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Distinguishing the effects of adhesive wear and thermal degradation on the tribological characteristics of paper-based friction materials under dry environment: A theoretical study

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ABSTRACT

Adhesive wear and thermal degradation are the main aging mechanisms of paper-based friction materials. However, how these aging mechanisms affect the tribological characteristics of such materials is not fully understood. In this paper, the respective influences of the two aging mechanisms on the tribological characteristics of the friction materials are investigated through simulation. It is assumed that adhesive wear pre-dominantly affects the surface topography, while thermal degradation significantly affects the mechanical properties of the friction material. The simulation results show that the static friction coefficient and both normal and tangential contact stiffnesses increase due to adhesive wear, but decrease due to thermal degradation. These trends are qualitatively in agreement with experimental observations reported in the literature and our previous work.

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1. Introduction

Paper-based friction materials have been widely used as lining materials in various applications, such as brakes and clutches, either under dry or wet (lubricated) environment. Such materials are porous composites, basically containing some ingredients such as fiber, solid lubricant and friction modifiers; which are all saturated and cured at certain pressure and temperature with the thermosetting resin acting as a binder [1].

To obtain high coefficient of friction (COF), a paper-based material has to be designed with following specifications: (i) *sufficiently* high porosity and resilience as recommended in [2–5] and (ii) plateaued (stratified) surface [6,7]. High porosity implies that lubricant can penetrate into the friction materials and expand the sliding area where boundary lubrication is dominant, thus resulting in a higher kinetic COF. Furthermore, a plateaued surface significantly contributes to larger micro contact area, *i.e.* real contact area, which consequently results in a higher static COF. This real contact area corresponds to the discrete contact spots area formed by the contacting "asperity" summits. A typical surface profile of a fresh paper-based friction material is shown in Fig. 1. Notably, the asperity heights distribution $\phi(z)$ is *asymmetric* as seen in the figure, which cannot be accurately approximated with a Gaussian distribution.

Significant improvements in the performance and durability of paper-based friction materials have been achieved in recent years through: (i) development of different types of fibers such as carbon fiber, aramid fiber (*e.g.* Kevlar©), ceramic fiber, and cellulose fiber [9,10], resins [11,12] and fillers [13]; and (ii) optimization of the combination and content ratio of the ingredients [14,12]. The performance and composition of a resin have a considerable impact on the mechanical properties of the friction material [11,12]. In order to design a paper-based friction material with optimal mechanical properties, heat resistance, friction and wear performance, Fei et al. [12] suggest that the composition of the resin in the material should be between 35% and 40%.

Despite great achievements in the performance and durability, the friction materials still suffer from inevitable aging process (degradation), while being in use. In the literature, adhesive wear and thermal degradation have been considered as the main sources of aging mechanisms in paper-based friction materials. Adhesive wear occurs when a friction material is under sliding against the mating surface, in which debris particles are formed due to the removal of the weakest asperities by the mechanism of plastic deformation. Thermal degradation occurs when the interface temperature is relatively high, such that the carbonization process of the cellulose fiber and the resin content in the friction material takes place [15,16].

As reported by Maeda and Murakami [17], lubricant (*e.g.* automatic transmission fluid) may also change the mechanical properties of the friction materials during their lifetime. In practical situations, both degradation mechanisms inevitably occur simultaneously, in

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Nomenclature

α	bandwidth parameter (–)
β	roughness parameter (–)
δ	deformation (m)
δ_c	critical deformation (m)
η	density of asperities (m^{-2})
κ	Weibull shape parameter (–)
λ	Weibull scale parameter (a.u.)
μ_s	static coefficient of friction (–)
ν	Poisson's ratio (–)
ϕ_W	Weibull distribution function
ψ	plasticity index (–)
ρ	porosity (–)
ρ_c	percolation threshold
σ_a	standard deviation of asperity heights (m)
σ_{R_a}	surface roughness (m)
σ_{sk}	skewness (–)
θ	angular displacement (rad)
ξ	degradation parameter
$\Delta, \varphi, \epsilon$	degradation model parameters
ζ	variable representing the progress of degradation
A	real contact area (m^2)
d	separation between two nominally flat surfaces (m)
G	shear modulus (Pa)
H	surface hardness (Pa)
K_n	normal contact stiffness (N/m)
K_t	tangential contact stiffness (N/m)
K_θ	torsional contact stiffness (Nm/rad)
L_x, L_y	pore size inn the x- and y-axes
M_s	static friction torque (Nm)
n	the expected number of asperities making contact (–)
p_{asp}	average pressure of asperities (Pa)
Q_s	static friction force (N)
R	mean radius of asperity (m)
V_T	bulk volume (m^3)
V_ν	void volume (m^3)
W	load (N)
x_t	tangential displacement (m)
Y	yield strength (Pa)
z	asperity height relative to Weibull zero plane (m)
$\mathcal{A}$	nominal contact area (m^2)
$\mathcal{D}_i$	inner diameter (m)
$\mathcal{D}_o$	outer diameter (m)
$\mathcal{D}_m$	mean diameter (m)
$\mathcal{L}$	number of pores (–)
$\mathcal{N}$	total number of asperities (–)
$\mathcal{R}_i$	inner radius (m)
$\mathcal{R}_o$	outer radius (m)
$\bar{\diamond}$	normalized quantity of $\diamond$
$\mathrm{E}[\cdot]$	statistical expectation
$\Gamma(\cdot)$	gamma function

which the interactions between the two may lead to a very complex phenomenon called *glazing*. As a result, the surface topography and the mechanical properties of the friction material change. Visually, the occurrence of this phenomenon is indicated by the appearance of a smooth and shiny surface, implying that the friction material has lost its porosity due to blocking by the deposition of debris particles [17–20].

Newcomb et al. [21] proposed the term "glazed" to describe damage in the friction material of wet clutches resulting *only* from the deposition of the degradation products of lubricant on the friction material surface. However, this suggestion is too oversimplified because a similar phenomenon can also be observed in the absence of lubricant (*i.e.* dry condition). Refs. [22,23] show that a glazed surface in the friction material of brakes is believed to be formed by debris particles bound by decomposed organic compounds. Therefore, it is more reasonable to define the term of glazing as the formation of a smooth and shiny film on the friction material surface formed by debris particles bound by decomposed organic compounds that may result from combined adhesive wear and thermal degradation of the friction material or/and deposition of the ATF products degradation.

Many intensive studies with the main objective of characterizing the contact characteristics of paper-based friction materials due to the aging have been reported in the literature, *e.g.* see [5,24–26,19,7,27]. However, the respective influences of adhesive wear and thermal degradation on the contact characteristics of paper-based friction materials during their lifetime remain unclear and therefore are subject to further investigation. It is reasonable to believe that an effective and accurate degradation model can be derived if the respective influences of the two major degradation mechanisms (adhesive wear and thermal degradation) are fully understood. The main objective of this study is to improve our understanding of the respective influences of the two degradation mechanisms on the contact properties of paper-based friction materials by means of modeling and numerical simulations.

The remainder of this paper is structured as follows. Section 2 provides an overview of some experimental observations of the effects of adhesive wear and thermal degradation on the surface topography and the mechanical properties of paper-based friction materials. Based on experimental evidences reported in the

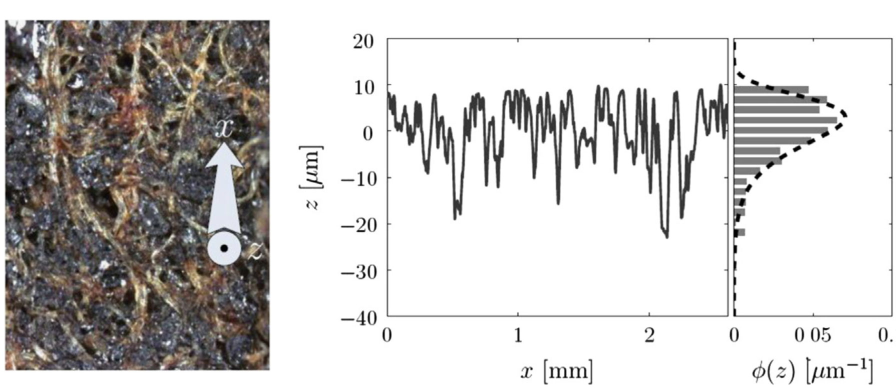

Fig. 1. Optical image (left panel) of a fresh paper-based friction material and the typical profile (right panel) exhibiting a plateaued surface. Note that the surface profile is measured along the sliding direction as indicated by the white arrow, reproduced from Ref. [8].

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