Fretting-wear of zirconium alloys

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ABSTRACT

Fretting tests of Zircaloy fuel sheath bearing pads in contact with zirconium alloy (Zr-2.5Nb) pressure tube specimens were conducted at temperatures varying from 25 to 315°C. The effects of motion type and amplitude, and water chemistry were also investigated.

The effect of temperature is the most significant. The pressure tube wear coefficient in the range of 225 to 286°C for all four motions studied is considerably greater than that above 300°C. In fact, the fretting rate for small amplitude motion due to excitation by flow turbulence is about equal at temperatures below 150°C and above 300°C, but is five to ten times greater in the 250 to 286°C range.

NOMENCLATURE

d_{p-p}	peak-to-peak displacement tangential to the pressure tube
f	frequency of motion
F_n	normal component of contact force
F_p	preload
K	pressure tube wear coefficient (see Eq. 2)
s	sliding distance
t	time
$\dot{V}$	volume wear rate
$\dot{W}$	work-rate (see Eq. 1)

INTRODUCTION

The core of a CANDU® reactor consists of horizontal fuel channels within a vessel of heavy water moderator. Within each channel, 12 or 13 fuel bundles rest on a Zr-2.5Nb tube that acts as the system pressure boundary. Thus, the integrity of these tubes, called "pressure tubes", is essential to safe reactor operation.

® CANDU = CANAda Deuterium Uranium

A typical CANDU fuel bundle (see Figure 1) consists of 37 fuel elements attached together into a cylindrical structure of ≈ 100 mm diameter by welding the ends of each element to end plates. The elements are restricted from rubbing against one another by inter-element wear pads (spacer pads) attached to the midplane of each element. Elements on the outer ring of the bundle are supported on the pressure tube by three wear pads (bearing pads) attached to each element: one at the midplane and one at each end.

FIGURE 1: Typical CANDU Fuel Bundle

Under operating conditions, heat generated within the fuel elements is removed by heavy water coolant flowing through each channel at approximately 10 m/s. Thus, each fuel bundle and all elements within each bundle are subjected to various flow-induced vibration excitation mechanisms.

To estimate pressure tube wear damage resulting from the vibration of fuel bundles, knowledge of fuel element bearing pad-to-pressure tube wear coefficients is required. Specifically, to relate vibration response to wear damage, the wear coefficients of the two materials at realistic levels of dynamic interaction and under realistic environmental conditions must be known.

The international data on wear of Zircaloy was reviewed in the mid 1970's by Brown [1] and Ko [2]. Brown focussed on pure impact data, while Ko included both impact and rubbing data. Ko summarized data from Italian, British and American sources and early data from Chalk River Laboratories (CRL), and drew the following qualitative conclusions:

- 1) Rubbing motion caused greater fretting than impacting motion.
- 2) Fretting increased with amplitude. A threshold amplitude appeared to exist at about $200\ \mu\text{m}$ tangential motion, above which fretting increased dramatically.
- 3) Fretting increased approximately proportionally with normal load.

- 4) Results from American sources indicated that the fretting of Zircaloy-2 at 315°C is less than one-half of that at 260°C, which itself is only one-tenth of that at 232°C.

CANDU-specific Zircaloy fretting tests were conducted at Westinghouse Canada Limited throughout the 1970's. These data have been reviewed and summarized by Hamilton and Stern [3]. The results from these tests are very difficult to analyse because each test consisted of a series of short-term tests (of approximately 24 h duration) with the vibration amplitude being changed continually. As well, the frequency of vibration was somewhat ambiguous because the excitation in the normal direction was commonly 15 Hz, while the excitation in the tangential direction was 45, 90, or 120 Hz.

Additional CANDU-specific data were generated by Ko [4] in short-term tests at temperatures between 23 and 97°C. These tests included one series in which Zircaloy-2 tubing was worn against flat specimens of various other materials at room temperature and 97°C. Wear rates for both tubing and corresponding flat-bar support were negligible for combinations using platinum and palladium.

Testing of bearing pads fretting against sections of pressure tube has been conducted at CRL over the past ten years. The purpose of these tests was to determine the effect of various parameters on pressure tube fretting rates. The most important parameter to be studied was temperature, with tests conducted at temperatures ranging from 25 to 315°C. Other parameters studied included motion type, vibration amplitude and dissolved oxygen content.

IMPACT FRETTING-WEAR TEST MACHINE

An impact fretting-wear test machine, shown schematically in Figure 2, consists of an autoclave, central vibrating tube, instrument platform, vibration generator and supporting structure. The bearing pad wear specimen, consisting of a short length of fuel sheath with a bearing pad, is attached to the central tube, as shown in Figure 3. The pressure tube wear specimen is mounted on the instrument platform. Additional bearing pad and pressure tube specimens are mounted on the instrument platform to monitor material oxidation.

The test rigs simulate the dynamic interaction characteristic of CANDU components such as fuel channels, steam generators and heat exchangers. Unlike conventional wear testing machines, where the contact motion is strictly controlled, the excitation in these rigs is remote from the point of specimen contact. This arrangement allows the wear surfaces to move relatively freely against one another, simulating the motion in real components.

During testing, high-temperature eddy-current displacement transducers mounted on the instrument platform monitor the position of the bearing pad specimen with respect to the pressure tube specimen. Interaction forces between the bearing pad and pressure tube specimens are measured at room temperature using four miniature piezo-electric force transducers.

The temperature and pressure inside each machine are independently controlled so both high-temperature, pressurized water and saturated steam conditions can be achieved. All of the tests in this program were conducted in pressurized water.

BEARING PAD-TO-PRESSURE TUBE RELATIVE MOTION

Fretting is dependent on the dynamic interaction between the contacting surfaces, which combines both relative displacement and contact force. The most appropriate parameter for expressing dynamic interaction is work-rate, which is defined as the time-averaged integral of contact force and sliding distance (see Equation 1).

$$\dot{W} = \frac{1}{t} \int F_n ds \quad (1)$$

FIGURE 2: Schematic of an Impact Fretting-Wear Test Machine

Fuel element motion and bearing pad-to-pressure tube interaction due to flow turbulence occurs at two frequencies: at approximately 10 Hz due to bundle rocking, and at approximately 30 Hz due to element bending. Maximum vibration levels generally occur at the side midplane of the inlet bundle (the bundle located at the fuel channel end where the coolant enters).

Prior to starting the fretting test program, scoping tests were conducted in one test machine to identify motion types that were repeatable and that caused measurable wear within a reasonable test duration. The intent of the program was to simulate the interaction occurring between fuel elements at the 4 to 5 and 7 to 8 o'clock positions in fuel bundles and the pressure tube due to flow turbulence. Such elements are postulated to be close to or lightly in contact with the pressure tube, such that contact could occur as a result of low levels of turbulence-induced vibration. The vibration level under these conditions would be in the order of 25 μm RMS, and would be in the normal and circumferential directions. Accordingly, the

scoping tests were conducted at fairly low levels of dynamic interaction and did not include axial motion or large preloads. Four stable but different motion types were identified:

- 1) large amplitude impacting at 15 Hz (LAI),
- 2) large amplitude rubbing at 15 Hz (LAR),
- 3) small amplitude impacting at 25 Hz (SAI), and
- 4) small amplitude rubbing at 25 Hz (SAR).

FIGURE 3: Bearing Pad and Pressure Tube Specimens Installed in Machine

The amplitudes of the two motion types at 15 Hz were typically three times greater than the amplitudes at 25 Hz. For both frequencies, the tangential components of vibration were equal, while the normal components were nearly zero for rubbing motion and almost equal to the tangential components for impacting motion. The contact force magnitudes for impacting motion at both frequencies were equal and about two or three times greater than the magnitudes for rubbing motion.

The motion type for the majority of the test program was small amplitude impacting at 25 Hz (SAI), as this is most typical of turbulence-induced interaction between fuel elements at the 4 to 5 and 7 to 8 o'clock position in fuel bundles and the pressure tube. Typical displacements, forces and work-rates for this motion type were $65\text{ }\mu\text{m}$ RMS, 5 to 10 N peak, and 0.5 to 4 mW, respectively.

TEST RESULTS

The test program consisted of 122 tests of 250 h duration and two long-term tests of 1000 h duration. The effects of environmental factors, such as temperature and dissolved oxygen content were investigated. As well, the effects of other factors, such as motion type and vibration amplitude were studied.

Wear coefficients for the pressure tube specimens were calculated from Archard's wear equation, expressed in rate form:

$$\dot{V} = K \dot{W} \quad (2)$$

In Archard's formulation, the wear coefficient, K , is defined as the volume wear rate, $\dot{V}$, divided by the work-rate, $\dot{W}$. The wear rates used to compute wear coefficients were those based on wear volumes, as that measurement is more accurate, especially when the wear damage is small (i.e., net weight losses in the order of 1 mg).

Work-rates for the impacting tests (SAI and LAI) were calculated from pre- and post-test recordings of relative displacement and contact force. Work-rates for the sliding wear tests (SAR and LAR) were estimated from the measured tangential amplitudes and preloads:

$$\dot{W} = 2 d_{p-p} f F_p \quad (3)$$

At least three tests were conducted at each test condition to assess test repeatability and increase data reliability. The smallest variation in test results was for tests conducted at 25°C, where wear coefficient standard deviations were less than 50 percent. However, at higher temperatures above 150°C, the standard deviations were as great as 100 percent. To increase data reliability, more than six tests were conducted at some high-temperature conditions where large variability was apparent.

Wear coefficients for the two long-term tests were comparable to those from shorter-term tests conducted at the same conditions. Therefore, there was no apparent effect of test duration so long as the duration exceeded 250 h.

Effect of Vibration Amplitude and Motion Type

Fretting rates for all four types of motion (SAI, LAI, SAR and LAR) were compared at two temperatures: 25 and 286°C. Greater fretting rates were observed for large amplitude motion than for small amplitude motion. However, work-rates for large amplitude motion were also greater, resulting in similar wear coefficients. Wear rates for rubbing and impacting motions at the same amplitude were approximately equal. Work-rates for rubbing motion were greater. Therefore, wear coefficients for rubbing motion were generally lower.

Effect of Oxygen Content

Fretting is a combination of both wear and corrosion processes, with material oxidation acting to accelerate the normal wear process. Therefore, tests were conducted with high levels of dissolved oxygen to assess the effect of dissolved oxygen content on the wear coefficient.

Results at 300 and 315°C appeared to show that more fretting occurs with high levels of dissolved oxygen, while results at 225 and 275°C indicated that less fretting occurs. At 250°C, the average wear coefficients were equal. Therefore, within the accuracy of the test results,

there is no consistent difference in the wear coefficient for low and high levels of dissolved oxygen content.

Effect of Temperature

The effect of temperature on fretting damage is very significant. Average results for small amplitude impacting tests are plotted in Figure 4. Error bars on each data point indicate the range of results of individual tests at each temperature. The range in results at lower temperatures (25 and 150°C) is a factor of two to three, which is typical repeatability for wear testing. The range in results at higher temperatures is much greater, approaching an order of magnitude at some temperatures. This increased scatter is thought to be characteristic of the fretting behaviour at these higher temperatures. Between 250 and 315°C, the average wear coefficient decreases by an order of magnitude. Therefore, it is likely that the increased scatter is due to slight variations in the test conditions resulting in changes in the wear regime.

FIGURE 4: Effect of Temperature on Pressure Tube Fretting

The maximum wear coefficient was observed in the 225 to 286°C temperature range. Less damage occurred at lower temperatures (25 and 150°C) and at higher temperatures (300 and 315°C). This observed decrease in wear coefficient with increasing temperature above some transition temperature has been observed for other alloys [5-7].

In a recent publication, Jiang et al. [5] investigated the development of wear protective layers in a nickel-base alloy at temperatures between 20 and 600°C using a pin-on-disk reciprocating wear machine. They observed that at temperatures above 250°C, the wear rate became negligible once fully developed wear was established.

To explain this behaviour, they postulated that the development of protective layers of wear debris was dependent on temperature. In fully developed wear, wear particles are fragmented between the contacting surfaces, oxidized and then agglomerated into surface layers. During subsequent wear, two competitive processes occur in these surface layers: break-down of the layers under the wear process, and consolidation of the layers due to sintering and cold-welding. At temperatures above a "transition temperature" (250°C for their alloy), the layers become solid and resist further wear, while at lower temperatures the layers are continually broken down.

A similar phenomenon may occur in zirconium alloys. The growth of an oxide layer itself may not be sufficient to protect against further fretting. However, layers formed at higher temperatures beyond some "transition temperature" may be more effective at limiting further fretting. Note that the hypothesis that this process occurs in zirconium alloys has not as yet been substantiated with direct evidence.

Fret Mark Topography

Three-dimensional surface profilometry was performed on all pressure tube wear specimens. The isometric 3-D profile for a long-term test is shown in Figure 5. The maximum depth of this fret mark was 100 μm .

FIGURE 5: Three-Dimensional Wear Profile from Test PT-124

CONCLUSIONS

The effect of temperature on fretting damage is very significant. The wear coefficient in the range of 225 to 286°C is much greater than that at both higher and lower temperatures. This effect is observed in both impacting and rubbing tests. The variability of results at higher temperatures approached an order of magnitude. This variability is thought to be characteristic of the fretting behaviour.

Tests conducted between 200 and 315°C to assess the effect of dissolved oxygen content (low or high) showed differences no greater than those observed between nominally identical tests at the same temperature. Therefore, the effects of dissolved oxygen content are not significant compared to the variability of test results at a particular temperature.

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