Effect of Fuel Cladding Surface Modification on Crud Deposition in a Simulated Primary PWR Condition

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1. Introduction

Crud is a corrosion product deposited on fuel cladding surface in the PWR primary coolant system [1]. These cruds can increase fuel cladding temperature due to an increased thermal resistance, resulting in accelerated fuel cladding corrosion. Above all, the thick crud may shift the core neutron flux from the top of the core to the lower half of the core along the axis of the fuel assemblies, called axial offset anomaly (AOA). This phenomenon leads to a low margin of safety and a power reduction of the NPPs [2,3].

Based on large scale laboratory experiments and fuel inspection results, it has been well known that crud is driven by sub-cooled nucleate boiling (SNB) on the fuel cladding surface and the crud mass is proportional to the degree of SNB [1-4]. This is because a sufficient corrosion product is supplied around the steam-liquid interface of a boiling bubble. In addition, porous crud through these SNB process is well formed on the fuel cladding. Because boron, which is added into the primary coolant for a neutron absorber, can be accumulated easily into pores of the deposits, porous crud deposition is a direct cause of the AOA phenomenon [2,3].

The SNB process occurs when the outer cladding surface temperature is higher than the saturated coolant temperature and the bulk coolant temperature remains below the saturation temperature. In this condition, vapor bubble density and size increase with an increase in the surface temperature.

In general, it has been known that the water boiling behavior depends on surface properties, such as wettability and microstructure or roughness (cavities, scratches, and grinding marks) [5,6]. Therefore, many researchers have investigated the effect of these parameters in order to elucidate the correlation between boiling dynamics and surface properties. However, because these studies have been performed under a low pressure, there are not enough data available to understand the boiling behavior in conditions involving high temperature and highly pressurized water, such as the primary coolant system. Furthermore, it is necessary to identify how these surface changes affect the crud deposition in PWR primary water conditions.

Therefore, the purpose of this work is to elucidate the effects of fuel cladding surface properties on crud deposition in simulated primary water at 328^{o}C and 130 bars. To identify water boiling behavior with surface properties, a series of visualization test is performed first in a transparent glass cell at atmospheric pressure. Based on the visualized tests at 1 bar, crud deposition tests were performed at 328^{o}C and 130 bars. In all tests, water boiling behavior on the fuel cladding surface is monitored using the acoustic emission (AE) technique.

2. Experimental

The test cladding tubes were prepared with the pure as-received cladding tube and the chemically etched cladding tube, respectively. The chemically etched cladding tube was prepared through immersion in an acid solution composed of 45 volume % of nitric acid (70% HNO_3), 5 volume % of hydrofluoric acid (60%-HF) and 50 volume % of distilled water for 3 min at room temperature. After the chemical etching, the cladding tube was rinsed immediately in distilled water. The surface properties of specimens were analyzed by contact angle and surface profiler measurements.

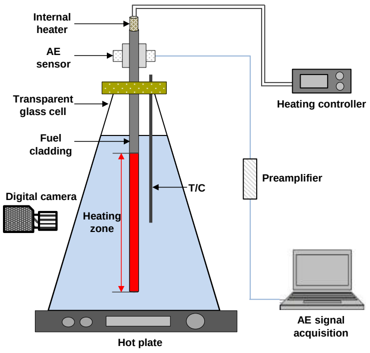

Fig. 1. Schematic of experimental apparatus used for visualized water boiling observation and AE data acquisition at atmospheric pressure.

Visualization tests at atmospheric pressure were performed to identify water boiling behavior on two different cladding surfaces. Fig. 1 shows the schematic of the test equipment. The water boiling was realized via a stepwise heating the cladding tube by the internal heater. The detailed control of the water boiling process is as follows: First, the bulk water was heated to 95^{o}C using a hot plate, i.e., 5^{o}C lower than the saturation temperature at atmospheric pressure. When the temperature of the bulk water was stabilized at 95^{o}C, the power of the hot plate was switched off. Afterwards, the internal heater was quickly powered on and the cladding tube was heated until the temperature of the internal heater (T_{IH}) was stabilized at 120°C. At this stage, the boiling behavior on the surface was observed using a digital camera and the AE data was simultaneously acquired for 500 sec. After these measurements were done, the cladding tube was heated by stepwise increasing the T_{IH} from 120°C to 160°C with an increment of 20°C per step. At each step of temperature, observation of the boiling behavior and acquisition of the corresponding AE data were made for 500 sec.

Crud deposition tests were performed in a circulation loop, as shown in Fig. 2. The inlet solution into the test section was preheated and the temperature of the flowing water adjacent to the cladding tube was maintained at 328°C. The temperature of the internal heater was maintained at 380°C to provide the condition of SNB on the surface of the cladding tube during the crud deposition test. The pressure of the test section was regulated at 130 bars. Dissolved oxygen was controlled to be less than 5 ppb and dissolved hydrogen was maintained at 35 $cm^3/kg \cdot H_2O$. The flow rate adjacent to the cladding tube in the test section was controlled at 5 m/sec. After all these conditions were stabilized, we started to inject the mixed Fe and Ni ions into the test section through the metering injection pump. The mixed precursor ions of Fe and Ni were injected with a flow rate of 1.1 ml/min from the injection tank directly to the downstream of the preheater. This precursor solution was diluted in the simulated primary water stream and then its final chemistry was calculated to be 4.0 ppm Fe and 0.16 ppm Ni in the test section. Each deposition test was conducted for 5 days. The acoustic sounds emitted from the water boiling on the heated cladding surface were monitored using the AE technique for 500 sec every 24 hrs during the deposition tests.

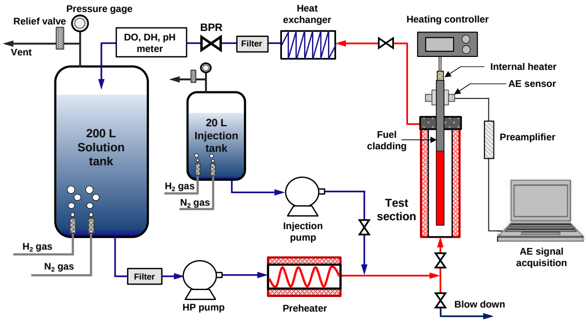

Fig. 2. Schematic of the crud deposition system.

3. Results and discussion

3.1 Surface properties of the specimens

Table 1 shows the roughness and contact angle measured on the surface of as-received cladding and chemically etched cladding, respectively. The surface roughness was measured as follows: 0.15 μm for as-received and 0.04 μm for chemically etched tube. This indicates that surface roughness of existing as-received cladding decreased by a factor of about four through chemical etching. The contact angles were measured to be 77±2.5° for as-received cladding and 39±2.5° for chemically etched cladding. Here, a high contact angle corresponds to a low surface wettability. That is, the chemically etched cladding surface has a more hydrophilic property.

Table 1. Values of roughness and contact angle of cladding tube surface.

Surface state	Surface roughness (Ra, μm)	Contact angle (°)
As-received	0.15	77
Chemically etched	0.04	39

3.2. Water boiling behavior at atmospheric pressure

Fig. 3 (a) and (b) show the visualization images of the water boiling behavior on as-received cladding and chemically etched cladding at atmospheric pressure, respectively. Water boiling increased in both cladding tubes with an increase in the internal heater temperature. However, when comparing the as-received cladding with the chemically etched cladding, vapor bubble density remarkably increased on the as-received cladding. Furthermore, onset of nucleate boiling was first formed on the as-received cladding at 120°C of the internal heater temperature. This means that water boiling is more favored on a rough and hydrophobic surface.

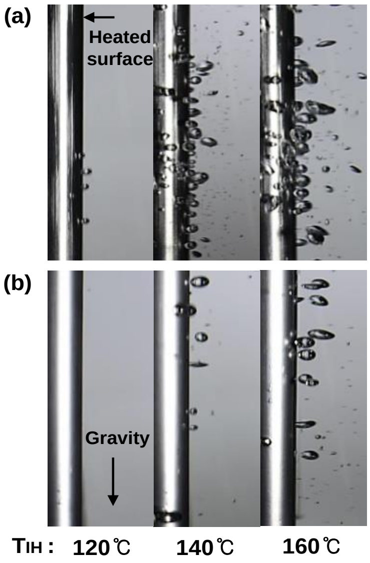

Fig. 3. Visualized water boiling images with increase in internal heater temperature (T_{IH}) at atmospheric pressure: (a) as-received and (b) chemically etched cladding tube.

Combined with the above observation, the boiling-AE signals were simultaneously acquired for 500 sec. Fig. 4 shows the AE hit number monitored at each heater temperature on the as-received tube and on the chemically etched tube. In this work, the AE hit number means boiling-AE events for vapor bubble dynamics, such as bubble formation, growth, departure, travel and collapse. As shown in visualized results, the AE hit number for two cladding tubes increased with an increase in the internal heater temperature. However, the AE hit number acquired on the as-received tube increased by about three times compared to that on the chemically etched tube. This implies that water boiling occurs actively on the as-received surface than the chemically etched surface. From these results, it is confirmed that a rough and hydrophobic surface lead to increase water boiling.

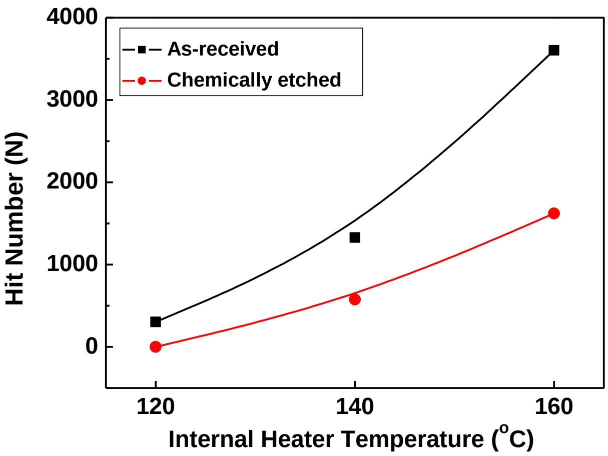

Fig. 4. Variation of AE hits number of the boiling-AE signals at atmospheric pressure.

3.3. Crud deposition behavior at 130 bars

Fig. 5 shows the AE hit number monitored for 500 sec every 24 hrs on the as-received tube and the chemically etched tube during the deposition tests. As time passed, the AE hit number increased on both of them. However, this data shows that the AE hit number remarkably increased on the as-received tube compared to that on the chemically etched tube. This indicates that the surface roughness and wettability affect water boiling in high temperature and pressurized water. Consequently, these factors on the as-received surface lead to increase the degree of SNB, resulting in an increase in the number of boiling signals.

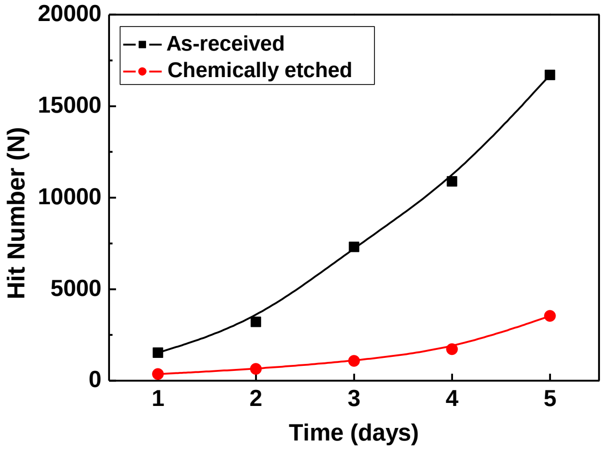

Fig. 5. Variation of AE hits number on as-received and chemically etched cladding during crud deposition at 328°C and 130 bars.

Fig. 6 shows the amount of cruds deposited on the as-received tube and on chemically etched tube after deposition tests. The deposit mass decreased by 51% for chemically etched tube compared to that for as-received tube. This should be caused by the change of water boiling behavior with the cladding surface modification. This means that the amount of cruds was heavily dependent on the surface roughness and wettability of the cladding.

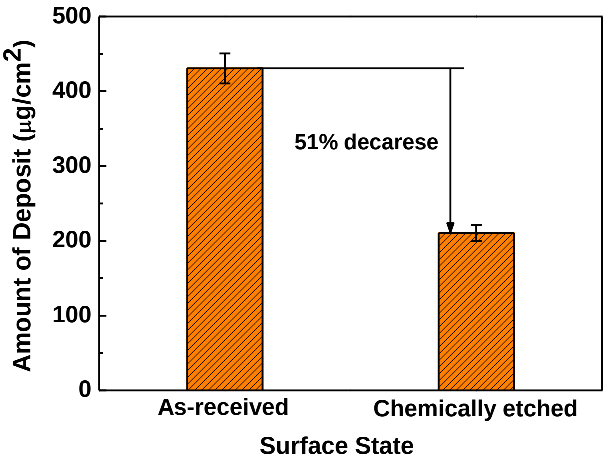

Fig. 6. Amount of crud after crud deposition tests at 328°C and 130 bars.

4. Conclusions

We investigated to identify the effect of surface modification on the crud deposition in a PWR primary condition. The chemically etched surface has properties of a relatively low roughness and a high wettability compared to the as-received cladding. Water boiling is more favorable for a high roughness and a low wettability surface, resulting in an increase of crud deposition on the as-received tube. Consequently, the amount of cruds on the chemically etched tube decreased by about 51% compared to that on the as-received cladding tube.

Acknowledgments

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