Tribology International 79 (2014) 151–161

Contents lists available at ScienceDirect

Tribology International

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

Non-Coulomb friction in gross sliding fretting conditions with aluminium bronze against quenched and tempered steel

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ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
6 June 2014
Accepted 9 June 2014
Available online 17 June 2014

Keywords:
Fretting
Friction
Wear
Topography

ABSTRACT

A series of fretting tests were performed in gross sliding conditions to study the properties of non-Coulomb friction occurring in the contact of an aluminium bronze sphere against a quenched and tempered steel plane. Measurements were analysed by studying measured fretting loops and the topographies of fretting scars with 3D optical profilometry. Measured fretting loops showed non-Coulomb tangential behaviour, in which the tangential force depended on the tangential displacement. Measurements in which the tangential displacement amplitude was suddenly increased or reduced showed a temporary reduction in the maximum friction force. Fretting wear modified initially polished surfaces producing a tangentially interlocked fretting scar surface profile, which may explain the non-Coulomb increase in the friction force.

1. Introduction

Fretting may occur between any two contacting surfaces where short-amplitude reciprocating sliding exists over a large number of load cycles. The running conditions of a fretting contact can be divided into partial slip and gross sliding. Under partial slip conditions, some contact regions are stuck and undergo no relative surface sliding, while the rest of the contact is slipping. However, under gross sliding conditions no such sticking regions appear within the contact. Sliding in the contact causes fretting wear, which can lead to surface degradation detectable by the appearance of material transfer and wear debris. Fretting movement can cause fretting fatigue due to high tractions and wear, potentially enhancing crack nucleation and decreasing fatigue life, typically affected by a high friction coefficient. Though precise knowledge of frictional behaviour is crucial, the phenomenon is sometimes poorly understood and often assumed to follow ideal Coulomb friction law. A more extensive account of fretting can be found, e.g., in [1,2].

When elastically dissimilar materials are fretted, the elasticity mismatch itself affects the slip and traction fields. The significance of this can be estimated by using Dundurs' parameter β/μ [1,3]. Munisamy et al. [4] studied the problem of elastically dissimilar spheres in partial slip conditions and discovered that after a shakedown period of about 10 load cycles, the contact behaves close to the Mindlin solution [5]. In a bronze–steel contact [6], such as in this study, Dundurs' parameter β/μ had a modest value of 0.16 and thus a small effect, especially in gross sliding conditions.

Knowledge of the frictional properties of a fretting contact can be obtained by studying the measured tangential force (Q) vs. tangential displacement (δ) plots, i.e., fretting loops; however fretting loop must be measured accurately and with a sufficiently high data collection frequency to capture the shape of the fretting loop in detail. The forces are often measured with a load cell [7–10], which is typically based on strain gage measurements [11]. Strain gages have been used to measure tangential force by gluing them directly to the test rig or specimen [12–14]. Piezo-force transducers have also been used to measure tangential force [15–17]. Tangential displacement can be measured, e.g., with LVDT [7,10,18], laser or other light based censors [15,19,20], eddy current probe, or other sensors based on induction [14,21]. Extensometers [8,22] are commonly used and may be based on different operating principles (strain gage, LVDT, capacitive, inductive, or other). Forces and displacements are often measured at a location which is different from where the fretting contact occurred introducing test-rig-dependent compliance that may affect the measured tangential displacement and tangential force. Advances have been made in measuring slip or displacement directly from specimens and thereby avoiding compliance by using laser interferometry (vibrometer) [15,19] and digital image correlation [7,10].

Fig. 1 illustrates the development of friction forces and the terminology for the properties of the non-Coulomb fretting loop in

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http://dx.doi.org/10.1016/j.triboint.2014.06.004
0301-679X/

Nomenclature

a	contact radius [m]
E	elasticity modulus [Pa]
$F\mu$	friction force [N]
G	shear modulus [Pa]
gs*	onset of gross sliding [m]
k	rigidity of the test device [m/N]
P	normal force [N]
Q	tangential force [N]
Q_a	tangential force amplitude [N]
R	sphere radius [m]
S_y	yield strength [Pa]
S_u	ultimate strength [Pa]
S_f	fatigue strength [Pa]
S_a	arithmetic surface roughness [m]
S_t	peak to peak surface roughness [m]
β	Dundurs' parameter [–]
σ_{bulk}	bulk stress [Pa]
δ	tangential displacement [m]
δ_a	tangential displacement amplitude [m]
δ_m	measured tangential displacement [m]
μ	friction coefficient [–]
ν	Poisson's ratio [–]

Subscripts

min	minimum
mean	average
max	maximum

the case of Hertzian sphere-on-plane contact. The friction force ($F\mu$) is defined here as the force resisting tangential movement between contacting bodies in gross sliding. After the loading direction changes ($\pm\delta_a$), the sphere-on-plane contact undergoes a brief partial slip phase, followed by gross sliding. The tangential force (Q) at the onset of gross sliding (gs*) corresponds to the minimum friction force ($F\mu_{min}$). Under non-Coulomb friction conditions, the friction force increases during gross sliding and achieves its maximum value ($F\mu_{max}$) when the tangential displacement (δ) is at its extreme position, producing a "hooked" end in the fretting loop.

Many fretting studies on gross sliding conditions have shown that the tangential force, instead of remaining constant, increases in gross sliding during one load cycle. Such non-Coulomb friction behaviour has been reported in fretting studies with different contact types, material pairs, and even coatings [7,8,15,20,22–29]; however, the studies have discussed the phenomenon only briefly, because it was not their main focus. Fouvry et al. [23] suggested that the "hooked" shape in the fretting loop may derive from changes in the contact conditions brought about by a macroscopic plastic deformation in the specimen caused by the test pad ploughing slightly into the specimen. Lavella et al. [15] arrived at a similar conclusion, though the change in the contact condition was also affected by fretting wear. Zhou et al. [26] explained the phenomenon by cyclic plastic deformation. Mulvihill et al. [9] studied non-Coulomb behaviour extensively and produced a non-Coulomb fretting loop by using a rotational fretting loading that eliminated macroscopic ploughing at the contact edges. Observations based on fretting wear scar profilometry showed evidence of tangentially interlocked fretting scar topographies. Furthermore, Mulvihill et al. found that tangential fretting scar interactions between interlocked protrusions and dents within the contact caused the fretting loop to produce a non-Coulomb shape, and that the curvature of the fretting loop was linked with the geometry of the interacting protrusions and dents. In a study of fretting fatigue in a bronze against steel contact, Hintikka et al. [6] reported that fretting scars showed evidence of interlocking fretting scar topography and suggested that this had an adverse impact on cracking behaviour. In the same study, curved non-Coulomb tangential behaviour was observed also in gross sliding conditions.

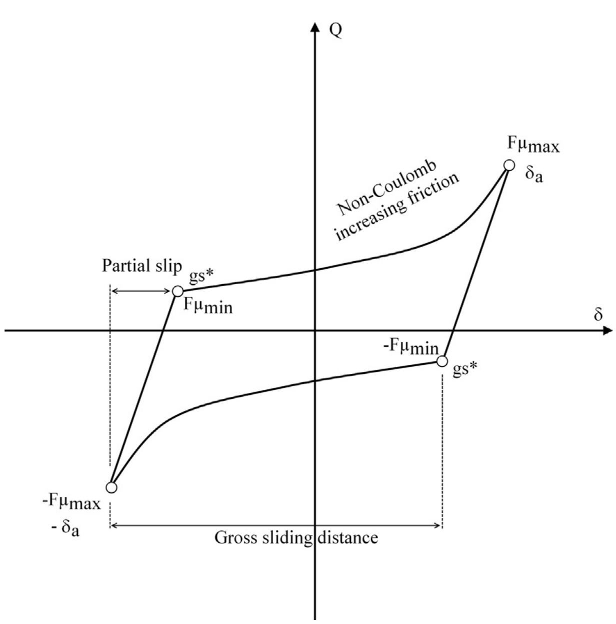

Fig. 1. The non-Coulomb fretting loop.

The need to increase power density, e.g., in diesel engineering, leads to high utilisation of the fatigue strength of the materials used. In such cases, accurate dimensioning of contacts susceptible to fretting is very important, because engine components undergo countless load cycles during their life time. Cyclic loadings and often also variable loading conditions bear on many joints that transfer high tangential traction, as in diesel engines, where load consists of firing forces, inertial forces, vibrations, and thermal effects, to name a few, which may vary not only due to different engine operating conditions but also during a combustion cycle [30]. Fretting has been tested using different variable stress amplitude or variable displacement amplitude schemes focused on fretting fatigue [31–33] and fretting wear [34,35], respectively; however not much attention has been paid to frictional behaviour. Exception is the study by Liskiewicz et al. [35] where it was reported that energy friction coefficient remained at a constant value regardless of changing displacement amplitude; however that study did not show non-Coulomb behaviour. If the coefficient of friction behaves in a non-Coulomb manner, the fretting loop and the values of friction forces ($F\mu_{min}$, $F\mu_{mean}$ and $F\mu_{max}$) may be affected by variable loading conditions.

Bronze–steel is one of the material pairs used in the frictional joints of engines, and this alloy has been shown to display non-Coulomb gross sliding friction behaviour. This study examined the properties of non-Coulomb friction occurring in an aluminium bronze vs. quenched and tempered steel pair by using dry fretting point contact under constant and variable loading conditions.