Tribology International 120 (2018) 350–357

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Effects of surface roughness on local friction and temperature distributions in a steel-on-steel fretting contact

W. Qin [a,b,*], X. Jin [a,c], A. Kirk [a], P.H. Shipway [a], W. Sun [a]

[a] *Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK*
[b] *School of Mechanical Engineering, Beijing Institute of Technology, Beijing 10081, China*
[c] *Rools-Royce@NTU Corporate Laboratory, Nanyang Technological University, Singapore*

ARTICLE INFO

Keywords:
Surface roughness
Friction
Temperature
Fretting contact

ABSTRACT

It has generally been assumed that initial surface roughness has significant influences on local frictional shear stresses and flash temperatures in fretting contacts. However, since these hypotheses are difficult to directly measure, the frictional shear stress and temperature rise distributions in a steel-on-steel fretting contact are investigated by finite element method. The rough contacting surfaces were modelled as fractal surfaces by the Weierstrass-Mandelbrot function. The simulation results show that the frictional shear stress distribution resulted from the rough contact model is discrete, and the local stresses are highly concentrated which result in higher peak temperature rise than that from the smooth contact model. The influences of the plasticity of materials, load and frequency on the temperature rise are also discussed.

1. Introduction

Fretting is a wear process which occurs in loaded contacts between two bodies when they are subjected to small oscillating displacements relative to each other. During this process, frictional power is dissipated over the relatively small area of true contact and thus causes high flash temperatures in these areas and a relatively steep temperature gradient into the substrate. The role of temperature in fretting has generally been attributed to changes associated with oxidation process which are thought to exert a significant influence on the rate and mechanisms of wear [1–5]. As such, friction and friction-induced thermal histories in fretting contacts have been the subject of investigation by many researchers.

Some research has focussed on investigation of friction behaviour at fretting contacts [6–9]; a number of researchers have investigated the temperature profile in the contact resulting from the dissipation of frictional power [2,10–16]. Since direct temperature measurement close to the fretting surface itself is often impractical, the actual contact temperature can only be estimated using analytical models and computer simulation tools and thus efficient models are needed at the design stage to predict the friction-induced temperature rise under such conditions [1,15]. For example, Wen and Khonsari presented an analytical approach for obtaining the transient temperature profile for different oscillating heat sources on a semi-infinite body and the analytic expressions for maximum surface temperature for these heat sources were provided based on an extensive number of simulations [15]. Jin et al. adopted a mathematical model and developed a finite element (FE) model to predict the temperature rise in a fretting contact based upon the frictional power dissipation, and explored the influences of various factors such as the presence of an oxide debris layer and frequency on the contact temperature within a stainless steel contact [2,16].

It has been found that surface roughness has significant influence on friction, wear and temperature rise in contacts [17–26]. Some researchers have studied the effects of surface roughness on friction by experiments [17–21]. For example, Lu et al. experimentally examined friction torque under different surface roughness and different texture directions with a torsional fretting wear device with a flat-on-flat contact and found that friction torque and accumulated dissipated energy at first increase and then decrease as the surface roughness increases [17]. Others adopted numerical methods to analyse the effects of surface roughness on friction and contact temperature [22–26]. For example, Reichert et al. determined the influence of elastic and plastic deformation on the friction coefficient as the effect of surface flattening in the run-in phase was taken into account with a numerical approach based on the FE model in which surface roughness of turning processes and plastic hardening due to deformation of the asperities are considered [22]. In some cases where experiments are difficult to carry out, numerical

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[*] Corresponding author. School of Mechanical Engineering, Beijing Institute of Technology, Beijing 10081, China.
E-mail address: qinwj@bit.edu.cn (W. Qin).

https://doi.org/10.1016/j.triboint.2018.01.016
Received 25 August 2017; Received in revised form 21 November 2017; Accepted 5 January 2018

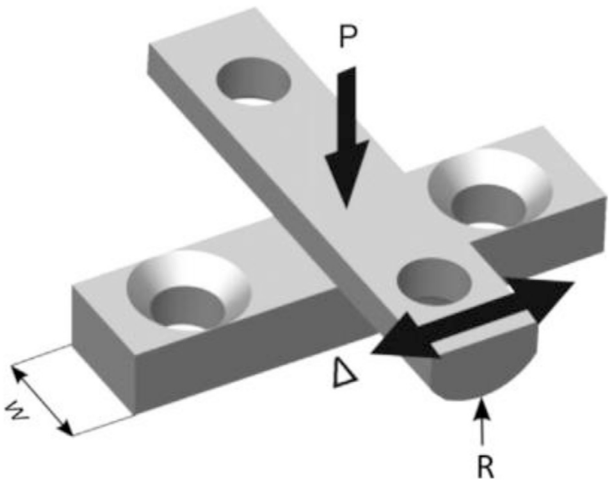

Fig. 1. Cylinder-on-flat configuration for fretting test.

calculations can often provide an alternative to give some indication about the possible effects of certain parameters. In the case of the contact temperature which is difficult to measure experimentally, Attia et al. have developed analytical models to predict the disturbed temperature field around the contact asperity in fretting contacts by assuming that the asperity has a uniform square cross section [14,25,26]. They presented the dimension of the thermally disturbed zone and the effect of reciprocating motion on the maximum surface temperature rise in dimensionless form.

Although analytical models can provide some general conclusions about the temperature field in fretting contacts, it is difficult to predict the frictional and thermal behaviour of a real fretting tribo-system of complex geometry with realistic surface roughness; however, more significant progress in this regard can be achieved with numerical methods, e.g., finite element (FE) modelling. In this paper, the dynamic local contact frictional shear stress and temperature rise distributions in a steel-on-steel contact during the fretting process are studied by the FE method taking into account the initial surface roughness. The rough contacting surfaces are modelled as fractal surfaces by the Weierstrass-Mandelbrot (W-M) function, and the FE models (including the surface roughness) are developed for the cylinder-on-flat configuration used in the experimental work (see Fig. 1) which results in a line contact on a macroscopic scale. FE analyses were carried out and the effects of surface roughness on the distributions of frictional shear stress and temperature rise are investigated by comparing the results obtained with those from the smooth contact model.

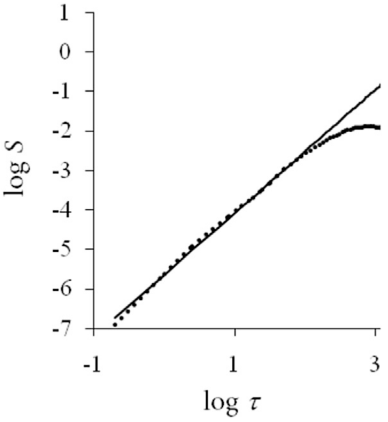

Fig. 2. LogS – logτ plot to derive the slop of the diagram line.

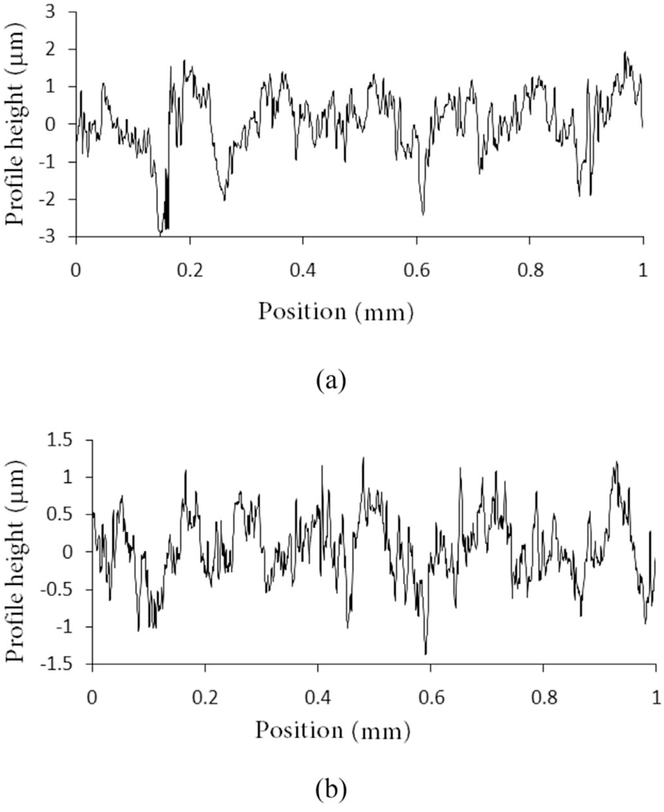

Fig. 3. Measured profile heights: (a) cylinder surface; (b) flat surface.

2. Representation of the rough surfaces

2.1. Description of surface roughness by fractal geometry

Statistical surface parameters which are often used to describe surface roughness are related to the sample size [27]; in light of this, surface topography in more recent contact analyses is commonly described by fractal geometry since this is characterized by the properties of continuity, nondifferentiability, scale invariance, and self-affinity [28–32]. In this study, the surface roughness is described by fractal geometry and its two-dimensional (2-D) surface profile height is given by the W-M function [33].

$$z(x) = G^{D-1}\sum_{n=n_1}^{n_2}\frac{\cos 2\pi\gamma^n x}{\gamma^{(2-D)n}}, \quad 1 < D < 2 \tag{1}$$

where D $(1 < D < 2)$ is the fractal dimension which determines the relative contributions of high- and low-frequency components in the surface profile, G is the fractal scale coefficient which reflects the amplitudes of the surface profile, γ $(\gamma > 1)$ is a constant which controls the density of frequencies in the surface profile ($\gamma = 1.5$ is typical for most surfaces), n is the fractal scale index and n_1 and n_2 are the lowest and highest cut-off indexes of frequency. Letting $\omega = \gamma^n$ be the spatial frequency of the profile, then ω_L is the starting frequency determined by the sample length L as $\omega_L = 1/L$, and ω_U is the upper limit of frequency which is determined by the profile resolution δ as $\omega_U = 1/2\delta$.

The fractal parameter D is determined by the structure function

Table 1
Fractal dimensions and fractal scale coefficients.

	Fractal dimension D	Fractal scale coefficient G
Cylinder	1.4108	5.72
Flat	1.3586	4.35