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Damage mechanisms in stainless steel and chromium carbide coatings under controlled environment fretting conditions

V. Chaudhry [a], Satish V. Kailas [b,*]

[a] Nuclear Power Corporation of India Limited, Mumbai 400094, India
[b] Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

Fretting is of a serious concern in many industrial components, specifically, in nuclear industry for the safe and reliable operation of various component and/or system. Under fretting condition small amplitude oscillations induce surface degradation in the form of surface cracks and/or surface wear. Comprehensive experimental studies have been carried out simulating different fretting regimes under ambient and vacuum (10^{-9} MPa) conditions and, temperature up to 400 °C. Studies have been carried out with stainless steel spheres on stainless steel flats, and stainless steel spheres against chromium carbide, with 25% nickel chrome binder coatings. Mechanical responses are correlated with the damage observed. It has been observed that adhesion plays a vital role in material degradation process, and its effectiveness depends on mechanical variables such as normal load, interfacial tangential displacement, characteristics of the contacting bodies and most importantly on the environment conditions. Material degradation mechanism for ductile materials involved severe plastic deformation, which results in the initiation or nucleation of cracks. Ratcheting has been observed as the governing damage mode for crack nucleation under cyclic tangential loading condition. Further, propagation of the cracks has been observed under fatigue and their orientation has been observed to be governed by the contact conditions prevailing at the contact interface. Coated surfaces show damage in the form of brittle fracture and spalling of the coatings. Existence of stick slip has been observed under high normal load and low displacement amplitude. It has also been observed that adhesion at the contact interface and instantaneous cohesive strength of the contacting bodies dictates the occurrence of material transfer. The paper discusses the mechanics and mechanisms involved in fretting damage under controlled environment conditions.

1. Introduction

Fretting is a complex synergistic damage mechanism. Fretting wear differs in two important aspects from the conditions experienced in other forms of wear. Firstly, the relative velocity of the two surfaces is very much lower and secondly, the surfaces are never brought out of contact, and therefore there is little opportunity for the products of the wear to escape [1]. The major parameters identified as influencing fretting include normal load, displacement amplitude, mechanical properties of the contacting bodies, and most importantly the environment conditions.

The contact condition during fretting is described by hysteresis loops, that is, tangential force plotted versus displacement amplitude. Fig. 1 shows three different types of characteristics hysteresis loops [2] observed under ambient conditions. Stick regime was identified under low displacement amplitude based on direct proportionality between tangential force and displacement (Fig. 1(a)). In this regime, very limited surface damage was observed which occurred mainly due to oxidation and wear. This regime was also referred to as “low damage fretting regime”. Mixed stick–slip regime showed elliptical hysteresis loop (Fig. 1(b)), and damage was observed in the form of surface cracks. Gross slip regimes showed quadratic hysteresis loop (Fig. 1(c)) and, severe surface damage was observed due to wear, with limited crack formation. Gross sliding was distinguished from reciprocating sliding based on the displacement amplitude. Reciprocating sliding occurs when the displacement amplitude is larger than the contact half-width, so that the contact area at the peak displacement in one direction does not overlap the contact area at the peak displacement amplitude in reverse direction. Thus, displacement amplitude categorizes fretting regimes and is based on the ratio of the relative displacement amplitude to the contact radius. This is referred to as Retention Ratio (RR) [3].

In 1992, Zhou and Vincent [4], independent of Vingsbo and Soderberg [2], proposed two kinds of fretting maps, that is, Running Condition Fretting Map (RCFM) and Material Response Fretting Map (MRFM). The maps were based on experimental studies conducted

* Corresponding author. Tel.: +91 80 22932301; fax: +91 80 23600648.
E-mail address: satvk@mecheng.iisc.ernet.in (S.V. Kailas).

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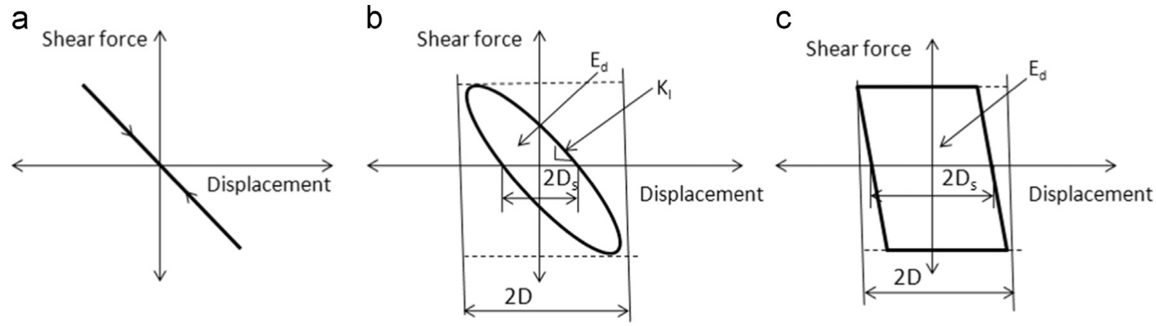

Fig. 1. Schematic of variation of tangential or frictional force with displacement amplitude under (a) stick regime (b) stick–slip regime (c) gross sliding regime (where Q is tangential or frictional force, U is tangential displacement, E_d is energy dissipated, D is imposed displacement amplitude, D_s is interfacial displacement amplitude, and K_l is slope of the loop) [20].

on an aluminum–lithium alloy. The contact mode was a sphere with a 0.5 m radius mated against a flat surface, and the experiments were performed at a frequency from 1 to 5 Hz in ambient laboratory air. Frictional log, a three-dimensional plot between tangential force versus displacement versus number of cycles, was used for the construction of RCFM. Three regimes were identified as partial slip regime, mixed fretting regime, and gross slip regime. Through post-test examinations, the MRFM was constructed and divided into three domains – slight degradation, cracking, and wear domain. Concerning correspondence to the RCFM, slight degradation was mainly located in the partial slip regime, whereas wear with severe particle detachment occurred in the slip regime. Accompanied with severe cyclic plastic deformation, the mixed fretting regime was identified as the most critical for crack nucleation and propagation.

Material and environment conditions play an important role in degradation mechanism due to fretting [5–8]. Mokhtar et al. [9] carried out experimental studies to find the correlation between frictional behavior and physical properties of the metals. From their studies they concluded that strong adhesion occurs in the material having low melting point, boiling point, and recrystallization temperatures, while hard metals with strong bonds, such as nickel and chromium, exhibit low adhesion and, hence, low values of coefficient of friction. Metals having high values of elastic modulus, hardness, and resistance to plastic flow reduce adhesion at the contact interface and, thus, result in low values of coefficient of friction. Further, surface hardness can influence fretting behavior in two possible ways; high hardness implies high ultimate tensile strength and high fatigue strength. Thus, reduction in damage is expected with an increase in surface hardness. Further, high hardness improves the abrasion resistance. Experimental studies on steel surfaces fretted in air and in oxygen show that the damage is almost identical in both atmospheres. However, fretting in vacuum produces less wear but more material transfer [6].

Hurricks [10], in his review paper, divided the fretting process into three stages – initial adhesion and material transfer, production of debris in a normally oxidized state, and finally the steady state wear condition. Halliday et al. [11] found that the initial stage in the fretting process is one with plastic flow of the surface contact points leading to the formation of an intermetallic junction. After this adhesion, the junctions rupture leading to the production of loose metallic debris and scoring of the opposite surface. Oxide debris forms either from initial surface oxide and/or by accelerated oxidation of virgin debris. The accumulation of oxide debris eventually results in the process of abrasion, and once the layer of wear products accumulates a steady state is achieved. Abrasion as a cause of fretting damage is favored only as a minor factor, the majority of damage being initiated in the initial stages, and being reflected in the steady state dispersal of debris. Further, when two fretted surfaces were separated they were found to be an intimate mixture of oxide and metal, and perhaps the damage could be thought of as a surface disintegration phenomenon promoted by fatigue. Scott [12] examined surfaces run-in by vibratory motion and found numerous fine cracks in the deformed surface regions; this suggested fatigue as a factor in surface damage.

Till date various researchers have investigated fretting damage and its characterization under ambient conditions. Limited work has been carried out to characterize fretting damage under vacuum conditions. Damage mechanisms involved in vacuum could be entirely different as those observed under ambient conditions [6]. Test conditions under vacuum simulate conditions similar as that expected in low oxygen environment, for example, fast breeder reactors and fusion reactors. There is a need to identify the existence of the different damage mechanisms under vacuum conditions at temperatures ranging from room temperature to operating temperatures, which for a fast breeder reactor is around 550 °C. Domains for each of the damage mechanisms based on normal load, displacement amplitude, environment conditions, and characteristics of the contacting bodies need to be identified. Taking these facts into consideration, a comprehensive experimental study has been carried out to not only characterize the damage mechanisms but also to study the mechanics involved in fretting damage. Studies have been carried out on stainless steel versus stainless steel, and stainless steel mated against chromium carbide with 25% nickel chrome binder coatings. Chromium carbide coatings have been chosen as it is one of the candidate coating materials for these low oxygen environments.

2. Experiment details

Friction and wear studies primarily depend on the kinetics and kinematics of the test rig, and more specifically its dynamic characteristics. Hamdy et al. [13] and others [14,15] discussed several advantages and disadvantages of different test rigs used to simulate fretting conditions. The primary requirement in the design of a fretting test rig is the ability to develop small amplitude tangential oscillatory relative motion between the contacting surfaces. The amplitude of the motion may be nominally the same at every point in the region of contact as under gross sliding condition or may vary point to point as under partial slip condition. In order to maintain a given displacement amplitude under constant normal load, the applied tangential force must be large enough to cope with increase in the coefficient of friction or shear force which may occur as a result of adhesion between contact surfaces. Further, the contact surfaces under cyclic loading are expected to show non-linear behavior at the inception of sliding, and can lead to unexpected oscillations. These oscillations can be controlled by increasing the stiffness of the system. Thus, a stiff system is desired to eliminate such undesired oscillations. Another stringent requirement is that there should not be any pivot or hinge in the load path, which may result in a clearance leading to inaccurate slip amplitude measurement, throughout the test. Further, the pivot or

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