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An energy approach for impact wear in water environment

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ABSTRACT

Wear induced by repetitive impacts between steam generator tubes and anti-vibration bars in pressurized water reactors is studied with an analytical impact wear apparatus. Repetitive impacts between an Inconel tube sample and a stainless steel flat bar target are performed in water environment at ambient temperature. 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 deeply analyzed and interdependences are highlighted. In particular, the evolution of restitution coefficient, ratio between tangential and normal impulses during impacts, energy loss and sliding distance during impacts versus incidence angle are identified. Impact wear is found to be strongly dependent to impact dynamics, in particular it is observed to be proportional to energy loss during impacts and dependent to incidence angle with a maximum near 20° to the tangential axis. Microscope observation of the wear scars shows the existence of numerous abrasive scratches whose length corresponds to the sliding distance during impact. An impact model is introduced to express energy loss and sliding distance as functions of incidence angle, incident energy, restitution coefficient and impulse ratio. Experimental wear is observed to be dependent on both incidence angle and energy loss.

1. Introduction

In Pressurized Water Reactors (PWR), Steam Generator (SG) tubes are subjected to repetitive impacts against Anti-Vibration Bars (AVB) which sometimes induce significant wear. When becoming too large, wear can lead to plug the SG tube. Therefore, the understanding of the wear formation processes and the analysis of the relationship between impacts characteristics and SG tube wear is a major concern for the safety of PWR.

Several types of impact wear exist according to the motions and the involved bodies [1]. Whether impacts involve substantial incident mass and low velocity (percussive impacts) or low mass and large velocity (particle erosion), two categories of wear models are proposed. Concerning percussive impact wear, Engel [2–4] proposes a model taking account of the surfaces conformance during wear formation and based on a strong dependence on the shear stress. Levy [5], Connors [6], Frick [7] and Hoffman [8] propose wear models based on a proportionality with load and sliding distance derived from Archard's equation. Lewis [9] takes over the Engel model by adding a new dependency with sliding distance. Gessesse [10] and Attia [11] extend the delamination theory of sliding wear from Suh 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 [12]. Finnie [13,14] and Bitter [15] propose models for a rigid grain cutting into a ductile metal. Hutchings [16], Follansbee [17], Ratner [18] and Sundararajan [19] develop fatigue models which involve a critical accumulated strain required to generate wear. Jahanmir extends the delamination theory of sliding wear from Suh [20] to erosion wear.

Impact characteristics are deeply studied by Stronge [21]. 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 [22,23] 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 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 [24] and Zaghdoudi [25] have listed many impact test machines and gather them into two categories whether or not priority is given to reproducing real PWR environment. Ko [26] , Cha [27] and Blevins [28] among others studied impacts and wear with real environment test machines. Sorokin [29], Rice [30] and Pick [31] developed analytical test

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Nomenclature

d_n	normal contact duration: $d_n=t_{rn}-t_{in}$
d_t	tangential contact duration: $d_t=t_{rt}-t_{it}$
e	restitution coefficient of impact
f	excitation frequency
f_{Engel}	slip factor
l_s	sliding distance during impact
m	projectile mass
m_a	apparent mass seen by one contact asperity: $m_a=m/N_a$
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_t	tangential position of the projectile
E^*	equivalent Young modulus in Hertz theory
F_n; F_t	normal/tangential component of load
F_{nm}; F_{tm}	maximum value of normal/tangential contact load during impact
K	impact wear energy coefficient
N_a	number of contact asperities
P_n; P_t	normal/tangential impulse during impact
R_q	roughness parameter
T_i	incident kinetic energy of the projectile
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
μ	impulse ratio
μ_c	critical impulse ratio
μ_{end}	impulse ratio at the end of wear test
μ_k	kinetic friction coefficient

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.

In the present work, wear of a SG tube sample subjected to repetitive impacts against an AVB sample is studied in water environment. Section 2 presents the experimental apparatus that has been designed and used. Section 3 presents a detailed statistical analysis of the impacts and their characteristics. Section 4 presents an analysis of the wear scars and volumes based on topographic measurements and energy considerations.

2. Experimental details

2.1. Impact wear apparatus

The experimental apparatus has been designed to study impact wear between a SG tube sample and an AVB sample in water. A schematic representation of the test machine is presented in Fig. 1 and a picture in Fig. 2. The stationary sample (AVB bar) is mounted inside a water container (volume capacity of 20 mL) on a very stiff support. The mobile sample (SG tube) is inside a tube holder supported by two springs (stiffness k = 590 N/m) in the YZ-plane. Due to experimental choices, the tube holder restricts the ovalization of the SG tube sample. Two shakers control the motion of the mobile sample. The geometry of the contact is cylinder-plane (line contact).

A 3-axis piezoelectric sensor is placed about 40 mm under the contact region and is used to measure the normal and the tangential loads during impacts. Two laser displacement sensors centered on the center of the tube sample are used to measure the incidence and rebound parameters of each impact. The shakers excitation and the dynamic data acquisition are controlled by computer. Signals are recorded with a high sampling rate (50 kHz) to obtain high quality measurements of the contact load time evolution during impacts. An extensive study of the test apparatus stiffnesses and the corresponding eigenmodes as well as their effect on the measurement signals has been carried out in reference

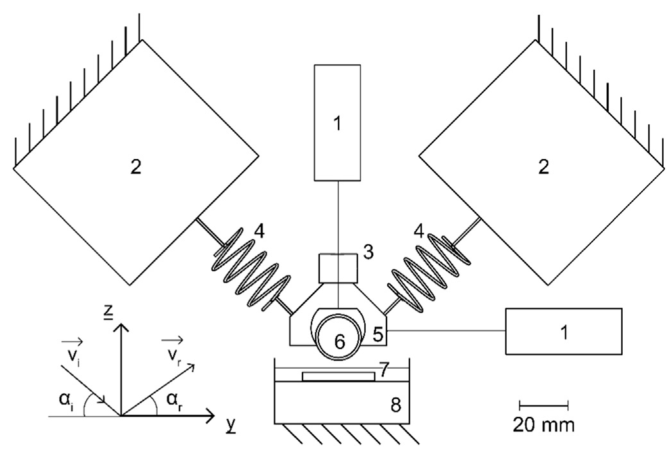

Fig. 1. Diagram of the impact wear test machine (1: Displacement sensors, 2: Shakers, 3: Loading mass, 4: Springs, 5: Tube holder, 6: SG Tube, 7: AVB holder with water container and AVB sample, 8: Force transducer).

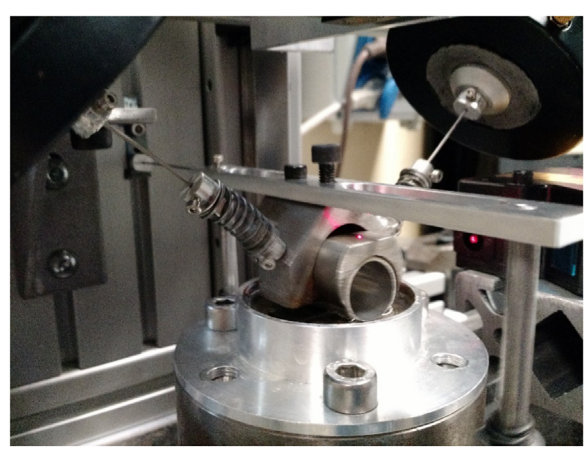

Fig. 2. Picture of the impact wear test machine.

[32]. A two-degrees-of-freedom dynamic model of the test apparatus is proposed and leads to conclude that the interface is governed by the contact asperities and the free vibration of the force