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# On the thermal origin of the antagonistic and synergistic effects of fretting and crevice corrosion processes in multi-phase flow environment

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ABSTRACT

Heat exchange systems usually operate in multi-phase environment and compose of non-conforming structural components in contact. In addition to crevice corrosion, fretting corrosion damage may also take place at the contact interface as a result of flow-induced vibrations. Local nucleate boiling in the crevice region between contacted bodies causes an increase in the chemical concentration of the solute flowing in this region. This in turn accelerates the crevice corrosion damage. Development of reliable thermal models is, therefore, critically needed for reliable design and safe operation of these heat exchange systems.

In this paper, a system approach is adopted to accurately predict the onset of nucleate boiling and accelerated crevice corrosion near the contact region of non-conforming bodies. The proposed methodology recognizes the nonlinear nature of the process and the presence of multi-dimensional closed loop interactions. On one level, there is interaction between the temperature field and the boiling process, through the changes in the conditions of heat transfer at adjacent water-cooled surfaces. On another level, this methodology allows due consideration of the mutual interactions between the crevice and the fretting corrosion processes. The thermal model accounts for the volumetric effect of the thermal constriction resistance $R_c$ and allows evaluating the thermal barrier effect caused by the increase in the $R_c$ due to surface coating and/or fretting corrosion. Analysis of the results indicated the significance of modeling the nonlinear behaviour of the system for accurate prediction of the extent of local nucleate boiling in the crevice region. The results also indicated that the increase in the $R_c$ with surface coating and/or fretting corrosion can cause the crevice corrosion process to be self-limiting.


## 1. Introduction

Heat exchange systems, like pressurized water reactors, operate in multi-phase environment and are composed of non-conforming bodies in contact, such as steam generator tube-support plates, and fuel bundle bearing pad (BP) pressure tubes (PT) [1]. The primary heat transport system in these reactors contains minimal chemical additives, e.g., lithium hydroxide LiOH for pH control, in order to minimize deposition and transport of crud [2]. Bearing pads and pressure tubes are made of zirconium alloys for their transparency to thermal energy neutrons. They are, however, known to be susceptible to crevice corrosion and have much lower fretting corrosion and wear resistance than other nuclear-grade materials, e.g., nickel-based alloys. Under normal operating conditions, local nucleate boiling may take place in the crevices formed by these structural components, resulting in the increase in the concentration of the chemical additives. This may lead to accelerated crevice corrosion when the solute concentration reaches a certain critical level $C_{cr}$. This critical concentration varies significantly with temperature. For lithium hydroxide, for example, $C_{cr}$ increases from 0.4 g/l at 360 °C to 6 g/l at 330 °C. It has been reported in the literature that only a few degrees rise in the surface temperature above the saturation point of the heat transport medium ($H_2O$ or $D_2O$) is sufficient to reach the critical concentration. It was also reported that a change in the concentration of LiOH solution from 2 to 10 g/l increases the corrosion rate of zirconium alloys by two orders of magnitude at 360 °C [3].

In heat transfer equipment, the sites which are susceptible to crevice corrosion are usually candidates for fretting corrosion as well, due to flow induced vibrations. Attia et al. established the significant effect of the friction-induced heat generation in fretting on the temperature rise in the contact and subsurface region [4–8]. This effect is expected to influence, or even eliminate, crevice corrosion through the suppression of local nucleate boiling. From the design point of view, this illustrates the importance of accurate modeling of the heat transfer process associated with crevice and fretting corrosion processes. Johnston et al. and others [9–11] stated that while the severity of localized

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corrosion in the steam generator tube-support plates of pressurized water reactor can be minimized through water chemistry and improved materials, the formation and maintenance of dry regions, as an initiator of corrosion damage, is a problem of heat transfer and fluid mechanics.

The objective of the present work is to develop a methodology that can predict the conditions that prevent accelerated crevice corrosion when the contacting bodies are subject to fretting corrosion. The formulation of the proposed model has to recognize the nonlinear nature of the process and the mutual interactions between the crevice and the fretting corrosion processes. The model should account for the volumetric effect of the thermal constriction resistance $R_c$ at the contact interface adjacent to the crevice region, and should allow evaluating the thermal barrier effect caused by the increase in the $R_c$ due to surface coating and fretting corrosion.

## 2. Thermal aspect of the fretting corrosion process

The fretting interface temperature $T_s$ has a decisive influence on fretting corrosion resistance $f_r$. When the growth rate of the protective oxide layer follows a parabolic law, the $f_r$–$T$ relation is governed by the following relation [12]:

$$f_r = A_0 \exp\left(-\frac{Q}{RT_s}\right) \tag{1}$$

where $A_0$ is Arrhenius constant, $T_s$ is the absolute surface temperature, $R$ is the Boltzmann constant, and $Q$ is the activation energy for oxidation. Once the surface temperature $T_s$ reaches a critical transition level $T_{tr}$, due to external and/or frictional heating, oxidation becomes the corrosive wear controlling mechanism.

Extensive investigation has been carried out by the author to characterize the fretting corrosion of Zr alloys at high temperature in air and steam environment. The results of the fretting corrosion of Zr-2.5% Nb against Zr-4 at 265 °C after $N = 4.94 \times 10^7$ cycles is presented in Fig. 1 [4]. The fretting conditions were: slip amplitude $\delta = \pm 37.5\,\mu m$, $f = 6\,Hz$ and the contact pressure $p_c = 1\,MPa$. Examination of the fretting scar showed that the material transferred to the Zr-2.5% Nb specimen is covered by white thick oxide layer that appears to be cohesive and adherent to the substrate. X-ray dispersion analysis of the oxidized surface showed strong Zr and O peak heights, as shown in Fig. 1(a). The distribution of the oxide thickness along the wear scar was measured using Fourier transform infrared interferometry (FTRI). In this analysis, the local thickness measurement was averaged over a circular spot of 100 μm. As an example, a set of spectra for the oxide film along the wear scar in the sliding direction is shown in Fig. 1(b). The occurrence of interference is recorded as an absorbance peak, and the oxide thickness was calculated from the spacing between adjacent peaks. Analysis of the results indicated that the fretting action of Zr-2.5% Nb resulted in a significant growth of the oxide from an initial thickness of $t_0 = 0.5$–$0.7\,\mu m$ to 2–15 μm thick layers.

Due to the topographical nature of engineering surfaces, a point-to-point contact is observed at the asperity level and, therefore, frictional heating is only generated over the real contact area. The ratio $\varepsilon^2$ between the real and apparent contact areas is typically of the order of 0.1–1%. As the heat flow lines approach the contact zone, they tend to converge towards the least resistance paths, i.e., the metallic micro-contact areas. This natural constriction of the flow lines gives rise to the phenomenon of "thermal constriction resistance" $R_c$ [5–7]. As a result, the local contact temperature may reach a relatively high level, accompanied by a steep temperature gradient in the subsurface layer. The constriction resistance $R_c$ can be expressed in terms of the equivalent additional length $\Delta\ell$ of a thermal resistor made of the same material as the parent solid bodies. Under fretting conditions, the equivalent thermal constriction resistance $\Delta\ell$ may reach a few mm, as shown in Fig. 2 [7].

The resistance $R_c$ is usually expressed in terms of a dimensionless constriction factor $\psi$:

$$R_c = \frac{\psi}{k\sqrt{A}} \tag{2}$$

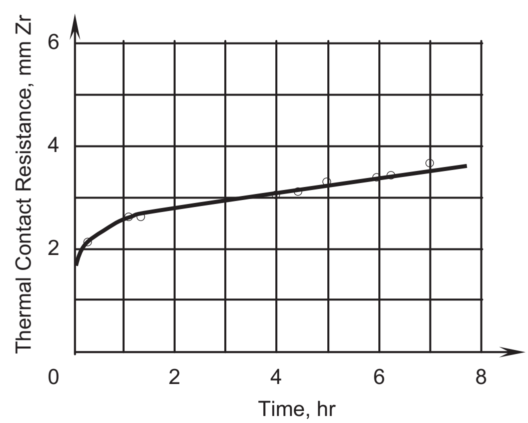


**Fig. 2.** Change in the thermal contact resistance with the progress of the fretting process; Zr-2.5% Nb/Zr-4, $p_c = 0.85\,MPa$, $\delta = \pm 45\,\mu m$, $f = 6\,Hz$, 150 °C.

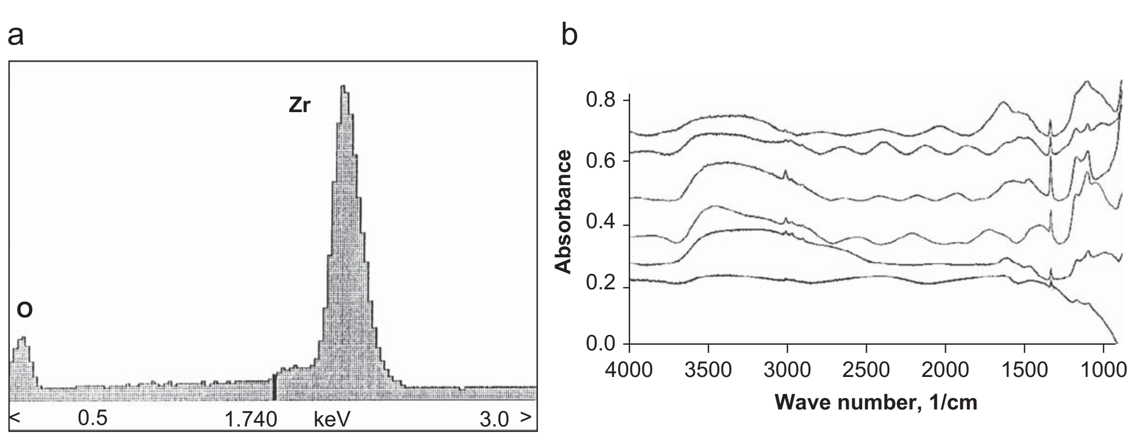


**Fig. 1.** Analysis of the oxide layer in the fretted zone: (a) X-ray dispersion analysis, (b) infrared reflection–absorption spectra from the oxide in the fretted area.