Non-local and Numerical Formulations for Dry Sliding Friction and Wear at High Velocities

Adam Łodygowski[1]

[1]*Department of Civil and Environmental Engineering, Poznan University of Technology*
Piotrowo 5, 60-965 Poznan, Poland
e-mail: adam.lodygowski@put.poznan.pl

Abstract

Severe contact stress problems generate high temperature and create thermomechanical gouging and wear due to high velocity sliding between two materials staying in contact. In order to improve the facilitation of the design of particular components and improve performance of these engineering applications, it is necessary to better understand the physical behavior of high speed environment. As presented here this environment is made up of two components in contact. Therefore, basing on the experimental approach [1, 2] the major consideration is aimed to develop an experimental/theoretical model for the material constitutive behavior in order to better characterize and predict the internal failure surrounding the gouging and wear events.

Keywords: contact mechanics, damage, multiscale problems, plasticity, solid mechanics

1. Introduction

There is an increasing need to improve the reliability and life of tribological components that are prone to severe contact stresses in engineering applications such as cutting tool for metals, gun tubes, engine exhaust valves, engine turbocharger components, rail gun environment, jet engine gear box splines and gears, and slippers on high-speed test track sleds. Severe contact stresses in such applications generate high temperatures and creates thermomechanical gouging and wear due to high velocity sliding between contacting materials. In order to better facilitate the design components and improve performance of these engineering applications, it is necessary to first understand the physical behavior of high speed environment that is made up of two major components in contact. This contact, at hypervelocity, can cause two important phenomena such as gauging and wear. These highly complex coupled problems require the solutions of three conservation equations such as mass, momentum, and energy, as well as the establishment of two relationships such as material constitutive model and an equation of state.

2. Theoretical Model for Contact Problems with Friction

The theoretical model is considered within a thermodynamic framework, where it is assured that the principles of thermodynamics are satisfied. Therefore, the virtual power relations are first defined and the principle of the virtual power along with the variational formulation are used to developed governing differential equations and their boundary conditions of the proposed theory. The principle of virtual power utilizes approach used in [3] where the principal of virtual power is modified by adding the contributions from damage and its corresponding gradients as a measure of micro motion of damage within the bulk. In addition two internal state variables are introduced on the contact interface, one measuring the tangential slip and another measuring the wear. By using these internal state variables together with displacements and temperature, the constitutive model is formulated with state laws based on the free energies and the complimentary laws based on the dissipation potentials. This model provides a potential feature for enabling one to relate the non-local continuum plasticity and damage of the bulk material to friction and wear at the contact interfaces.

In order to achieve it one needs to define a region $V \subset \Re^d$ $(d = 2, 3)$ with a piecewise smooth boundary Ω that occupies a continuously deformable body. The boundary Ω is divided into three disjoint parts; Ω_t is the part of the boundary where the tractions are prescribed whereas the displacements are prescribed at the boundary Ω_u, and the unilateral contact interface is defined by the boundary Ω_c. The contact interfaces surface energy is considered as material boundary following the concept of [4] and its corresponding modification by [5].

The modified form of the internal virtual power is expressed in terms of the plastic strain, plastic strain gradient, damage and its gradients contribute to work per unit volume. Since contact interface plays an important role for the plastic deformation at the micron scale therefore it is further assumed that if internal work develops in the region occupied by the damaged elastic plastic continuum, an additional contribution to the internal virtual work should be considered.

$$\begin{aligned} P_{int} = \int_V (\sigma_{ij}\dot{\varepsilon}^e_{ij} + X_{ij}\dot{\varepsilon}^p_{ij} + S_{ijk}\dot{\varepsilon}^p_{ij,k} \\ +Y_{ij}\dot{\phi}_{ij} + \Gamma_{ijk}\dot{\phi}_{ij,k})dV + \int_{\Omega_c} \Re^c_{ij}\dot{\varepsilon}^{cp}_{ij} d\Omega_c \\ + \int_{\Omega_c} \aleph^c_{ij}\dot{\phi}^c_{ij} d\Omega_c + \int_{\Omega_c} Q^c\dot{\varphi}^c d\Omega_c + \int_{\Omega_c} q^c_i v^t_i d\Omega_c \end{aligned} \quad (1)$$

This new formulation does not only provide the internal interface energies but also introduces two additional internal state variables for the contact surfaces.

The external virtual power is expressed as

$$P_{ext} = \int_{\Omega_t} t_i v_i d\Omega_t + \int_{\Omega_t} m^t_{ij}\dot{\varepsilon}^p_{ij} d\Omega_t + \int_{\Omega_t} \eta_{ij} m^t_{ij}\dot{\phi}_{ij} d\Omega_t \quad (2)$$

Finally, the governing equations for the coupled viscoplastic damage behavior are defined [1]. The effective nonlocal flow rate $\dot{E}^p = \sqrt{\dot{\varepsilon}^p_{ij}\dot{\varepsilon}^p_{ij} + l^2_p\dot{\varepsilon}^p_{ij,k}\dot{\varepsilon}^p_{ij,k}}$ and the nonlocal effective damage flow rate $\dot{\kappa} = \sqrt{\dot{\phi}^p_{ij}\dot{\phi}^p_{ij} + l^2_d\dot{\phi}^p_{ij,k}\dot{\phi}^p_{ij,k}}$ are defined. In this constitutive model two characteristic material length scales are introduced. They are the plastic length scale, l_p and the damage length scale, l_d respectively. Length scales may be obtained experimentally as demonstrated in [6]. The functional form of the flow rule of plasticity is given as follows

$$\sigma(\dot{E}^p) = \sigma_y + R(\dot{E}^p)\left[1 + (c_p(T - T_r)\dot{E}^p)^{1/m}\right] \tag{3}$$

where σ_y is the initial yield strength, and c_p is the specific heat. The evolution equations for isotropic and kinematic hardening laws are given respectively as follows

$$\dot{R} = \mu \dot{E}^p q e^{-\mu E^p} \tag{4}$$

$$\dot{\mathbf{X}} = \frac{2}{3} C \dot{\boldsymbol{\varepsilon}}^p - \gamma \mathbf{X} \dot{E}^p + \beta \dot{\boldsymbol{\sigma}} \tag{5}$$

and [7] defined q as

$$q = q_m + (q_m + q_0)e^{-2\mu q} \tag{6}$$

and m, q_m, q_0, μ, C, γ and β are the material constants to be calibrated from available experimental data. Similarly, one can define the flow rules of damages as follows

$$\sigma(\dot{\kappa}) = Y_0 + K(\dot{\kappa})\left[1 + (c_p(T - T_r)\dot{\kappa})^{1/m}\right] \tag{7}$$

where Y_0 is initial damage threshold, $\left(\dot{\kappa} = \sqrt{\dot{\tilde{\boldsymbol{\phi}}} : \dot{\tilde{\boldsymbol{\phi}}}}\right)$, and the nonlocal damage tensor isdefined as $\tilde{\boldsymbol{\phi}} = \boldsymbol{\phi} + \frac{1}{2}\boldsymbol{\ell}^2 \boldsymbol{\nabla}^2 \boldsymbol{\phi}$. The evolution of damage anisotropic hardening equation is given as follows

$$K(\kappa) = \lambda \zeta \left(\frac{\kappa}{\lambda}\right)^{\xi} \delta_{ij} \tilde{\phi}_{ij} + \delta_{ij} \lambda Y_0^2 \tag{8}$$

The proposed theoretical model is further implemented as user defined subroutine VUMAT in the explicit finite element code ABAQUS to analyze the structural response of the ultra high speed sliding experiment between Steel and VascoMax steel conducted at National School of Engineering in Metz, France.

3. Computational Modeling and Conclusions

Severe contact stress problems are theoretically modeled through coupling continuum damage with strain gradient plasticity. This is achieved by introducing the contributions of damage and its corresponding gradients in the virtual power relations as measures of micro motion of damage within the bulk. By using these internal state variables together with displacement and temperature, the constitutive model is formulated with state laws based on the free energies and the complimentary laws based on the dissipation potentials. The temperature is taken into consideration as the major variable in the analysis of the high velocity contact problem.

The proposed theoretical model is implemented as user defined subroutine VUMAT in the explicit finite element code ABAQUS to analyze the structural response of the ultra high speed sliding experiment between Steel and VascoMax steel at National School of Engineering in Metz, France (for experimental details see [1]). The proposed theory is verified successfully in the simulation of the material response with respect to hardening and softening behaviors under uniaxial and cyclic loading cases. The reliable and robust simulation capability of the model shows that the theory is extremely adequate in characterizing the material behavior.

The simulations of the above experimental set up are performed with the finite element commercial software ABAQUS according to the proposed theory and coded as a VUMAT subroutine. The set of simulations is performed for different values of normal force and sliding velocity capturing the development of surface temperatures, plastic deformations as well as the frictional forces. Different mesh sizes are also considered to show the lack of mesh dependency due to the non-local gradient formulation adopted in this work according to the proposed theory. The simulations are carried out for a set of sliding velocities between 10m/s and 200m/s.

The increase of sliding velocity causes the increase of the average temperature. This increase is in good agreement with the theoretical approach presented by [8]. Moreover, due to gradient approach the mesh dependency problem is eliminated. Despite the chosen mesh size the obtained results are very similar and hence the normalization procedure with the gradient approach is adequate.

References

[1] A. Lodygowski, *Friction and Wear at Elevated Velocities*. PhD thesis, Department of Civil Engineering at Louisiana State University, Baton Rouge, LA 70803, April 2010.

[2] A. Lodygowski, L. Faure, G. Voyiadjis, and S. Philippon, "Dry sliding friction experiments at elevated velocities," *Submitted to Journal of Experimental Mechanics*, 2010.

[3] G. Z. Voyiadjis and B. Deliktas, "Formulation of strain gradient plasticity with interface energy in a consistent thermodynamic framework," *International Journal of Plasticity*, vol. 25, no. 10, pp. 1997–2024, 2009.

[4] M. Fremond and B. Nedjar, "Damage, gradient of damage and principle of virtual power," *International Journal of Solids and Structures*, vol. 33, no. 8, p. 1103, 1996.

[5] P. Ireman, A. Klarbring, and B. Stromberg, "A model of damage coupled to wear," *International Journal of Solids and Structures*, vol. 40, pp. 2957–2974, 2003.

[6] A. Almasri and G. Voyiadjis, "Nanoindentation in fcc metals: Experimental study," *Acta Mechanica*, vol. 12, pp. 1–10, 2010.

[7] G. Z. Voyiadjis and R. Abu Al-Rub, "Thermodynamic based model for the evolution equation of the backstress in cyclic plasticity," *International Journal of Plasticity*, vol. 19, no. 12, pp. 2121–2147, 2003.

[8] F. P. Bowden and P. A. Persson, "Deformation heating and metling of solids in high speed friction," *Proceedings of Royal Society of London A*, vol. 260, pp. 433–458, 1960.