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Fretting wear of a nitrided 316L/304L contact subject to in-phase normal force fluctuation in dry and lithium-boron solution: An R_P-friction energy wear approach

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ABSTRACT

In nuclear power plants, tubes of the rod cluster control assemblies undergo impacts at low contact pressures against guides, causing specific wear on the contact surfaces. The present study investigates fretting wear behavior under variable loading, using an original double-actuator fretting wear system which allows independent control of tangential sliding and normal force fluctuation. Using this test system the fretting wear response of a nitrided 316L SS cylinder fretted against a 304L SS plate in air and in a lithium-boron solution is investigated.

The effect of normal force fluctuations quantified using the $R_P = P_{min}/P_{max}$ ratio was investigated keeping constant the tangential sliding amplitude. Surface damage evolution was followed by 3D profilometry and several analyses were conducted on specimen surface and cross-sections (SEM, EDX). To quantify the wear volume extension, an R_P-weight friction-energy-wear parameter (i.e., $R_P{}^{\eta} \times \Sigma Ed$) is introduced. This new loading parameter allows us to take into account both friction work and normal force fluctuation.

For a dry interface the η exponent was found to be very small (0.15) suggesting that the wear volume is directly related to the friction energy dissipated in the interface. In contrast, in lithium-boron solution the best fitting was achieved with $\eta_w = -0.9$ which implies an energy wear rate nearly inversely proportional to R_P. The larger the normal force fluctuation (i.e., the smaller R_P) the larger the contribution of tribo-corrosion and the faster the surface wear. Besides, unexpected erosion-corrosion wear phenomena were identified at the inlets of the contact. These different wear mechanisms are discussed and quantified.

1. Introduction

In nuclear power plants, pressurized water reactor rod cluster control assemblies, located inside the reactor pressure vessel, are subject to relative motion due to operational processes or flow-induced vibration ([1,2]). Sliding and impact loadings combined with high temperature (320 °C), solution chemistry (deaerated, low-conductivity water), and high pressure (154 bars) leads to specific wear of the rod cluster control assemblies ([3,4]). Guide cards are made of AISI 304L, whereas rods are made of nitrided AISI 316L. Investigations of pressurized water reactors suggest that the harder nitrided 316L surface is nearly undamaged and all the surface wear takes place on the softer 304L surface. A detailed description of specific power-plant wear and a review of scar patterns were published by Ko in 2003 [5].

The wear of nitrided 316L/304L stainless steel interfaces has been investigated for several years. In 1998, Carpentier [6] looked at the influence of the test environment on a pin-on-disk contact. According to their results the nitrided 316L SS component showed no greater wear in solution than in dry conditions; moreover, mean friction coefficients were equivalent. Later, Kaczorowski studied the wear behavior of this austenitic stainless steel using a tribometer operating in pressurized water at high temperature. Tests which included both impact and sliding displayed the highest wear rate [7]. Kaiser [8], working on the same tribometer, demonstrates that impact damage increased with increasing normal force. These results are in agreement with those of Hong and al. [9], who investigated an Inconel 600 and 690 tube / 409 SS plane contact subjected to impact-fretting slidings.

Following these authors, different wear models were proposed. However, the most usual approach is the Archard model ([10,11]) which relates the wear volume to the product of sliding distance (L) and normal force (P) (i.e., sliding work $W = P \times L$) which infers:

$$V = K \times W \quad (1)$$

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Nomenclature

Sample dimensions

Φ	Diameter (mm)
R	Radius (mm)
t	Thickness (mm)
L	Length (mm)

Contact loading

P	Normal force (N)
P_0	Mean linear normal force during a fretting cycle (N/mm)
P_{max}	Maximum linear normal force (N/mm)
P_{min}	Minimum linear normal force (N/mm)
P_a	Linear normal force amplitude (N/mm) ($P_a = (P_{max} - P_{min})/2$)
R_P	Normal force ratio ($R_P = P_{min}/P_{max}$)
Q	Fretting linear tangential force (N)
Q_{max}	Maximum fretting linear tangential force (N)
Q^*	Fretting linear tangential force amplitude ($\pm$ N)
f	Fretting test frequency (Hz)
N	Number of cycles
μ	Friction coefficient
μ_e	Energy friction coefficient
δ	Fretting displacement (µm)
δ^*	Fretting displacement amplitude ($\pm$ µm)
δ_0	Displacement apparatus (µm)
δ_g^*	Sliding displacement amplitude ($\pm$ µm)
a_{final}	Final contact radius(µm)
a_H	Hertzian contact radius (µm)
Δa	Variation in contact radius
p_H	Hertzian contact pressure (MPa)
e_H	Relative proportion of contact exposed to the ambient

Wear volume

V	Wear volume
V_-	Negative wear volume (µm^3)
V_+	Positive wear volume (µm^3)
V_{TB}	Third-body wear volume (µm^3)
$S_{(-)}$	Negative wear area (µm²)
$S_{(+)}$	Positive wear area (µm²)
S_{TB}	Third-body wear area (µm²)
S_{NM}	Net missing worn surface (µm²)
S_{ec}	Wear area related to erosion-corrosion (µm²)
S_f	Fretting worn surface (µm²)
V_{NM}	Net missing wear volume (µm^3)
V_{ND}	Net damage wear volume (µm^3)

Wear energy approach

α	Friction energy wear coefficient defined from wear volume analysis (µm^3/J)
Ed	Dissipated energy (J)
ΣEd	Accumulated dissipated energy (J)
ΣEd_{th}	Threshold dissipated energy (wear activation) (J)
ΣEd_{eff}	Effective accumulated dissipated energy (J)
η	Power introduced in weighted R_P–friction energy formulation

Superscripts

c	Related to tube specimens
p	Related to plane specimens

Subscripts

d	Related to dry condition
w	Related to lithium-boron solution condition
$pred$	Related to predictive models
exp	Related to experimental results

Materials

SS	Stainless steel

However, numerous studies of fretting wear confirm that surface damage is driven by the interfacial shear stress and strain imposed on the fretted interface. This aspect is taken into account when quantifying the extension of wear volume considering the interfacial shear work [12], also defined by the accumulated friction energy (ΣEd) imputed in the interface. This approach which was also used to simulate surface wear profiles using friction energy density [13], provides stable and reliable predictions as long as a single wear mechanism is activated. Note that the friction energy wear model is usually applied for a constant normal force and dry interface.

The purpose of this study is to evaluate how this friction energy wear approach can be adopted in order to formalize the wear volume extension when the tangential fretting sliding is combined with an in-phase fluctuation of the normal force. Here, a nitrided AISI 316L cylinder is fretted against an AISI 304L plane in dry condition and lithium-boron solution. A constant gross slip sliding amplitude of ± 80 µm is imposed whereas the normal force follows an in-phase sinusoidal evolution from P_{min} to P_{max}. For quantification of the normal force fluctuation a $R_P = P_{min}/P_{max}$ ratio is used. The fretting wear rate from a reference constant normal loading condition ($R_P = 1$) is compared to a near contact opening situation ($R_P = 0.1$). The purpose of this investigation is to evaluate how the wear volume extension, induced by such complex sliding condition, can be quantified combining both friction work (ΣEd) and normal force ratio (R_P).

This study also considers the ambient effect in relation with the contact size fluctuations induced by the normal force variation. Indeed by exposing the fretted interface to the lithium-bore solution, tribocorrosion wear phenomena are more or less activated modifying the surface wear extension. Different models have been developed to formalize this aspect mainly for reciprocating and constant normal force condition ([14–18]). The purpose of this research work was not to develop a tribocorrosion description of the observed wear phenomena. However some of these concepts will be considered in the discussion to explain how the proposed $R_P - \Sigma Ed$ description of mechanical wear varies depending on the ambient conditions.

2. Experiments

2.1. Materials and contact condition

In this study a cylinder/plane contact configuration was used. Specimen materials were similar to those of a reactor. The AISI 316L austenitic stainless steel tube specimens came from real rod cluster control assemblies in a 1300 MW pressurized water reactor