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# Characterization of the Corroded Surface Morphology of a Carbon Steel Piping Elbow Affected by Flow-Accelerated Corrosion

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**ABSTRACT**

It has been widely recognized that the inner surface of carbon steel piping affected by relatively severe flow-accelerated corrosion (FAC) shows typical morphology in terms of roughness in many cases. Although hydrodynamic parameters would determine the characteristics of the rough surface developed in such cases, the detailed mechanism of the roughness formation is not fully known. In this study, the local FAC rate profile and morphology in terms of surface roughness for an entire 90-degree carbon steel piping elbow used in a fossil power plant have been investigated under two-phase flow in order to discuss the relationships between the FAC rate and characteristics of the inner surface morphology. For the axial direction, the FAC rate gradually increased with distance from the inlet, and it reaches the peak value in the downstream side, beyond which, the value kept decreasing slightly. Distributed horse-shoe pits and scalloped patterns were observed on the extrados side. The finding suggests that the extrados side of the pipe wall was covered with a continuous liquid film (single-phase). The result shows the possibility of the occurrence of FAC by a single-phase flow in the area where there is a sudden change in flow regime, even when the nominal phase state of the fluid is a two-phase flow regime. Both the local FAC rate and scallop coverage increase steeply near the middle parts of the elbow. There was a good correlation between the two, but it was not a one-to-one relationship because a significant decrease in FAC rate was observed in the downstream side; in contrast, the entire surface was covered with a fine scalloped pattern. The change in the morphology in terms of surface roughness clearly indicated that the overlapping of horse-shoe shaped pits gave a scalloped appearance. The results revealed that the inner surface shape affected by FAC is considered to essentially depend on the number density of nucleation sites for pit formation.

**KEYWORDS**

*Pipe wall thinning, Flow-accelerated corrosion, Turbulence, Surface roughness, Scallop pattern, Horse-shoe pit, Carbon steel, Piping elbow, Fossil power plant*

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## 1. Introduction

Wall thinning in carbon steel piping, mainly caused by flow-accelerated corrosion (FAC), is recognized as a degradation issue that needs to be paid careful attention, particularly in the nuclear and fossil power industry. FAC usually becomes a problem in applications where there is a significant level of turbulence (e.g., elbows, downstream of an orifice, branch or junction pipes). The phenomenon of FAC is understood to proceed via the acceleration of chemical or electrochemical dissolution of the oxide layer under very fast mass transportation between the pipe wall and bulk water; there are a number of parameters that influence this process, including component geometry, water chemistry, material composition, and hydrodynamics [1-4]. Since the transport of ferrous ions to bulk water is widely recognized as the rate-limiting process in FAC, the driving force of the process is considered to be the concentration gradient of ferrous ions across the concentration boundary layer. The mass transfer coefficient, which is determined mainly by the hydrodynamic parameter, that affect the thickness of the boundary layer, resulting in a change in the concentration gradient of ferrous ion.

It is widely recognized that the inner surface of carbon steel piping affected by relatively severe

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FAC shows a typical morphology in terms of roughness in many cases; a "scallop pattern" or "orange peel" appearance is observed for a single-phase flow, while a "tiger stripe" appearance is commonly observed for a two-phase flow [5-8]. A scalloped pattern was also observed in experiments on the dissolution of pipes made of plaster of Paris [9, 10]. It is possible that surface roughness promotes the development of local turbulence that results in accelerating the FAC rate. It has been reported that the experimental mass transfer coefficient on a rough surface, which simulates a scalloped surface, seemed to be around 2-3 times that observed for a smooth pipe [11]. Although hydrodynamic parameters would determine the characteristics of the rough surfaces developed in such cases, the detailed mechanism of the roughness formation is not fully known.

The authors recently have discussed the relationship between the FAC rate and surface roughness based on the characteristics of a scalloped appearance (scallop size, depth, and density) in a circumferential direction on the carbon steel piping elbow [12]; however, investigation of these characteristics in the axial direction (parallel to the flow direction) in consideration of the development of turbulence was not carried out because the size of the piping specimen was very limited. In this study, we investigate the local FAC rate profile and morphology in terms of surface roughness for an entire 90-degree carbon steel piping elbow used in a fossil power plant under two-phase flow.

## 2. Experimental

### 2.1. Sample information and operating conditions

A 90-degree elbow component of an ascending pipe in an evaporator (deaerator) taken from a fossil power plant in Japan was used. The appearance of the sample is shown in Fig. 1. The inner surface shows a partly brown appearance on a black substrate due to surface oxidation and corrosion during long term storage in air. The surface has a shiny black appearance just after being removed. The outer diameter, the nominal piping wall thickness, and the radius of curvature are 140 mm, 6.6 mm, and 420 mm, respectively. The steel grade is carbon steel pipes for high temperature service (STPT410-S in JIS G 3456). The chemical composition of the sample and the history of the operating conditions for the region of interest are summarized in Tables 1 and 2, respectively. The phase state


**Fig. 1. Appearance of the 90-degree elbow piping**

**Table 1 Chemical compositions of the sample, wt%**

| Steel grade | C | Si | Mn | P | S | Cr |
|---|---|---|---|---|---|---|
| STPT410-S | 0.10 | 0.27 | 0.62 | 0.012 | 0.007 | 0.028 |

**Table 2 History of the operating conditions of the region of interest**

| Duration of service | Temperature (Drum water) | Dissolved oxygen | Flow rate (PV) | Pressure | Phase state | pH |
|---|---|---|---|---|---|---|
| 260,000 h (Approx.) | 128 ℃ (Full load) | 1~2 ppb | 8.55m/s (Full load) | 0.15MPa (Full load) | Two-phase flow | 9.0 (initial ~ 27% of duration)<br>9.3 (66% of duration)<br>9.6 (last 7% of duration) |

has been estimated to be a two-phase flow; however, the information about a two-phase flow regime and void ratio were not available. The controlled pH value was increased in a step-by-step manner because of the change in water chemistry treatment to mitigate FAC. For example, high-AVT (All Volatile Treatment with a high pH value without using hydrazine) was conducted in the last stages of the operation.

### 2.2. FAC rate and surface morphology evaluation

The local FAC rate was obtained by dividing the loss in thickness by the operation duration. The extrados side half part of the piping, which shows significant loss in thickness compared with intrados side, was investigated. One half of the piping was cut into 12 parts in order to precisely measure the residual thickness using a dial caliper gauge of which needle head diameter is smaller than the size of scallops. The average value of 3 measurements which was selected randomly was adopted as the residual thickness. For the thickness measurement of scalloped surface parts, the bottom of scallops were measured.

The morphology of the inner surface of the piping was observed by using an optical microscope. Detailed characteristics of the scalloped appearance (coverage of scallops, number density, and size) along the axial direction of the center of extrados were also investigated. The coverage of scallops was obtained from image analysis of a 15 mm square area in each measurement. The coverage of scallops was defined as the ratio of the area with scallops / (the area with scallops + the area without scallops). A single horse-shoe pit was also considered as a scalloped surface. The number density of scallops was obtained by counting the number of scallops or parts of scallops included in a 10 mm square area. The average length of long side of 3 scallops was adopted as the size of the scallop.

## 3. Results and discussion

### 3.1. Local FAC rate profile on the extrados side of elbow piping

The local FAC rate profile on the extrados side of the elbow piping is shown in Fig. 2. For the location in axial direction, 0 mm and 800 mm correspond in position to 0-degree and 90-degree of the elbow, respectively. For the circumferential direction, a significantly higher FAC rate was observed at the center part of the extrados (0-degree). The FAC rate decreased linearly with distance from the

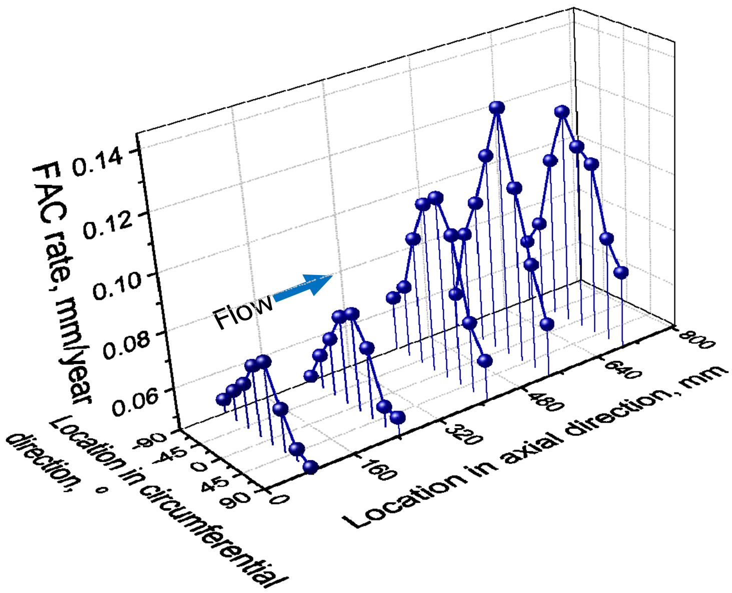


**Fig. 2. Local FAC rate profile on the extrados side of elbow piping**

center of the extrados to the intrados side. The difference in the local FAC rate was caused by the difference in the hydrodynamic parameter, and was not due to the material or water chemistry. These local FAC rate profiles should correspond closely to the local turbulence level affected by the piping geometry. For example, it was clearly demonstrated that the actual FAC rate and estimated mass transfer coefficient showed a maximum on the intrados for the short-radius bend; in contrast, the maximum of the above parameters were observed on the extrados for the long-radius bend [13]. Additionally, local hydrodynamic conditions should be considerably complicated because of the two-phase flow. For the axial direction, the FAC rate gradually increased with distance from the inlet, and it reached the peak value in the downstream side, beyond which it continued to decrease slightly. This tendency also suggested the development of local turbulence from the upstream to the downstream side in the elbow piping.

## 3.2. Characteristics of the inner surface morphology

The transition in the morphology in terms of surface roughness on the extrados piping is summarized in Fig. 3. A relatively smooth surface with a sparse distribution of horse-shoe pits was observed on the upstream side, and the density of the pits gradually increased toward the downstream side (Fig. 3 (b) and (c)). Overlapping of the pits was observed near the middle parts of the elbow, and on the downstream side, the entire surface was found to be covered with a fine scalloped pattern. No tiger striping pattern was observed. As mentioned above, the scallop pattern and horse-shoe pit are widely recognized as typical morphologies for corroded surfaces affected by significant FAC in a single-phase flow. The finding indicates that the extrados side of the pipe wall was covered with a continuous liquid film (single-phase) like a “water slide”. The result shows the possibility of the occurrence of FAC by a single-phase flow in the area where there is a sudden change in flow regime, even when the nominal phase state of the fluid is a two-phase flow regime. As shown here, characterization of the inner surface morphology can occasionally give important information to estimate the local flow regime. Fig. 3 also clearly indicates that the occurrence of overlapping horse-shoe shaped pits gives a scalloped appearance [14]. Although the detailed mechanism for the formation of horse-shoe pits is still unclear, our results have revealed that the inner surface shape of piping affected by FAC is considered to essentially depend on the number density of nucleation sites for pit formation.

## 3.3. Characteristics of the scalloped surface and its relation to the local FAC rate

The profiles of the local FAC rate and coverage of the scallops along the center of the extrados in the axial direction with each 30 mm distance are shown in Fig. 4. The general FAC rate profile has already been explained in Fig. 2. The coverage of scallops increased from 0% (upstream) to 100% (downstream). Both the local FAC rate and coverage of scallops increase steeply in the region 300 to 400 mm away from the inlet of the elbow. Since there was a good correlation between the two, it seems that a significant acceleration in the FAC rate is possible due to scalloped surface formation. However, the local FAC rate and scallop coverage did not show a one-to-one relationship because there was a significant decrease in FAC rate observed in the downstream side; in contrast, the coverage of scallops was still maintained at 100%. The authors have already reported in another work that there was no significant increase in the FAC rate as a result of scallop formation although the local turbulence should increase by a hydrodynamic effect due to the formation of a scallop surface [12].

The profiles of the local FAC rate, number density, and size of the scallop are also shown in Fig. 5. The profile of the number density of scallops closely corresponded to the FAC rate profile. Both gradually increased with distance from the inlet, reached a peak at the same location, and then gradually decreased. The maximum size of the scallop (horse-shoe pit, in practice) shown in here was around 5 mm. The scallop size decreased with increasing FAC rate in the area most of which is covered with fine scallops. The inverse relationship between the FAC rate and scallop size corresponds to that observed in other findings, including examples from an actual power plant [15]. Fig. 5 also indicates that the FAC rate essentially corresponds to the number density of nucleation sites for pit formation, as mentioned above.

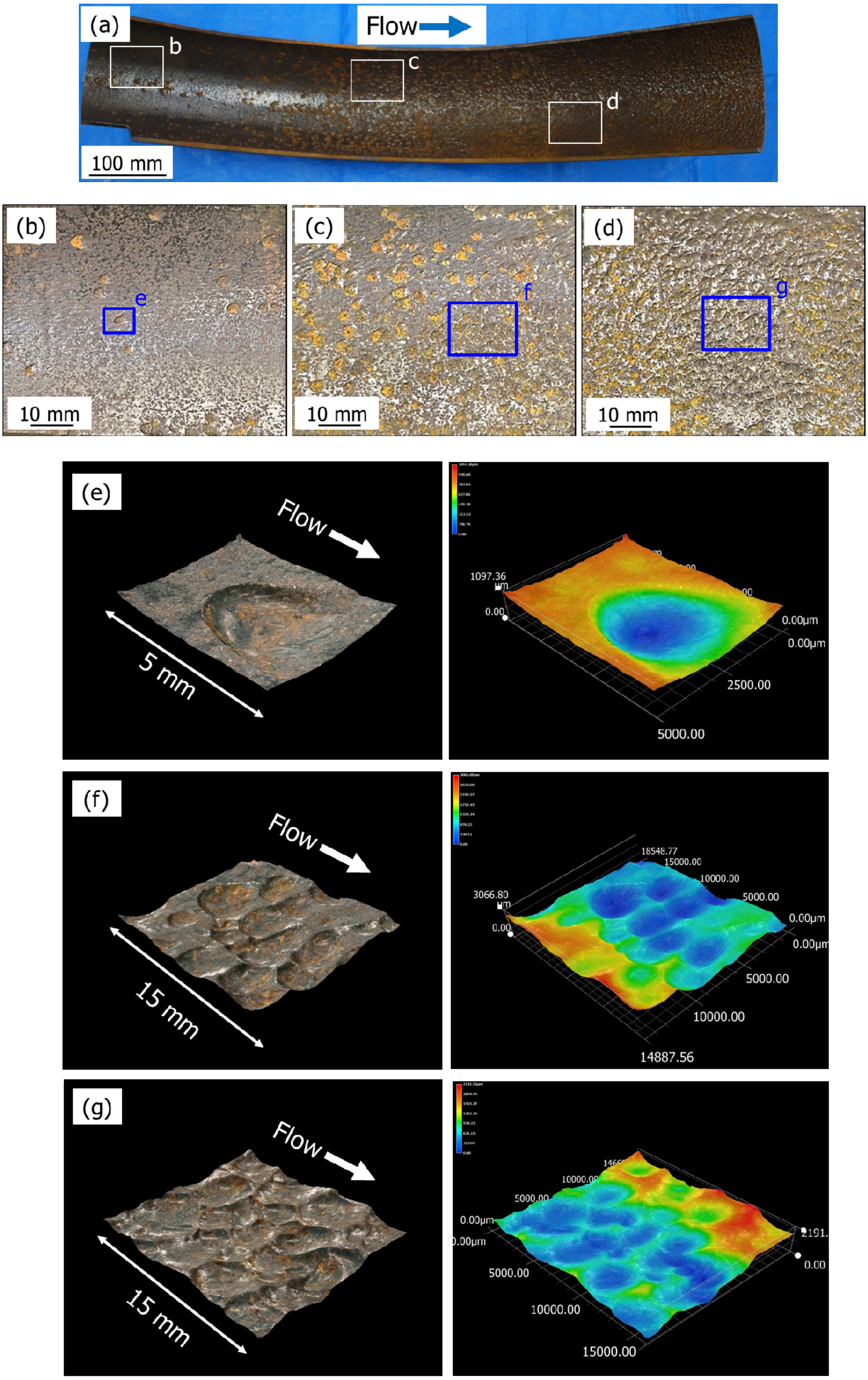


**Fig. 3. Transition in the morphology in terms of surface roughness on the extrados piping. (a): Overall appearance of the inner surface of the extrados side, (b)-(d): Enlarged figures of the white squares in (a), (e)-(g): Enlarged 3D figures of the blue squares in (b)-(d), the left and right indicate color map and height contour map, respectively.**

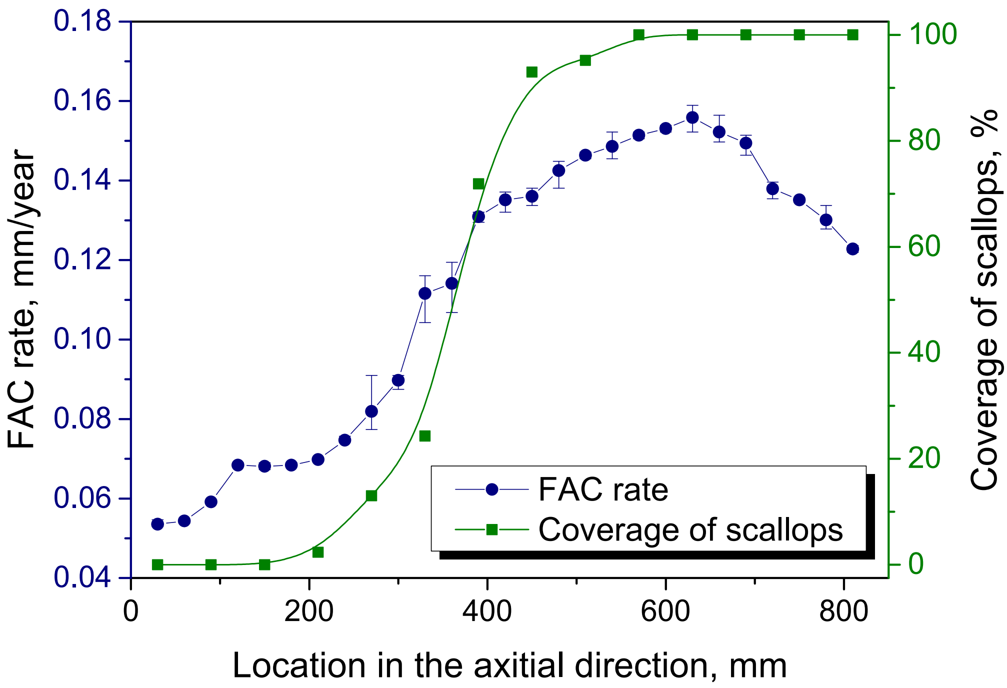


**Fig. 4. Profiles of the local FAC rate and scallop coverage along the center of the extrados in the axial direction**

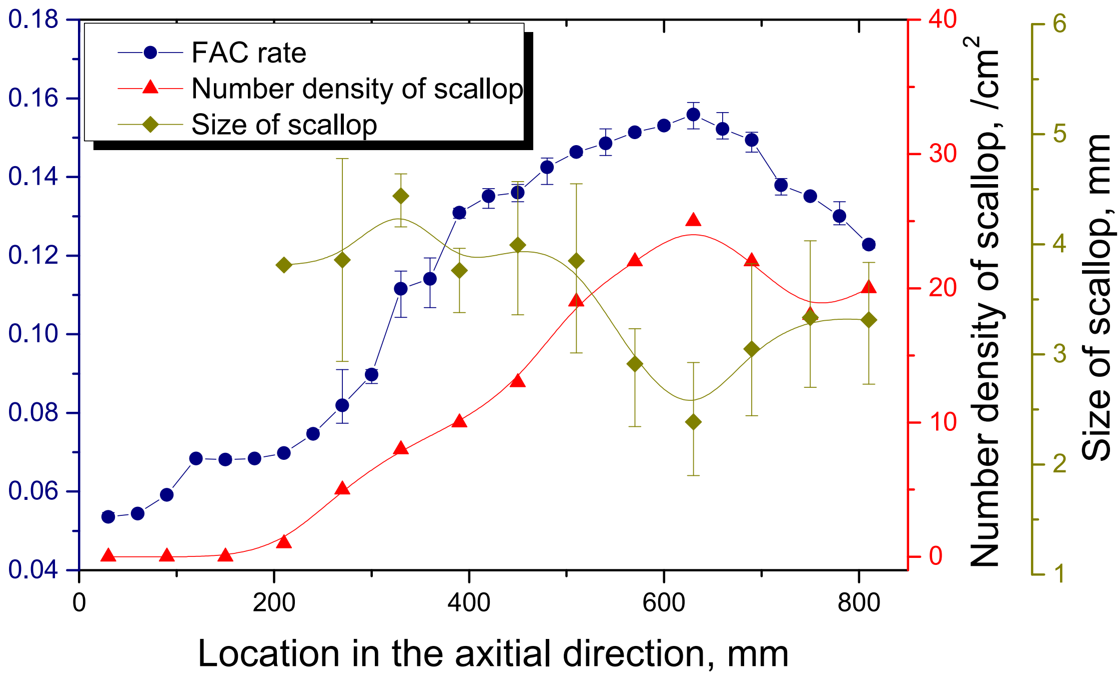


**Fig. 5. Profiles of the local FAC rate, number density and size of scallop**

## 4. Conclusion

The local FAC rate profile and morphology in terms of surface roughness were investigated for an entire 90-degree carbon steel piping elbow used in a fossil power plant under two-phase flow in order to discuss the relationships between the FAC rate and characteristics of the inner surface morphology. Our main findings are summarized as follows:

(1) Distributed horse-shoe pits and a scalloped pattern were observed on the extrados side. The finding suggests that the extrados side of the pipe wall was covered with a continuous liquid film (single-phase) like a “water slide”. The result shows the possibility of the occurrence of FAC by a single-phase flow in the area where there is a sudden change in flow regime, even when the nominal phase state of the fluid is a two-phase flow regime.
(2) Both the local FAC rate and scallop coverage increase steeply near the middle parts of the elbow. Since there was a good correlation between the two, it seems that a significant acceleration in FAC rate was possible due to the formation of a scalloped surface. However, the local FAC rate and scallop coverage did not show a one-to-one relationship because a significant decrease in FAC rate was observed in the downstream side; in contrast, all of the surface was covered with a fine scalloped pattern.
(3) The change in the morphology in terms of surface roughness clearly indicated that the overlapping of horse-shoe shaped pits gave a scalloped appearance. The results revealed that the inner surface shape affected by FAC is considered to essentially depend on the number density of nucleation sites for pit formation.

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