied pressure P (12) then equation (11) turns in (13).

$$m = \alpha P \tag{12}$$

$$\tau = \widetilde{Y}\left[(\alpha + g)\,P - \beta\frac{h_b}{h_a}(\Theta_b - 300)\right] \tag{13}$$

Finally the friction coefficient is obtained:

$$\mu = \frac{\tau}{P} = \widetilde{Y}(\alpha + g) - \widetilde{Y}\beta\frac{h_b}{h_a}\frac{(\Theta_b - 300)}{P} \tag{14}$$

$$\Rightarrow \begin{cases} \mu = \mu_0\left(1 - k\frac{(\Theta_b - 300)}{P}\right) \\ \mu_0 = \widetilde{Y}\,(\alpha + g) \\ k = \frac{\beta}{\alpha + g}\frac{h_b}{h_a} \end{cases} \tag{15}$$

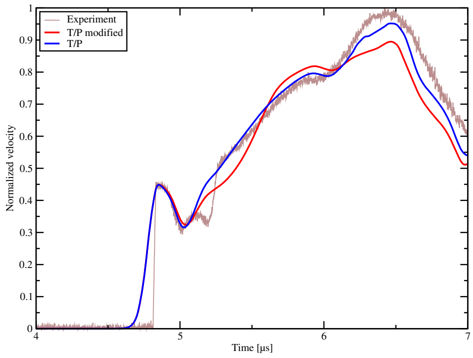
Noting $T_i = \Theta_b$, the T/P model simplifies into:

$$\begin{cases} \tau = min(\mu(P, T_i)P; Y(P, T_i)) \\ \mu(P, T_i) = \mu_0\,(1 - k\frac{(T_i - 300)}{P}) \\ Y(P, T_i) = f\,\frac{Y_{max}}{\sqrt{3}}(1 + g\,P - \beta\,(T_i - 300))\,e^{\frac{-0.001 * T_i}{T_F - T_i}} \\ f \in [0; 1]. \end{cases} \tag{16}$$

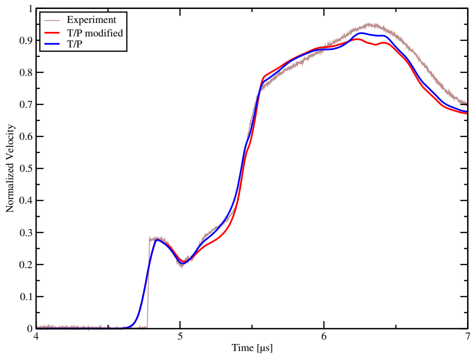
3 Comparison to experiment

In order to test the T/P model, the experimental setup of Juanicotena [2006] has been used for two metallic materials. It consists in an plate impacting a target. It is composed of a male cone, A, inserted into a female one, B, whose impedance is higher in order to ensure contact between them (Fig. 2).

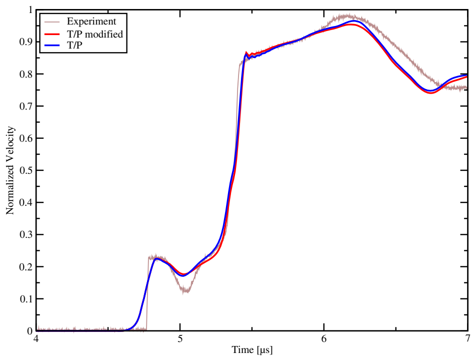
Figure 3 presents the velocity at the center of the cone, V_{SL1} on Fig. 2 (see Juanicotena [2006]) for four different experiments. The contact pressure and the sliding velocity increase from the first shot to the the third one. Fourth shot is the same as the second one except that the angle of the cone



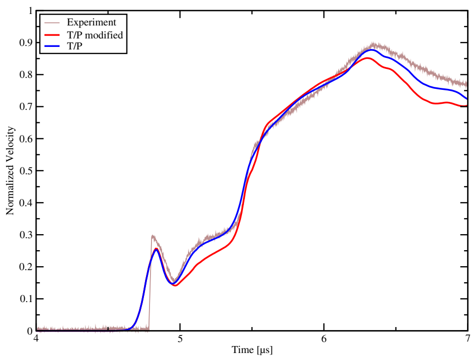
(a) First shot



(b) Second shot



(c) Third shot



(d) Fourth shot

Fig. 3. Comparison between the models and the experiments.

is smaller. We note a very good agreement between experiments and model T/P. The same model but with a constant friction coefficient inside the Coulomb part (called T/P modified model in Fig. 3) gives different results especially in the bottom of the curves and for the shot with the smallest contact pressure (first one). It underlines the fact that the T/P model is suited for relatively low contact pressure (up to 3 GPa), where the asperities are not totally flat.

4 Conclusion

A new model, named T/P, has been set up to take into account the influence of asperities and surface deformation on the behavior of a surface submitted to frictional shock loading. It is able to calculate the flash temperature rise thanks to a subgrid model developped by Dambakizi et al. [2009]. This model is made of a temperature and pressure dependant Coulomb friction law and of a Tresca law.

It has been checked by comparison with experiments designed by Juanicotena [2006] on two metallic materials. The numerical results are in agreement with experimental ones.

Despite its simplicity, the Coulomb law improves the low pressure description of the model. Thus, with three friction parameters, μ_0, k and fY_{max}, the T/P model allows good correlation between experimental and numerical signals.

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