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Analysis of thermo-mechanical wear problems for reciprocal punch sliding

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ABSTRACT

The relative sliding motion of two elastic bodies in contact induces wear process and contact shape evolution. In the case of a punch sliding on a substrate the transient process tends to a steady state for which the fixed contact stress and strain distribution develops in the contact zone. This state usually corresponds to a minimum of the wear dissipation power. The optimality conditions of the wear dissipation functional provide the contact stress distribution and the wear rate compatible with the rigid body punch motion. The present paper is aimed to extend the previous analyses [1–5] of steady state conditions to cases of periodic sliding of punch, assuming cyclic steady state conditions for both mechanical and thermal fields.

1. Introduction

The present paper extends the previous analyses of steady-state wear processes for monotonic sliding and fixed loading conditions of two contacting bodies B_1 and B_2, cf. Páczelt and Mróz [1–5] to the cases of periodic sliding of contacting bodies, assuming cyclic steady state conditions with account for the heat generation at the contact surface. In particular, the body B_1 can be regarded as a punch translating and rotating relative to the substrate B_2. When a punch of conforming contact surface slides along a rectilinear path on a substrate, the contact zone is fixed respective to material points of B_1 and translates relative to material points of B_2. The steady wear state then corresponds to fixed stress and temperature states in the contact zone, translating relative to the substrate. When the punch translates along a circular (or closed) path on the substrate (such as in pin-on-disk test or in disk brake), the fixed stress and temperature states are reached in the contact zone of punch, combined with the periodic evolution of thermo-mechanical states in the substrate. For the case of reciprocal sliding of punch along a rectilinear path, the steady wear state corresponds to periodic variation of stress and temperature fields in both punch and substrate. More general cases occur when the contact zone S_c moves with respect to both bodies and a steady wear process occurs due to periodic motion of S_c and periodic evolution of thermo-mechanical states (eg. wear of gear teeth or roller bearings).

The concept of *a quasi-steady wear state* has been proposed in [6,7] for the case of non-conforming contact surface of B_1 (such as for parabolic punch or ball sliding on a flat substrate), when both size and form of contact zone varies during the wear process, combined with the shape variation of contact surface. The stress distribution in the contact zone then tends to a quasi-steady state related to the actual zone parameters (fast process), next evolving due to variation of geometric zone parameters (slow process).

For cases of monotonic sliding motion the minimization of the wear dissipation power provides the contact pressure distribution and rigid body wear velocities directly without time integration of the wear rule until the steady state is reached, cf. [1–5]. In cases of periodic sliding motion, the steady state cyclic solution should be specified and the averaged pressure in one cycle and the averaged wear velocity can be determined from the averaged wear dissipation in one cycle [6].

For the case of reciprocal punch sliding motion the steady state contact surface shape and pressure can be determined from the respective steady state solution for monotonic sliding. The specific examples are related to analysis of punch wear induced by reciprocal sliding along a rectilinear path on an elastic strip. Specifying the steady state contact pressure distributions for an arbitrarily constrained punch, it is noted that the pressure at one contact edge vanishes, and the maximal pressure at the other edge is twice the mean pressure value, cf. [6]. The analysis of the same example with account for heat generation demonstrates that the thermal

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distortion affects essentially the evolution of contact shape and of transient contact pressure distribution. However, it will be shown that in the steady wear state for reciprocal sliding, the contact pressure reaches the same distribution for both cases, that is for neglecting and accounting for heat generation, though the steady state contact shapes are different.

The present analysis extends the previous work [7], where the slow evolution of contact shape and pressure distribution during the transient period was numerically specified for the case of reciprocal punch sliding. In order to illustrate the contact state evolution due to wear process and generation of steady state regimes, two cases will be considered: first for a punch allowed to translate in the normal contact direction during the wear process, second for a punch allowed to translate and rotate.

The extended examples illustrate evolution of transient pressure and temperature distributions tending to the steady cyclic states. The variational method applicable to the cases of monotonic sliding is in this paper extended to the cases of periodic sliding with account for the elastic strain energy of contacting bodies and the wear dissipation during one cycle. In the numerical examples the error assessment is provided for the wear velocity and the relative sliding velocity specified with the neglect of elastic deformation. The Appendix A is enclosed to clarify the details of steady state for monotonic and cyclic solution and the variational framework generating the contact pressure distribution in consecutive semi-cycles.

The numerical analysis of oscillating contact sliding motion without heat generation by Peigney [8], Kim et al. [9], McColl et al. [10] and analytical treatment by Goryacheva et al. [11] demonstrate the existence of steady cyclic states attained in the wear process. The present numerical analysis will also demonstrate that for the case of heat generation during the periodic sliding motion, the steady state cyclic wear process occurs with periodically varying mechanical and thermal fields. The thermo-mechanical problems for sliding bodies along contact interfaces were treated by Komanduri and Hu [12], Zagrodzki [13], Gao and Lin [33], Fialho et al. [34] and numerical techniques to solve coupled temperature and stress fields were presented in papers by Zavarise et al. [15], Strömberg [16], Pantuso et al. [31] and Ireman et al. [32]. The numerical procedure used in this paper is described in detail in Ref. [5] with application of hp-version of the finite element method, described by Páczelt et al. in [18] and the operator split technique used in specifying mechanical and thermal fields, cf. Agelet de Saracibar [35], Argyris and Doltsinis [36]. For the fundamental background, the reference is made to books by Bathe [14], Szabo and Babuska [17] and Johansson [29].

In our analysis it is assumed that the gross slip (or sliding) regime develops instantaneously between the contacting bodies. In this case the slip and sticking zones no longer exist and the whole contact zone undergoes sliding. The tangential contact traction can then be directly calculated from the contact pressure and the coefficient of friction. In our analysis it will be assumed that contact pressure distribution is fixed during the semi-cycle and varies discontinuously during sliding reversal in consecutive semi-cycles. The temperature distribution is assumed to vary continuously during the sliding reversal occuring in the cycle period. The wear of punch accumulated during the cycle period is compatible with the rigid body punch motion allowed by boundary constraints.

The present assumptions for sliding wear response differ from those for fretting wear analysis, when for small cyclic displacement amplitudes the partial slip regime develops at the contact zone perimeter and the sticking domain remains in the central zone portion. The problem of fretting wear and fatigue has been treated in numerous papers. The cyclically varying slip displacement induces progressive wear and contact pressure evolution, combined with damage growth in the sub-surface layer. The numerical analysis of fretting wear was presented by Johansson [19] and the dissipated energy criterion for prediction of damage and wear was discussed by Liskiewicz and Fouvry [20], next applied for simulation of sliding wear by Ramalhoa and Miranda [24]. The combined numerical and experimental analysis of fretting wear and fatigue strength estimation was presented by Mc Coll et al. [10], Kim et al. [9], Hattori and Watanabe [21], Lee et al. [22]. The analytical treatment of partial slip contact and wear growth was presented by Goryacheva et al. [11], where both transient and steady state conditions were considered. The steady state wear conditions and parameters were specified by Yang [26]. The oscillatory sliding of sphere and the corresponding quasi-steady wear state was analyzed both numerically and experimentally by Páczelt et al. [25] with specification of wear parameters. The test methods aimed at determination of wear parameters for coated brake elements were presented by Blau and Jolly [23]. Numerical methods for wear simulation with account for contact pressure evolution were discussed by Pereira et al. [27], Mukrasa et al. [28]. Temizer and Wriggers [30] applied the multi-scale homogenization method to simulate the third body effect on friction and wear at the interface. The transient temperature fields in brakes were analyzed by Gao and Lin [33] and thermo-mechanical fields inducing wear in hip joints were numerically simulated by Fialho et al. [34]. The review presented here is not complete and refers mostly to papers devoted to analysis of problems related to the topic of this paper.

The paper is organized as follows. In Section 2 the wear rule is stated and the steady state wear conditions are discussed for both monotonic and reciprocal sliding cases. The steady cyclic variations of contact pressure and temperature are presented. The heat generation and conduction problem is next presented with account for transient and steady state conditions. In Section 3 the numerical analysis of thermo-mechanical fields and of progressive wear is outlined with application of the operator split technique. The reduced number of half periods is taken for the analysis of evolution of transient fields before reaching their steady states. In Section 4 the analysis of wear for a plane punch reciprocally sliding along a plane substrate is presented for two cases, first for allowed translation of punch along normal direction, second for punch allowed to translate and rotate during periodic sliding. The pressure and temperature evolutions to their steady state distributions are illustrated by diagrams. The error analysis of presented numerical results is next discussed. The last Section 5 contains the concluding remarks synthesizing the major results.

2. Monotonic and reciprocal sliding wear regimes

2.1. Wear rule and wear rate vector

The modified Archard wear rule [1] specifies the wear rate $\dot{w}_{i,n}$ of the i-th body in the normal contact direction. Following the previous work [1,3] it is assumed that

$$\dot{w}_{i,n} = \beta_i (\tau_n)^{b_i} \|\dot{\boldsymbol{u}}_\tau\|^{a_i} = \beta_i (\mu p_n)^{b_i} \|\dot{\boldsymbol{u}}_\tau\|^{a_i} = \beta_i (\mu p_n)^{b_i} v_r^{a_i} = \tilde{\beta}_i p_n^{b_i} v_r^{a_i}, \quad i = 1, 2 \tag{1}$$

where μ is the friction coefficient, β_i, a_i, b_i are the wear parameters, $\tilde{\beta}_i = \beta_i \mu^{b_i}$, $v_r = \|\dot{\boldsymbol{u}}_\tau\|$ is the relative sliding velocity which, taking simplifying assumptions, is specified from the relative rigid body motion of two bodies, constrained by the boundary conditions. The shear stress at the contact surface is denoted by τ_n and calculated in terms of the contact pressure p_n by using the Coulomb friction law $\tau_n = \mu\, p_n$.

The relative sliding velocity is composed of elastic, wear and rigid body terms [4]