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Energy-based wear law for oblique impacts in dry environment

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ABSTRACT

Wear generated by repetitive impacts between an Inconel tube sample and a stainless steel flat bar target is studied through experiments in dry environment. Incident energy and angle of impacts are controlled, normal and tangential loads during impact are measured as well as rebound energy and angle of impacts. Impacts characteristics are analyzed and the influence of the energy loss during impacts and the incidence angle on generated wear is analyzed. Wear volume is found to be proportional to the energy loss, for which a maximum is observed at an incidence angle close to 25° from horizontal. An impact wear energy coefficient is introduced and an impact wear law with a strong mechanical meaning is proposed. This energy-based law well predicts the observed experimental wear.

1. Introduction

Repetitive impacts between Steam Generator (SG) tubes and Anti-Vibration Bars (AVB) in Pressurized Water Reactors (PWR) can lead to substantial wear over time. When wear is too large, costly maintenance operations are required. Thus, understanding the relationship between impacts characteristics and wear is of great interest.

Impacts lead to several types of wear according to the motions and the bodies involved [1]. Specifically, two main categories of impacts exist whether it involves important incident mass and low velocity (percussive impact) or low mass and large velocity (particle erosion) [2]. Consequently, two very different categories of wear models are proposed. Concerning percussive impact wear, Engel [3–5] develops a model for which wear formation depends on surfaces conformance and wear time evolution depends on shear stress. Levy [6] proposes a model for which wear is proportional to load and sliding distance during impact. Connors [7], Frick [8] and Hoffman [9] also propose impact wear models derived from Archard equation. The wear law proposed by Lewis includes both a term derived from Engel model and a dependency with sliding distance [10]. Gessesse [11] and Attia [12] extend the delamination theory of sliding wear from Suh [13] to percussive impact wear, with a specific interest to the contact geometry at the asperity scale. Concerning erosion wear, three types of models can be distinguished [14]. Finnie [15,16] and Bitter [17] propose models for a rigid grain cutting into a ductile metal. Hutchings [18], Follansbee [19], Ratner [20] and Sundararajan [21] develop fatigue models which involve a critical accumulated strain required to generate wear. Jahanmir [22] extends the delamination theory of sliding wear from Suh [13] to erosion wear. The atomistic simulations of Aghababaei [23] lead to a better understanding of wear mechanisms in general, and of impact wear in particular.

Impact characteristics are deeply studied by Stronge [24]. The analysis of velocities, kinetic energy, forces, friction, stick and slip regions of the contact during impact results in a rich but complex formulation of impact characteristics. Brach [25,26] uses a classical impulse and momentum theory to express these characteristics, especially the energy loss during an impact. It leads to simpler and more intelligible formulations with a high degree of physical meaning. Brach [26] observes a good correlation between the energy loss during an impact and erosive wear results from literature. No comparison is carried out between this model and percussive impact wear observations.

A lot of experimental studies have been carried out in the last decades about impact wear in nuclear field. Guinot [27] and Zaghdoudi [28] have listed many impact test machines and gather them into two categories whether or not priority is given to reproducing real PWR environment. Ko [29], Cha [30] and Blevins [31] among others studied impacts and wear with real environment test machines. Sorokin [32], Rice [33] and Pick [34] developed analytical test machines to study normal impact only. These test machines are expected to have better characteristics than the ones which reproduce real environment but the precision of the dynamics control is very different from one apparatus to another. A lack of analytical experimental apparatus with a large range of possible incidence angles is to be noted.

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Nomenclature

c_s	piezoelectric sensor damping
c_c	contact damping
d_{imp}	contact duration
e_n	restitution coefficient of impact
f	excitation frequency
f_0	first natural frequency of the projectile
f_c	frequency of the projectile mass m oscillating on the contact stiffness k_c
f_s	internal resonance frequency of the impact wear test machine
k	stiffness of the projectile
k_a	surface asperities crushing stiffness
k_c	contact stiffness
k_{ft}	force transducer stiffness
k_h	Hertzian contact stiffness
k_s	piezoelectric sensor stiffness
k_t	tube ovalisation stiffness
l	mean experimental value of apparent contact length
m	projectile mass
m_s	mass supported by force transducer
t	time
t_{in}; t_{it}	time location of normal/tangential load beginning during impact
t_{rn}; t_{rt}	time location of normal/tangential load end during impact
v_r; v_{rn}; v_{rt}	rebound velocity; normal/tangential component of rebound velocity
v_i; v_{in}; v_{it}	incident velocity; Normal/Tangential component of incident velocity
D_s	normal displacement of piezoelectric sensor
D_n; D_t	normal/Tangential component of displacement
E^*	equivalent Young modulus in Hertz theory
F_n; F_t	normal/tangential component of load
K	impact wear energy coefficient
N	number of impacts during a complete impact wear test
P_n; P_t	normal/tangential impulse during impact
R^*	equivalent radius in Hertz theory
T_i	incident energy
T_L; T_{Ln}; T_{Lt}	Energy loss; Normal/Tangential component of energy loss
T_L^*	normalized energy loss
V^-; V^+	negative/positive wear volume
V_{imp}	wear volume per impact
α_i	incidence angle of the projectile
α_r	rebound angle of the projectile
β	asperity radius of curvature
λ	particle shape coefficient
μ	impulse ratio
μ_c	critical impulse ratio

In the present work, wear of a SG tube sample subjected to repetitive impacts against an AVB sample is studied. Section 2 presents the experimental apparatus that has been designed and used. Section 3 presents a description of the impacts based on the time evolution of normal and tangential displacements and loads during them. Section 4 presents the impacts characteristics experimentally obtained: restitution coefficient, impulse ratio and energy loss. Section 5 presents an energy-based analysis of generated wear and introduces an energy-based impact wear law.

2. Experimental apparatus and method

2.1. Impact wear test machine

The experiment aims to analytically study impact wear between a SG tube sample and an AVB sample. The principle of the experiment is the following. The SG tube sample is repetitively thrown against the AVB sample with a controlled incidence energy and angle. At the end of the experiment, wear mainly observed on the SG tube sample is measured. The experimental set-up is shown in Fig. 1.

The impact wear test machine consists of an excitation system, a projectile, and a target. The target is composed of the AVB sample maintained by a holder. The latter is fixed to a force transducer. The set of sample, holder, and force transducer is designed to be very stiff. The projectile is composed of the SG tube sample fixed to a holder. A loading mass is attached to the holder (total mass of the projectile: m=0.12 kg). The projectile is connected to two shakers (reference Brüel & Kjær Type 4810). They are placed at ± 45° to the vertical by two identical springs (stiffness k = 590 N/m). The natural frequency f_0 of the impactor (projectile on its springs) is $f_0 \cong 10$ Hz. The projectile is attached at the extremity of a horizontal flexible beam (not represented in Fig. 1). This beam being stiff in the X-direction (traction-compression) and compliant in the YZ-directions (flexion), the movement of the projectile is enforced to stay in the YZ-plane.

The trajectory of the SG tube sample is controlled using the two shakers. The shakers apply to the SG tube sample two orthogonal forces which can be controlled independently. The desired value of incident energy is obtained by controlling the amplitude of the sinusoidal inputs. The incidence angle α_i to the horizontal is obtained by setting a particular phase difference between the two inputs. Any impact with an incident energy from 10^{-3} mJ to 2 mJ and an incidence angle between 5° and 90° can be performed.

2.2. Signal measurement

The normal and the tangential contact loads are measured during impacts using a 3-axis piezoelectric force transducer (reference Kistler 9067) fixed to the AVB sample. The force transducer stiffness is equal to 4500 N/µm and its sensitivity is −3.8 pC/N for normal axis. Its stiffness is equal to 700 N/µm and its sensitivity is −8 pC/N for tangential axis. Signals are acquired using a dynamic acquisition card

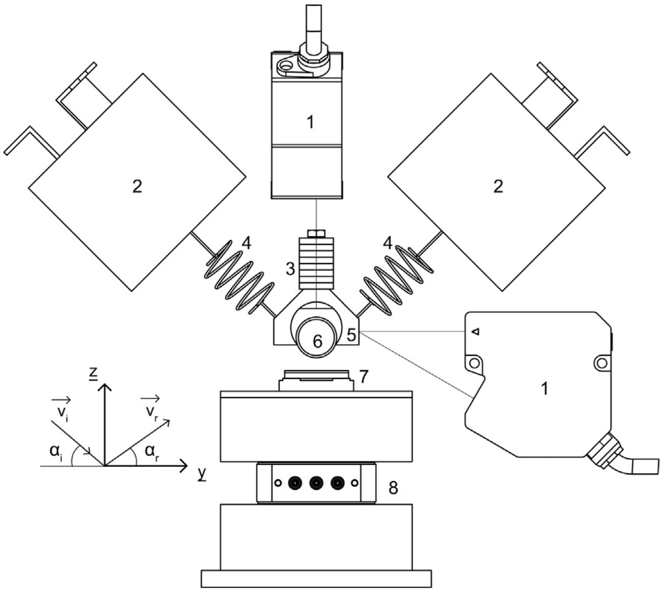

Fig. 1. Diagram of the impact wear test machine (1: displacement sensors, 2: shakers, 3: loading mass, 4: springs, 5: tube holder, 6: SG tube, 7: AVB holder and AVB sample, 8: force transducer).