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A simulation method of thermo-mechanical and tribological coupled analysis in dry sliding systems☆

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ABSTRACT

A numerical method is developed to investigate the thermal, mechanical, and tribological behaviors in dry sliding systems simultaneously. It is based on the finite element method (FEM) and incorporates a subroutine, considering Archard's law, which is used to calculate wear and to cyclically update the position of the nodes at the surface. The method is applied to analyze the operation of a given brake system with gray cast iron and low metallic friction material interacting surfaces, in terms of stress, temperature and wear distribution. Simulation results are consistent with experimental measurements and indicate that these three aspects are connected by contact pressure and thermal expansion. The loss of material changes contact situation and influences temperature and stress indirectly.

1. Introduction

Sliding contacts are universal in mechanical applications, such as brakes, tires, sliding bears and slipper pairs. These components usually work under very severe conditions for physical phenomena coupled in tribology systems: normal loading, shear loading between interfaces, heat generation and conduction, physical-chemical transformations and material degradations, etc. [1–3].

When external loads are applied, counter surfaces would bear normal pressure immediately. The contact pressure is inhomogeneous even between two uniform flat plats because of the exsitence of asperities. Once relative sliding starts, friction happens and the slider could penetrate and cut deeply into the surface and cause an extensive plastic deformation, resulting in a great amount of heat and material loss [4]. Therefore, inhomogeneous contact pressure leads to uneven wear and heat flux.

Meanwhile, owing to thermal distortions and material degradations, the heat flux is able to impact stress distribution in turn. So contact pressure is a result of thermo-mechanical coupled process. And more importantly, the profile of the contact surface is also varying due to the loss of the material related with pressure. It means that tribological behaviors need to be coupled in the sliding process as well.

Hence we arrive at the following conclusion: the dry sliding system is a cross-disciplinary subject which involves the tribological, thermal and mechanical aspects. When studying dry sliding systems, of particular importance is to understand how these factors interact with each other and to build an effective model to describe it.

Plenty of numerical and experimental research of the dry sliding contact has been conducted. The focus of thermal-elastic studies is to obtain thermal-mechanical behaviors, such as thermal stress, elastic and plastic deformations, and thermo-elastic instability. At the beginning, some thermal models were proposed with defined partition coefficient estimated in experiments [5,6] to solve temperature and stress separately. Then, experiments indicated that these friction heating and thermo-mechanical factors may have significant impact on tribological behaviors [7–10]. Next, analytical or FEM methods were developed based on simplified geometries with primary heat conduction and elastic-mechanical equations, such as two dimensional models with Hertzian pressure distribution [11] and thermo-mechanical models of regular three dimensional mechanical components [12].

In addition to the thermal-elastic studies, interacting surfaces are generally investigated. Archard [13] was one of the first to try to describe wear mechanism, whose work has been followed by lots of researchers. After that, Ko [14] conducted experiments under a wide range of conditions and drew a conclusion that the friction characteristic is an important parameter in predictive wear models. With the development of experiment detection techniques, scanning electron microscope (SEM) and scanning tunneling microscope (STM) can be applied to observe microstructure, especially in investigating tribological behaviors in advanced composite material. Mazahery [15–18] conducted systematic

☆In the order of the given name followed by the family name.

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Nomenclature

$\phi(\mathrm{K})$	temperature
$k(\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}))$	coefficient of thermal conductivity
$\rho(\mathrm{kg}/\mathrm{m}^3)$	mass density
$c(\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K}))$	specific heat capacity
$Q(\mathrm{W}/\mathrm{kg})$	internal heat source density
$q(\mathrm{W})$	external heat flux
$t(\mathrm{s})$	time
$\mathbf{n}$	direction cosine vector of the boundary outward normal
$h(\mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K}))$	coefficient of heat transfer
Γ	heat boundary
Ω	material domain
ω	weight function
$\mathbf{N}$	shape function of temperature
$\mathbf{\Phi}$	nodal temperature vector
$\mathbf{C}_\phi$	thermal capacity matrix
$\mathbf{K}_\phi$	thermal conductivity matrix
$\mathbf{P}$	heat load vector
$\mathbf{K}_u$	displacement stiffness matrix
$\mathbf{u}$	nodal displacement vector
$\mathbf{f}$	nodal force vector
$\boldsymbol{\varepsilon}$	thermal strain
$\alpha(1/\mathrm{K})$	thermal expansion coefficient
n^e	the number of elements
$\mathbf{B}$	strain matrix
$\mathbf{D}$	elastic matrix
$\mathbf{K}_{u\phi}$	contribution matrix of the nodal temperature rise to the nodal force
$V(\mathrm{m}^3)$	removed volume of the material
$F_\mathrm{N}(\mathrm{N})$	normal force
$H(\mathrm{Pa})$	hardness of the softer material
$A(\mathrm{m}^2)$	contact area
μ	dimensionless wear coefficient
$\delta(\mathrm{m})$	wear depth
$s(\mathrm{m})$	sliding distance
$\kappa(1/\mathrm{Pa})$	dimensional wear rate coefficient
$p(\mathrm{Pa})$	local pressure
$\beta(\mathrm{J}\cdot\mathrm{s}/(\mathrm{Pa}\cdot\mathrm{m}))$	Coulomb friction coefficient
$v(\mathrm{m}/\mathrm{s})$	relative velocity
ξ	flux distribution coefficient
$d_{gap}(\mathrm{m})$	distance of the gap
$k_\mathrm{debirs}(\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}))$	thermal conductivity of the debris
$l(\mathrm{m})$	characteristic length
$k_l(\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}))$	air thermal conductivity
Nu	Nusselt number
Re_D	Reynolds number characterized by drum diameter
$D(\mathrm{m})$	drum diameter
$v(\mathrm{m}/\mathrm{s})$	linear velocity of the drum
$\upsilon(\mathrm{N}\cdot\mathrm{s}/\mathrm{m}^2)$	dynamic viscosity

superscript

e	element

subscripts

o, a	initial, ambient
x, y, z	three directions of Cartesian coordinate system
ϕ, u	temperature, displacement
v, s, ε	volume, surface, thermal strain
t, c	contact heat transfer, heat convection
1, 2, 3	the first, second and third boundary

experiments on wear behaviors of Aluminum matrix composites (AMCs), explored the mechanism of the compact zone, and proposed a method which combined genetic algorithm, finite element methods, and artificial neural networks to realize the prediction of tribology properties. Furthermore, Tofigh [19] raised a search technique to optimize the material processing procedures of AMCs reinforced with carbide particles.

On the other hand, most numerical simulation models of wear are in mesoscopic view and based in general. They can simulate the plastic deformation and material loss with the simple wear mechanism, though several mechanisms may act simultaneously or sequentially. Some review articles divided the wear simulation methods into two categories: one is to embed the wear model into the material constitutive model at the element level, and the other is to calculate wear accumulations and adjust mesh in the post-processing step.

For example, Lundvall [20] added constitutive principle into surface elements to achieve the material loss, and coded user subroutine UMAT of wear material. But this method need to invoke the subroutine in every cycle for all the elements. A few complex models were also proposed with different wear models such as wear map [21] and Archard wear model [22,23].

Currently, with the development of the remeshing technique, the second method becomes more practical and efficient. A lot of research has been conducted with this method [24–30]. Ander Soderberg [31] simulated wear and contact pressure distribution at the pad-to-rotor interface by importing the modular approach, and integrating the wear routine in post-processing steps. Rezaei [25] employed an adaptive wear modeling method to study the wear progress in radial sliding bearings and the remesh procedure is also executed for adjacent elements to avoid element distortion. Abbasi [26] developed a numerical method to study the transient thermo-elastic behaviors during pin-on-disc tests by calculating pressure, temperature and wear in each cell at each time increment. Those wear simulations mostly rely on relatively complex mesh techniques, from which the calculation of regular geometries can be carried out.

In 2013, Bortoleto [27] developed a mechanical model of a pin-on-disc system using finite element software ABAQUS® and self-defined wear subroutine. The author provided a numerical model to predict the worn track and mechanical behaviors by assuming that temperature effect at the contact interface was negligible. Due to this assumption, the approach is not suitable for achieving accurate thermo-mechanical results where friction heat released is strongly impacted by mechanical and tribological behaviors, such as in drum brakes.

In all, few methods have been developed to sufficiently illustrate how to combine the thermal-elastic analysis and tribological behaviors together utilizing general purpose finite element analysis software. To the knowledge of the author, no existing method has effectively explained the interaction among tribological, thermal and mechanical factors of dry sliding systems in complicated mechanical components so far.

Therefore, a numerical method aiming at simulating the dry sliding process is proposed in this paper, which especially fits for engineering applications. Archard linear wear model is coupled into the classical FEM of thermal-stress problems and adjust mesh in the post-processing model. The method is applied to analyze