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Investigation of non-Coulomb friction behaviour in reciprocating sliding

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ABSTRACT

A commonly observed phenomenon where the friction force increases during the gross slip phase of individual fretting cycles is investigated with the aim of identifying the physical origins of this type of frictional behaviour. Measurements of sliding friction from linear and torsional fretting tests, using the aerospace nickel alloy Udimet 720, and subsequent analysis of the post-test worn surfaces were used to investigate the phenomenon. It was found that this friction variation is due to wear–scar interaction effects. These interactions were primarily found to occur at sites distributed throughout the nominal contact area via the interference of local interlocking peaks and troughs on the worn surfaces. Cross-correlation and auto-correlation analysis of the worn surfaces was used to identify, and to show the approximate size of, these local features. Many of the features were found to be similar in size to the applied fretting stroke, but on average, the features were somewhat larger. A simple one degree-of-freedom model of the interaction of an idealised surface peak with a corresponding surface groove was developed to show how these interactions produce the type of friction variation which is commonly observed during the sliding phase.

1. Introduction

Fretting occurs when small amplitude cyclic relative slip displacement takes place between two clamped components in a frictional joint. If the oscillation amplitude is small enough, some points in the contact may remain permanently adhered while others undergo slip and this is known as the *partial slip* regime. This regime promotes the nucleation of cracks, and generally gives rise to fretting fatigue where failure may occur by propagation of cracks [1]. If, however, the oscillation amplitude is sufficiently large, all points in the contact region will undergo slip and this is known as the *gross sliding* regime. Gross sliding tends to give rise to material removal and surface degradation rather than crack formation, and usually causes fretting wear rather than fretting fatigue [1]. The fretting wear process itself involves the transfer or dislodgement of fragments of material by adhesive metal-to-metal interaction, and the subsequent oxidation and further formation of wear debris [2]. Engineering examples of frictional joints that may undergo fretting include bolted joints [3], blade-disk dovetail connections [4] and spline couplings [5]. When joints such as these are subjected to dynamic loading, fretting occurs, and the joint may influence the performance and life of the overall structure by affecting two very important aspects of design: structural integrity and vibration response. From a structural integrity viewpoint, fretting fatigue can cause sudden catastrophic failure while fretting wear degrades the joint so that it may no longer satisfy design tolerance requirements [1]. From the vibration response viewpoint, joints affect both the stiffness and damping of the overall structure [6,7]. Contacts undergoing fretting in the gross slip regime are the subject of the present paper, and it is, therefore, useful to understand the factors that affect the resultant wear and vibration response. A plot of tangential force Q (which is equal to the limiting friction force during the gross slip part of a fretting cycle) against relative displacement δ for a single cycle of oscillation is useful in this regard (Fig. 1a), and is often called the *tangential force hysteresis loop*. The area of the loop corresponds to the energy expended by the joint in frictional work during a given cycle [8]. It is this dissipation of energy which gives rise to vibration damping [6], and it is the investment of some of this energy in material deformation which promotes fretting wear [8]. In many practical situations there is a trade off between designing for high vibration damping and low fretting wear. There is also some coupling between the two phenomena; since, although the fretting process damps vibrations, it is the vibrations themselves which drive the fretting oscillation. The hysteresis loop area is largely determined by the actual displacement amplitude δ_{actual}, the friction force during sliding Q, and the tangential contact stiffness K_t (the slope of the micro-slip part of the loop (see Fig. 1a), which occurs as the displacement direction reverses) [9]. Hence, higher friction is likely to increase vibration damping and wear rate simultaneously. For the above reasons, the hysteresis loop is

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Nomenclature

f	coefficient of friction
F_n	local normal force at peak-trough interface
K_t	tangential contact stiffness
L, M	number of divisions in the radial and angular directions
m	mass
N	number of cycles
n	order of groove polynomial
P	applied normal load
p_a	average normal contact pressure
Q	tangential force
q_a	average tangential traction
r, r_i, r_o	variable, inside and outside ring radii
r_j, θ_k	discrete radial and angular coordinate positions
S_q	areal root mean square surface roughness
T	total torque arising from both contact pairs
t	time
x, z	tangential and normal coordinates
x_o, z_o	groove half-width and groove depth
z_p, z_s	pad and specimen surface heights
$\Delta\theta$	relative angular position of two worn surfaces
δ	relative displacement
δ_{actual}	actual displacement amplitude (zero-to-peak)
δ_{app}	applied displacement amplitude (zero-to-peak)
δ_{slip}	slip displacement amplitude (zero-to-peak)
δ_θ	relative angular displacement
$\delta_{\theta,app}$	applied angular displacement amplitude (zero-to-peak)
η	segmented ring area as a fraction of the continuous ring area
σ_z	standard deviation of wear–scar surface heights
$\sigma_{z,p}$, $\sigma_{z,s}$	standard deviation of pad and specimen wear–scar surface heights
ω	angular frequency
ACF, CCF	abbreviations meaning: auto-correlation and cross-correlation functions

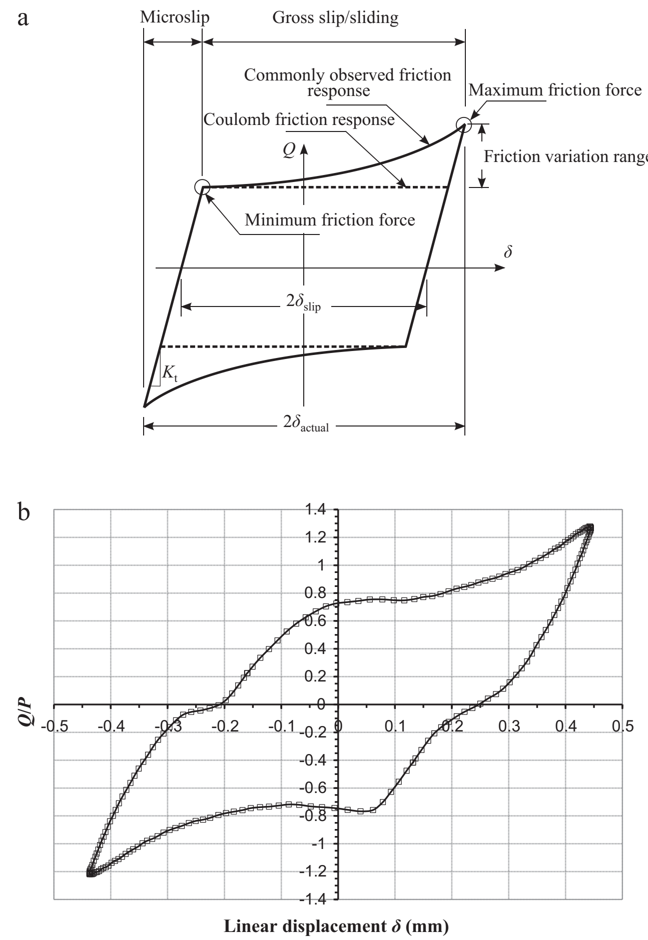

Fig. 1. Illustration of the type of frictional hysteresis loop observed in gross slip fretting tests: (a) schematic hysteresis loops showing both Coulomb and commonly observed frictional behaviour and (b) example loop showing normalised tangential force Q/P versus displacement δ measured after 400 cycles for linear fretting of nickel alloy-on-nickel alloy (Udimet 720) using flat pads with rounded edges pressed against a flat specimen at a normal pressure p_a of 70 MPa. (Note: the slight deflection as the loop crosses the displacement axis is simply a degree of 'backlash' in the pad holding system – see Section 2).

frequently used by both the tribology and vibrations communities to characterise dynamically loaded frictional contacts.

Simple models of frictional behaviour such as those proposed by Amontons [10] and Coulomb [11] are frequently used to describe the measured loops. However, an interesting feature is present in the hysteresis loops reported by many researchers, namely that the friction force varies during sliding between the two extremities of motion (most often, the friction force increases more and more rapidly as sliding proceeds resembling a *hook feature*). Fig. 1a shows a schematic of such a hysteresis loop, while Fig. 1b shows a measured loop (from a nickel alloy-on-nickel alloy test of the type described in Section 2) exhibiting this behaviour. This effect, which is usually not present in the initial fretting cycles (but develops thereafter) [12–15], has been observed for a variety of material pairs and contact geometries: titanium alloy-on-titanium alloy with cylinder-on-flat contact geometry [12,13,16–18], aluminium alloy-on-steel with the sphere-on-flat configuration [14], aluminium alloy-on-aluminium alloy for the sphere-on-flat arrangement [15], steel-on-steel with cylindrical punch-on-flat contact geometry [19], and both titanium alloy and nickel alloy pairs using a flat pad with rounded corners pressed against a flat sided specimen [20]. Very recently, Eriten et al. [21] observed the effect when carrying out fretting tests on both steel and aluminium lap-joints. This increase in friction force during sliding (Fig. 1a and 1b) is contrary to the Amontons/Coulomb model of friction which predicts constant friction force during the sliding phase (Fig. 1a). Since knowledge of the friction force during fretting is needed for predicting both the severity of wear and the damping characteristics, it is important to understand the mechanism behind the increasing friction phenomenon. Given that the applied displacements in most of the above studies are sinusoidal functions of time, the sliding velocity decreases as the point of motion reversal is approached. It is tempting, therefore, to ask whether the so called 'velocity weakening' effect (the increase in friction as velocity decreases) may be responsible for the phenomenon. Al-Bender et al. [22,23] and De Moerlooze et al. [24] have developed sophisticated friction models based on the physics of point masses on springs interacting with a rigid rough surface. The models simulate a wide range of frictional behaviour such as velocity weakening, frictional hysteresis, and stick-slip phenomenon. These studies show that a model incorporating velocity weakening can reproduce the commonly observed friction variation effect for periodic sinusoidal displacement oscillations. Other similar models developed by the dynamics/control community which show non-Coulomb friction during gross slip are outlined in [25–27]. Lampaert et al. [28] observed the variation in friction force during slip in reciprocating sliding experiments, and their data were later used in [22] for comparison with the fric-