Tribology International 44 (2011) 1188–1198

Contents lists available at ScienceDirect

Tribology International

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

Measurements of pressure and area dependent tangential contact stiffness between rough surfaces using digital image correlation

M.E. Kartal *, D.M. Mulvihill, D. Nowell, D.A. Hills

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

ARTICLE INFO

Article history:
Received 25 January 2011
Received in revised form
17 May 2011
Accepted 19 May 2011
Available online 30 May 2011

Keywords:
Friction
Contact stiffness
Fretting wear
Titanium alloy

ABSTRACT

The present paper describes an experimental technique to accurately measure the tangential contact stiffness between two rough contacting surfaces manufactured from the titanium alloy Ti–6Al–4V. The digital image correlation method is employed to measure the local displacement field. The effect of normal contact pressure, nominal contact area and fretting wear on tangential contact stiffness is investigated. The experiments indicate that the tangential contact stiffness is approximately proportional to the nominal contact area and the normal pressure raised to the power of 0.64. Multiple experiments with the same parameters show good repeatability given the number of variables involved.

1. Introduction

Most contacts can be classified into two types. The first type of contact where at least one of the contact surfaces has a convex profile, and hence the contact size depends on the normal load, is referred to as an incomplete contact, and the second type, in which the contact size is independent of normal load and defined by a surface profile with discontinuities in surface slope, is called a complete contact [1]. Other types include receding contacts [2] and size matched contacts [3–4]. Provided that the two contacting bodies, for any of these kinds of contacts, are elastically and geometrically similar, relative tangential displacement of two corresponding surface points (one on each body) will be the same when they are brought into contact by application of a normal load and no relative slip will be observed. This is known as the 'fully stuck' case. If a remote tangential force is then applied, tangential slip displacement may be observed on some parts of the contact surface while the remaining parts remain stuck. This is known as the 'partial slip' regime. If the applied tangential load is large enough, however, then all points on the contact surface will undergo slip and this is referred to as the 'gross sliding' regime. When the contacting surfaces are subjected to oscillating tangential force, the behaviour of the contact will involve all three of these regimes, and hence fretting occurs [5]. Damage due to fretting depends on the slip conditions. Fretting fatigue predominantly occurs in partial slip, whereas fretting wear is more significant in gross sliding. Dobromirski [6] has pointed out that parameters such as, coefficient of friction,[1] tangential displacement amplitude and normal load largely determine the severity of the fretting process.

The tangential contact stiffness[2] of a frictional interface is a significant parameter as it affects both the vibration response and (indirectly) the structural integrity of an assembly comprising frictional joints. This is because the tangential stiffness of a joint will affect vibration amplitudes, which in turn prescribe the fretting response (i.e. partial slip, gross slip, etc.). The other major parameter that affects the vibration response and the structural integrity of structures incorporating joints is the coefficient of interfacial friction. This is a more complicated parameter to predict, but the behaviour of the friction force in fretting wear tests has been examined recently by Kartal et al. [7] and Mulvihill et al. [8]. At present, the vibration response of monolithic components can be predicted very accurately, but when components are joined together to form an assembly, the overall response is more difficult to predict because of a lack of capability in predicting important joint parameters such as contact stiffness. For example, if a sufficiently accurate dynamic model of an aero-engine fan is to be achieved, accurate modelling of the contact stiffness in the blade-disc dovetail joints is necessary. Therefore, questions such as how contact stiffness is influenced by parameters such as nominal contact area and normal pressure require attention, and accurate experimental techniques for measurement of contact stiffness are also required. Researchers involved in aero-engine dynamics research [9] have traditionally modelled

[1] The coefficient of friction is calculated by dividing the tangential force by the normal force using the Coulomb friction law.

[2] The tangential contact stiffness is obtained as the slope of the linear region of the microslip part of the tangential load vs. relative tangential displacement plot.

* Corresponding author. Tel.: +44 1865 283489.
E-mail address: mehmet.kartal@eng.ox.ac.uk (M.E. Kartal).

0301-679X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.triboint.2011.05.025

joint stiffness by linear springs, which take no account of the effects of normal loading on the joint stiffness (though they have accounted for area effects by assuming direct proportionality between nominal area and tangential contact stiffness). Tangential contact stiffness is obtained experimentally from the hysteresis loop obtained by plotting tangential force against relative tangential displacement during a fretting cycle. However, the measured hysteresis loops usually show non-linear behaviour, especially in transition from the partial slip to the gross sliding regime. Hence, in order to obtain a linear relation between tangential load and relative tangential displacement, the microslip region of the loop that occurs just after the reverse in sliding direction is used to obtain constant tangential contact stiffness from the slope of the load–displacement curve in this region. Fig. 1 shows a schematic diagram of a frictional hysteresis loop and the region in which tangential contact stiffness is calculated.

A number of experimental measurements of contact stiffness have been reported in the literature [10–16] using a range of techniques. Results obtained using the ultrasound technique [14–16] appear to show that tangential contact stiffness is approximately proportional to the square root of normal pressure and this will be investigated more closely in the present paper using a different experimental approach. In order to determine contact stiffness, it is necessary to measure both load and relative displacement. Measurement of tangential load is relatively straightforward using a conventional load cell. However, the displacement in microslip is much smaller than the overall rigid body motion, and it is therefore more challenging to measure relative displacement with a high degree of accuracy. Furthermore, the measured displacement is almost inevitably made up of contributions from the compliance of the interface and from the 'bulk' compliance of the contacting bodies themselves. It is often difficult to obtain displacements from points sufficiently close to the interface so as to exclude the bulk contribution. Although conventional measurement equipment such as extensometers [10] and differential transformers [11] can be used to measure tangential contact stiffness, these measurement methods usually underestimate the stiffness values due to the inclusion of a bulk compliance contribution. To obtain the ideal measurement, it is necessary to get a full-field displacement map very close to the contact interface. In this way, the tangential contact stiffness can be obtained as a function of the position of the measurement points.

Aside from conventional methods, tangential stiffness of contacting surfaces has also been studied by techniques such as laser interferometry [12] and ultrasound methods [13–16]. These approaches can eliminate bulk compliance, but they do not produce a full-field measurement of displacement close to the interface. Optical methods can be used to overcome this restriction: Kartal et al. [7] have developed a digital image correlation (DIC) technique to characterise the local response of frictional properties of rough contacting surfaces. In this work, measurements of both force and displacement in the tangential direction were obtained from a series of in-line fretting tests involving flat pads with rounded corners clamped against the flat surface of a specimen oscillated by a hydraulic tensile testing machine. The authors [7] investigated the effect of materials (titanium and nickel alloys) and surface roughness on the tangential contact stiffness, as well as on the friction coefficient. However, this study did not investigate issues such as measurement repeatability, or the effect of nominal contact area and normal contact loading on the stiffness. The aim of the current paper is to extend [7] to include these effects. For this purpose, two different contact areas and four different normal pressures were examined. Moreover, by repeating a number of tests under the same experimental parameters, the repeatability of the results has been investigated. Finally, the experimental results have been compared with finite element predictions and an analytical solution based on a Greenwood–Williamson type approach derived by Medina et al. [17].

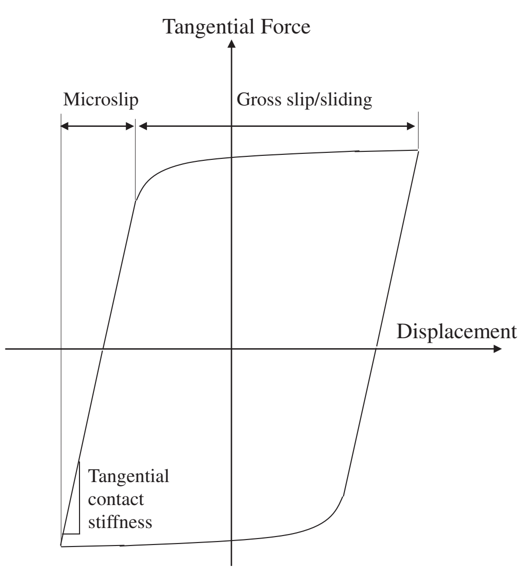

Fig. 1. Schematic diagram of a frictional hysteresis loop.

2. Experiments

For the experimental work, two pads were pressed against opposite sides of a specimen by normal load in the horizontal direction, and cyclic displacement was applied in the vertical direction to produce slip. In addition to a conventional linear variable displacement transducer (LVDT), a high speed camera and microscopic lens were used to implement digital image correlation for the measurement of relative tangential displacements close to the contact interface. In the following section, details of the experimental configuration are given.

2.1. Material and specimens

The material used for testing in this study (supplied by Rolls-Royce plc) is the titanium alloy Ti–6Al–4V, which is widely used for aerospace and power generation applications owing to its high strength-to-weight ratio. The typical mechanical properties and chemical composition of Ti–6Al–4V are shown in Table 1 [18]. The main reason for choosing this material was that the effect of contact area on tangential contact stiffness could be assessed by

Table 1
Mechanical properties and chemical composition of Ti–6Al–4V [18].

Young's modulus (GPa)	Poisson's ratio	0.2% Yield stress (MPa)	Chemical composition (wt%)							
			Al	V	N	C	O	Fe	H	Ti
115	0.31	999	5.5–6.8	3.5–4.5	0–0.05	0–0.08	0–0.2	0–0.4	0–0.02	Bal.