SHORT NOTE

Acceleration of Zircaloy-Steam Reaction Rate by Deformation under High Temperature Transient

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The rate of zircaloy-steam reaction at high temperature is a matter of concern in the light water reactor safety field. The reaction heat released induces the temperature rise of zircaloy cladding. The oxygen uptake due to the reaction also causes the degradation of mechanical properties of zircaloy cladding. In recent years, many investigators have actively studied the reaction rate to determine the degree of conservatism of the Baker-Just’s correlation\(^{(11)-(15)}\). The analysis of emergency core cooling systems in the regulations must now apply the maximum temperature and oxidation criteria to the region of clad ballooning or burst. On the other hand, it is pointed out that deformation under high temperature transient\(^{(6)}\) or applied stress at low temperature\(^{(7)}\) can enhance the rate of steam oxidation of zircaloy cladding. The deformation of the cladding will be likely to occur under a loss-of-coolant accident (LOCA), as deformation by ballooning will result from internal pressure increase, either from fission product gases or inert gas introduced into the fuel rod to prevent collapse of the cladding under normal operating conditions. Local deformation or ballooning will be likely experienced at temperature range from about 900 to 1,100 K on the basis of rod-burst experiments\(^{(9)-(11)}\). The cladding will be severely oxidized under or after deformation. While, almost no attention in the safety evaluation is paid to any acceleration of the rate in zircaloy-steam reaction due to deformation of the cladding. Then, we tried a few experiments on the oxidation kinetics following deformation.

The zircaloy-4 cladding material has the following chemical analysis: Sn 1.46 wt.%, Fe 0.22 wt.%, Cr 0.10 wt.%, C 80 wt.ppm, O 1,400 wt.ppm, H 20 wt.ppm, N 18 wt.ppm, Zr bal. The two

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tensile specimens, individual of which has 30 mm in gauge length and 1.2 mm in thickness, were set in a vertical quartz tube installed on an Instron universal testing machine. But, one of the specimens was cut off at one grip end to measure oxide thickness as undeformed control data. The steam with flow rate of 0.22 kg/m².s was fed into one end of the quartz tube. During heating transient in flowing steam, tensile deformation under the speed of 0.83 mm/s was applied on one of the specimens at temperatures of 973, 1,073, 1,173 and 1,273 K respectively. Temperature was measured by a Pt-Pt/Rh thermocouple attached to the side of specimens. The rise in temperature during the course of the tensile test was estimated within 30 K, because the time to failure took about 10 s in the heating rate of 3 K/s. The time allowed for oxidation was varied from zero to 600 s at 1,273 K. The thicknesses of oxide and ξ (oxide+alpha) layers were measured on metallographically polished cross sections at each segment of specimens. Layer thickness was measured by an Olympus PMG-2 microscope at the magnification of 200.

The specimens were tested to failure in tension in order to determine the degree of oxide thickness produced by the deformation at each temperature. **Figure 1** shows the ratio of oxide thickness (deformed/undeformed) as a function of distance from a rupture lip. The lateral axis represents strain introduced into the specimen, because the amount of strain on each place of fractured specimen depends on the distance from a rupture lip. The oxide thicknesses of undeformed four specimens were almost equal in the measured regions. The oxide thicknesses of deformed specimens are thicker than those of undeformed at any deformation temperature, and increase with strain at each deformation temperature. The acceleration effect of deformation is remarkable at lower temperature. **Figure 2** shows thicknesses of oxide and ξ layers as a function of reaction time at 1,273 K for specimens given a strain of 7~8 or 17~18% at 973 K. The curve obtained from an oxidation tests on undeformed specimen is also illustrated in this figure. The thicknesses of oxide and ξ layers of deformed...

![Fig. 1 Ratio of oxide thickness (deformed/undeformed) as function of distance from rupture lip for zircaloy-4 cladding in oxidation during 300s exposure to steam at 1,273 K](image1)

![Fig. 2 Thicknesses of oxide and ξ (oxide+α) layers as function of reaction time at 1,273 K for zircaloy-4 cladding given a strain of 7~8 or 17~18% at 973 K](image2)
specimens are thicker than those of undeformed within 600 s in the oxidation time, but the differences in both thicknesses between deformed and undeformed specimens decrease with progression of oxidation time at a given strain. The thicknesses of oxide and $\xi$ layers at given time within 600 s increase with amount of strain introduced into the specimen. It would be concluded that the deformation applied during a heating transient will be effective only in the early stage of the zircaloy-steam reaction and large strain can enhance the rate of steam oxidation of zircaloy. Figure 3 shows thicknesses of oxide and $\xi$ layers as a function of amount of strain introduced into the specimen deformed at 973 K. Both thicknesses increase with strain, but they have a trend toward saturation with increasing strain.

The oxidation evaluation of the current safety analysis must take the average wall thickness just before severe oxidation into consideration, if the wall thinning of cladding occurs under a LOCA. We have already found out that the wall thinning due to ballooning reached $20\sim40\%$ to the initial wall thickness in the rod-burst experiment\(^{(1)}\). Though the wall thinning does not correspond to the strain directly, the large strain due to ballooning will be likely introduced into the cladding under a LOCA. It is, also, pointed out that the time allowed for severe oxidation during a LOCA transient is fairly shorter. Therefore, the enhancement of the reaction rate by deformation should be taken into consideration in the oxidation evaluation of zircaloy cladding under a LOCA condition.

![Fig. 3 Thicknesses of oxide and $\xi$ (oxide+$\alpha$) layers as function of amount of strain introduced into zircaloy-4 cladding deformed at 973 K](image)

**REFERENCES**