Experimental Investigation of Surface Roughness and Oxidation on Clad Quenching

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1. Introduction

The emergency core cooling system (ECCS) injects cooling water into the reactor core in the event of postulated accidents such as a loss-of-coolant accident (LOCA). The cladding temperature is predicted to increase above 1000 ^{o}C in case of large-break LOCA (LBLOCA) because the reactor coolant in high pressure rapidly losses through the break [1, 2]. The safety limit for peak clad temperature is 1204 ^{o}C for LBLOCA [3]. The ECCS water will cool down the hot cladding by quenching process. This study was performed to experimentally investigate the effect of surface roughness and oxidation on clad quenching. This quenching experiment measured surface temperature of zircaloy tube and recorded the video image of transient boiling process from film boiling to convective heat transfer.

2. Experimental Apparatus and Method

An experimental apparatus was built to perform a pool quenching using test rodlets or tubes [4]. The circular tube specimen was used in this experiment. The three independent tests were conducted to confirm the repeatability of experiment. Three runs of test were also made for each specimen to investigate the effect of clad oxidation.

2.1 Experimental Apparatus and Test Specimen

The quenching apparatus consists of test specimen (Zircaloy-4 tube), furnace, glass beaker (quenchant pool), air slide and data acquisition system (DAS). The furnace is used to heat up test specimen by radiation with a maximum power of 1.2 kW. Four K-type thermocouples are installed to measure the inside temperature of furnace. The glass beaker is placed on hot plate to maintain the coolant temperature at target value. The coolant temperature in pool is also measured by thermocouple. The air slide with compressor is used to drop the test specimen into quenchant pool (beaker). The high speed camera and video camera were used to capture the dynamic image of transient boiling during quenching process.

The test specimen is a zircaloy-4 tube with outer diameter and length of 9.5 mm and 70 mm, respectively. The K-type thermocouples are installed inside Zircaloy tube using a grooved ceramic tube to measure clad temperature. The surface of test specimen is polished with different mesh sizes of sandpaper, i.e., #220, #1000, #2400 and #4000. Table I lists the surface roughness of fresh test specimen depending on the mesh size. The surface roughness is measured using a roughness tester, Mitutoyo SJ-201. The average roughness (Ra) is 0.86 μm and 0.20 μm for the mesh #220 and #2400, respectively. The roughness decreases significantly if the sandpaper mesh is higher than #2400. However, the roughness appears to not decrease even if the specimen is polished with sandpaper of mesh #4000.

Table I: Surface Roughness of Fresh Specimen

Mesh size	Ra(μm)	Rq(μm)	Rz(μm)
#220	0.98	1.33	9.96
#1000	0.50	0.74	5.64
#2400	0.20	0.26	1.91
#4000	0.20	0.26	1.66

2.2 Experimental Method

The test specimen is placed inside furnace using moving holder and turned on the furnace heater. The specimen is gradually heated to a target temperature of 600 ^{o}C. The quenchant pool is also kept at constant temperature using hot plate. Since the coolant subcooling for this study is 0 ^{o}C, the pool temperature is maintained at 100 ^{o}C. When the test specimen and pool reaches a target temperature, the specimen is plunged into the beaker pool by air slide system. The transient temperature and boiling images were taken using DAS and high-speed camera.

Three runs of quenching test were performed to examine the effect of surface oxidation in clad and three repeatability tests were also conducted using three specimens. The surface roughness and contact angle were measured for the fresh specimen and the three-run specimen.

3. Results and Discussion

The quenching curve in Fig. 1 shows the effect of surface roughness on clad quenching for fresh specimen. The quenching curves for all surface roughness show film boiling region in early stage (i.e., t < 35 sec) and transit to nucleate boiling at around 35 sec. The minimum film boiling temperature (MFBT) is approximately 320 ^{o}C. The nucleate boiling changes to forced convective heat transfer as the clad temperature

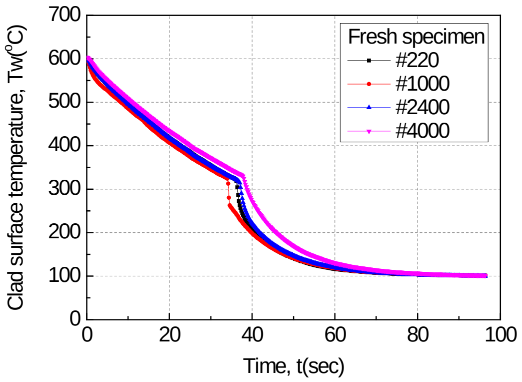

Fig. 1. Quenching curve depending on surface roughness for fresh specimen.

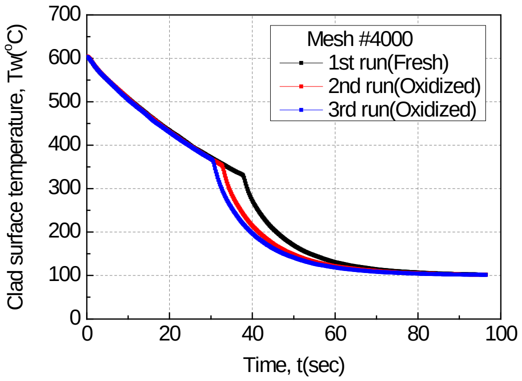

Fig. 2. Quenching curve depending on clad oxidation.

decreases. The surface roughness does not show a significant effect on the quenching performance of clad.

Figure 2 shows the effect of surface oxidation in Zircaloy-4 clad (mesh #4000). The MFBT for the second and third runs is above 350 °C while the MFBT for the first run (fresh specimen) is 320 °C. The quenching time also reduces to 30 sec from 36 sec due to the clad oxidation. This implies that the surface oxidation in clad appears to enhance the queening performance by 17%.

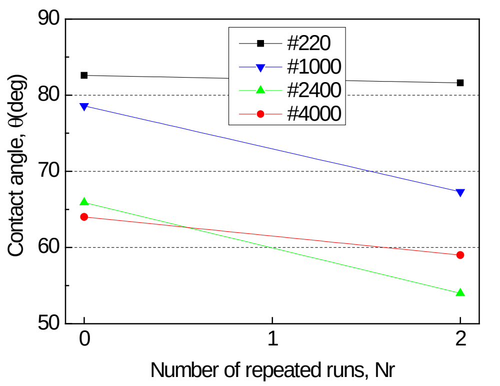

Fig. 3. Variation of contact angle depending on the number of repeated runs.

Figure 3 shows the variation of contact angle before and after the quenching test. The contact angle of fresh specimen is about 80 deg for the high surface roughness (mesh #220, #1000) which is greater than the contact angle (65 deg) for the low roughness (mesh #2400, #4000). The contact angle for the third run (Nr=2) tends to decrease by 5-10 deg compared to the case for fresh specimen.

4. Conclusions

A quenching experiment was conducted to investigate the effect of surface roughness and oxidation on clad cooling. The Zircaloy-4 tube was heated up to 600 °C and plunged into quenchant pool with the coolant subcooling of 0 °C. The surface roughness in clad tube does not significantly affect the quenching performance. However, the clad oxidation decreases the contact angle by as much as 10 deg and increases the MFBT by more than 30 °C. Hence, the oxidation in clad surface is expected to enhance the cooling performance of fuel clad in the event of LOCA. In the future, the quenching performance of accident tolerant cladding will be investigated.

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