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# ASSESSMENT OF EFFECT OF TAKING MINIATURE SAMPLE SCOOP ON CREEP LIFE OF GRADE 91 STEEL PIPE

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## ABSTRACT

The effect of taking miniature sample scoops on the creep life of ASME Grade 91 steel pipes was experimentally and analytically assessed in this work. Internal pressure tests were conducted on tubular specimens having defects on their outer surface, which simulate sampling scoops. The creep life did not decrease until the depth ratio of the defect to the wall thickness of the specimens was about 5%, and the creep life decreased with increasing defect depth when the depth ratio exceeded about 5%. When the depth ratio was about 11%, the creep life decreased to four-fifths of that of a specimen with no defects. In addition, as a result of investigating the stress concentration around a defect with a depth ratio of about 5% by the finite element method, stress concentration was clearly observed around the defect. These results suggest that taking a miniature sample up to a depth of 5% of the thickness of a Grade 91 steel pipe in service has a negligible effect on the creep life of the pipe.

## INTRODUCTION

Heat-to-heat variations exist in the creep life of Grade 91 steel pipes even under the same test conditions [1]. Since the heat of the materials actually used in each structure is unknown at the design stage, the heat-to-heat variations are considered as one of the safety factors in setting the permissible tensile stress. On the other hand, since the heat of the materials used for the target structure is known in the remaining life evaluation stage, it is considered possible to consider the heat-to-heat variations in principle. However, at present, there is almost no work on the remaining life evaluation technology taking into account the heat-to-heat variations in the range that does not affect the facilities of the power plant. To estimate the remaining life of high-temperature structural materials with high accuracy, it is necessary to develop a creep life evaluation method that can consider the material properties specific to each structure. Therefore, the authors of [2]–[5] have developed a remaining life evaluation method that takes into account the creep characteristics inherent in the target pipe by taking a miniature sample from the pipe base material and analyzing and testing this sample [2]–[5]. It is expected that the accuracy of remaining life evaluation will be greatly improved by applying this method. However, a precondition of this method is that the removal of the miniature sample does not affect the structural integrity of the targeted pipe.

Therefore, the authors of this paper are conducting various creep tests and analyses to quantitatively evaluate the effect of taking miniature sample scoops on the creep life of a pipe. This paper, reports on the results of internal pressure creep tests and FE analysis on ASME Grade 91 steel pipes with defects on their outer surface, which simulate sampling scoops.

## EXPERIMENTAL PROCEDURE

### Materials

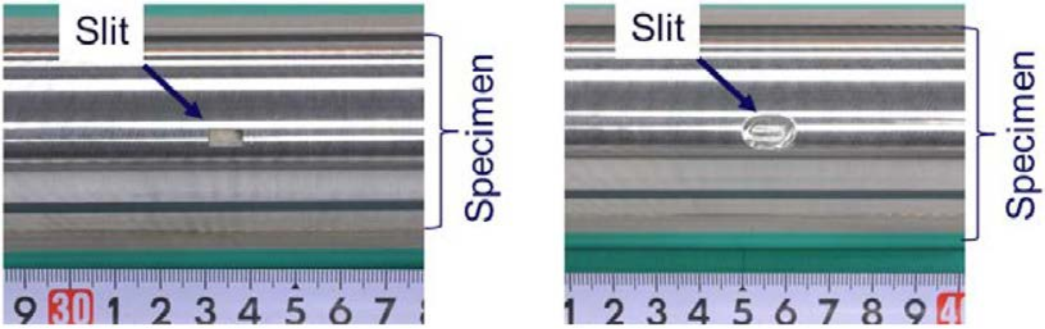
The two types of material examined in this work were taken from ASME Grade 91 steel pipes. The first type was a virgin material, taken from a small-diameter unused tube that had been normalized and tempered. The tube had an outer diameter of 65 mm and a wall thickness of 15 mm. The second type of material was taken from a pipe that had been in long-term use at a power plant. This was a high-temperature reheat steam pipe with an outer diameter of 835 mm and a wall thickness of 73 mm, used at a steam temperature of 600 °C and a steam pressure of 4.3 MPa for an operation time of 132,000 h.

### Experimental Procedure

The above-mentioned test materials were processed into cylinders with an outer diameter of 64 mm, a wall thickness of 12 mm, and an axial length of 300 mm, and used as internal pressure creep specimens. Because the virgin material was taken from a small-diameter tube, the specimens were manufactured by cutting the pipe to a predetermined value on the inner and outer surfaces. From the long-term used/or service exposed material, round bars with a diameter of 64 mm were manufactured from the inside of the pipe thickness of 73 mm, and then the center portion of each bar was hollowed to obtain a specimen with a predetermined inner diameter. The radius / thickness ratio of the internal pressure creep specimens used in this work was 2.7, which was the thickness ratio of the main steam pipe.

Specimens with slits of 0.64 mm, 0.96 mm, and 1.29 mm on the outer surface simulating sampling marks, were manufactured to evaluate the effect of the depth of a miniature sample scoop on the creep life of the pipe. The ratio of the depth of each slit, to the specimen thickness, hereinafter referred to as the "slit depth ratio", were 5.3%, 8.0%, or 10.8%. The axial and circumferential dimensions of the slit were constant regardless of the slit depth ratio; the axial dimension was 7.7 mm and the circumferential dimension was 3.8 mm. Slits of the same depth were made at three points in the axial direction in each specimen in this work. Since grinder finishing is applied when taking actual miniature samples from a power plant so that the edge of the sampling mark is smooth, edge processing was applied on the test specimens so that the edge of each slit did not become acute in the specimen. The maximum axial and circumferential dimensions of the slit were increased by this edge processing, but the radial dimension, which is the depth dimension of the specimen, was the same as before the edge processing. Figure 1 shows an example of the appearance of a specimen before and after edge processing.

The test temperature was 650 °C and the pressure ranged from 32 MPa to 42 MPa. The pressure was set so that the circumferential stress on the smooth part (no slits) ranged from 70 MPa to 90 MPa. Here, the circumferential stress applied to the pipe was calculated using an equation based on the mean diameter with the dimensions of the pipe and the steam pressure.
All tests were conducted until a crack penetrated in the thickness direction. Also, for comparison with the specimens with slits, internal pressure creep tests were performed on smooth specimens of the virgin material and the service exposed material without slits.




*(1) Before edge processing* *(2) After edge processing*

*Figure 1: Example of a slit*
*(initial size: depth 0.64 mm, axial length 7.7 mm, circumferential length 3.8 mm)*

## EXPERIMENTAL RESULTS

### Rupture Time

Figure 2 shows the results of the internal pressure creep test. The horizontal axis shows the slit depth ratio and the vertical axis shows the value obtained by dividing the internal pressure creep life of each specimen with slits by the internal pressure creep life of the smooth specimen without slits in Figure 2.

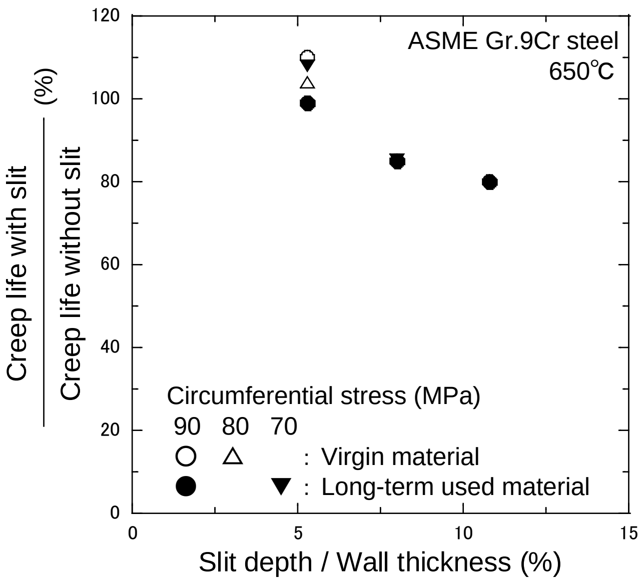
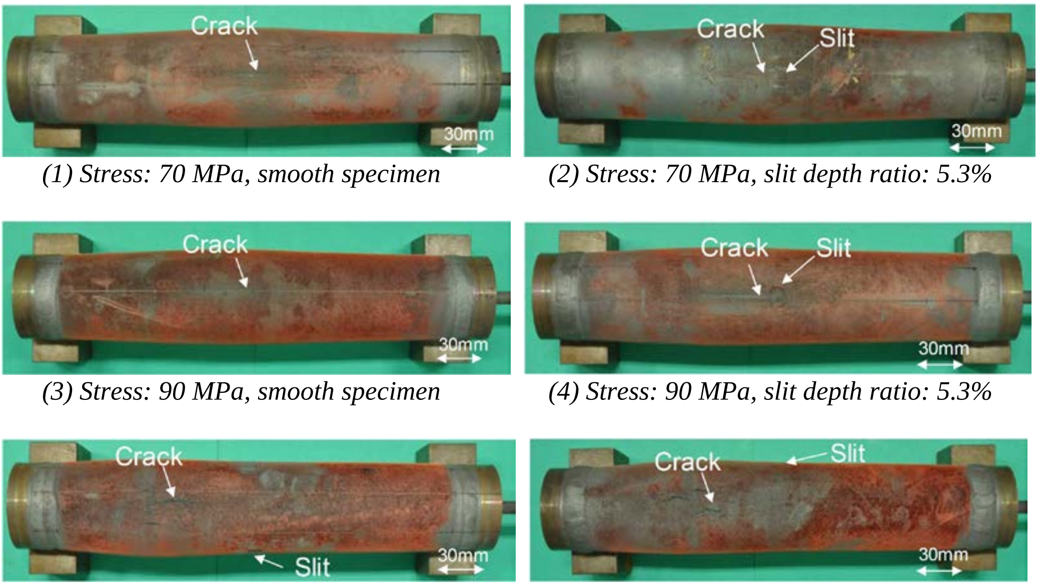



*Figure 2: Relationship between internal pressure creep life and slit depth ratio*

Although the only slit depth ratio of the virgin material was 5.3%, the creep life of the specimen with the slit was greater than or equal to that of the smooth specimen without the slit for circumferential stresses of 80 MPa and 90 MPa. The specimens of the service exposed material with a slit depth ratio of 5.3% had a creep life greater than or equal to that of the smooth specimens without slits regardless of the circumferential stress. The specimens with slit depth ratios of 8.0% and 10.8% tended to have a shorter creep life than the smooth specimens without the slit. The creep lives of the specimens with slit depth ratios of 8.0% and 10.8% were 85% and 80% of those of the smooth specimens without slits, respectively.

## Rupture Form

Figure 3 shows examples of the appearance of specimens after a rupture.




*(1) Stress: 70 MPa, smooth specimen*   *(2) Stress: 70 MPa, slit depth ratio: 5.3%*

*(3) Stress: 90 MPa, smooth specimen*   *(4) Stress: 90 MPa, slit depth ratio: 5.3%*

*(5) Stress: 90 MPa, slit depth ratio: 8.0%*   *(6) Stress: 90 MPa, slit depth ratio: 10.8%*

*Figure 3: Appearance of specimens after rupture during internal pressure test (service exposed ASME Grade 91 steel, test temperature: 650 °C)*

In the case of the slit depth ratio of 5.3%, a penetrating crack was generated at or near the slit. On the other hand, when the slit depth ratio was 8.0% or more, a penetrating crack was generated away from the slit. Note that no macroscopic cracks other than the penetrating crack were found when the slit depth ratio was 5.3%, but when the slit depth ratio was 8.0% or more, several macroscopic cracks were found other than the penetrating crack. When the hardness distribution in the thickness direction was measured for each specimen after rupture, the overall decrease in hardness was found to be significant, and the hardness was about 10% to 25% lower than that in the initial state. At the slit marks, the hardness had a local minimum at a point slightly inside from the outer surface. In addition, when the number density of voids was measured in the thickness direction at smooth parts and at slits where no penetration cracks occurred, a small number of voids were observed on the outer surface side at slits (about 40voids / $mm^2$), but there were almost no voids elsewhere.

## FE ANALYSIS

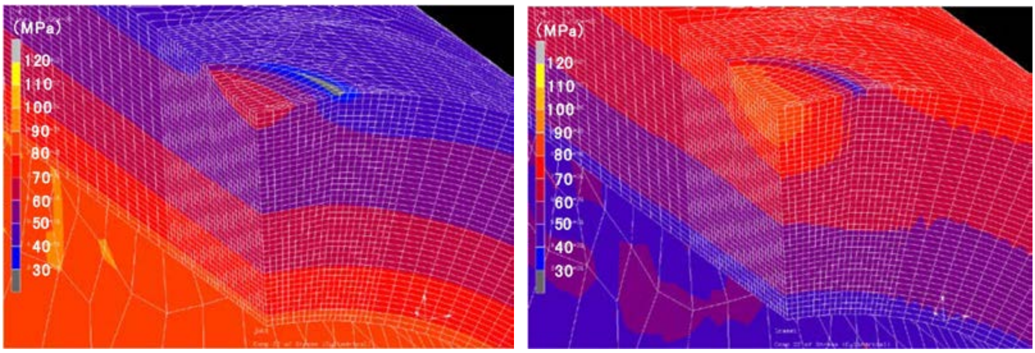
FE analysis was performed to determine the effect of slits on the stress–strain state of internal pressure creep specimens.

### Analysis Method

The analysis target was an internal pressure creep specimen after edge processing with a slit depth ratio of 5.3%. Meshes were created for a quarter of the specimen, considering axial and circumferential symmetry. The elements used were 20-node quadratic elements. The material properties used were the values for ASME Grade 91 steel at 650 °C given in [6]. A pressure, of 37 MPa, at which the circumferential stress according to the mean diameter formula was 80 MPa, was applied to the inner surface of the tube as a distributed load. The creep analysis time t was set to 2000 h, which corresponds to the creep rupture time of the virgin material without the slit. For comparison, the same analysis was carried out on an internal pressure creep specimen of the smooth material without a slit.

### Analysis Results

Figure 4 shows the analysis results for the circumferential stress near the slit.




*(1) t = 0* *(2) t = 2000*

*Figure 4: FE analysis results for circumferential stress internal pressure specimen with a slit depth ratio of 5.3%*

Immediately after the start of loading, t = 0, and after stress redistribution due to creep deformation, t = 2000, the area near the slit remained in a stress–strain state different from elsewhere. The stress and strain increased near the center of the bottom of the slit rather than near its edge.

Figure 5–7 show the distribution of the circumferential stress in the thickness direction at the center of the bottom of the slit, the von Mises equivalent stress, and the stress triaxiality factor TF, respectively. Analysis results for the specimen when there is no slit are also plotted in each figure.

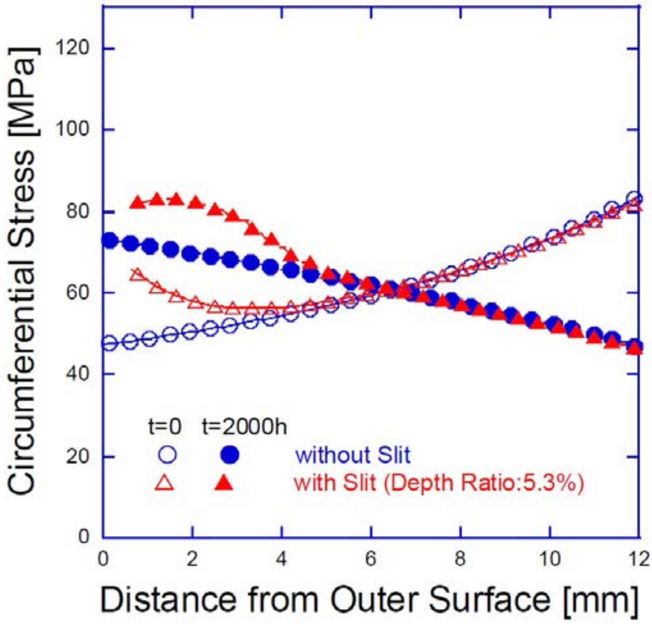


*Figure 5: Circumferential stress of internal pressure specimen*

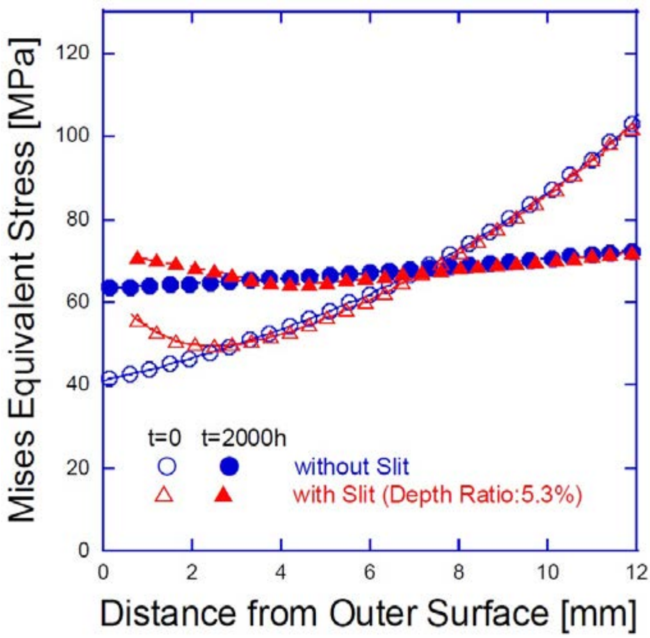


*Figure 6: Equivalent stress of internal pressure specimen*

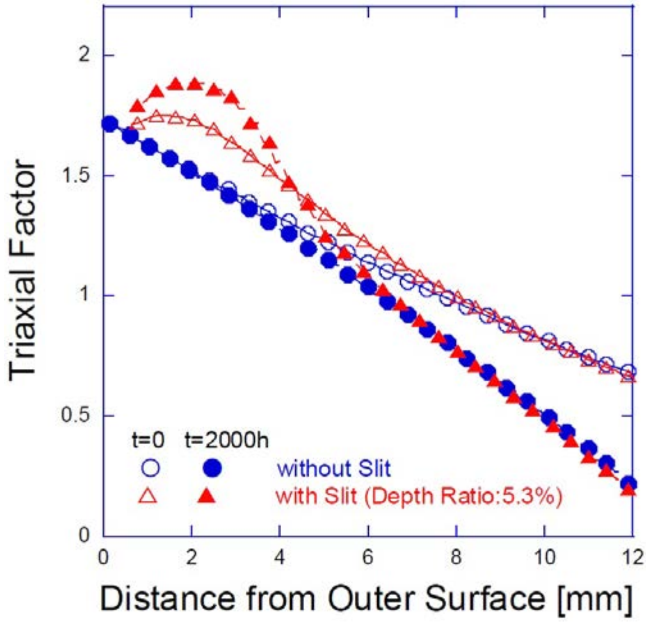



*Figure 7: Stress triaxiality factor TF of internal pressure specimen*

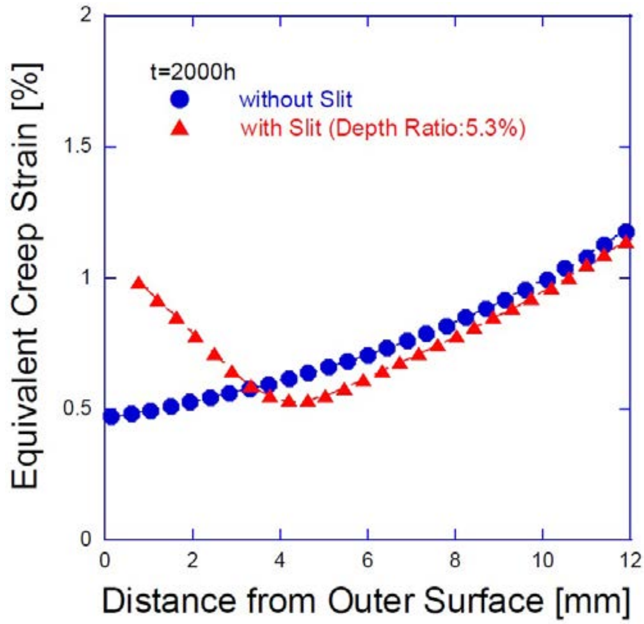



*Figure 8: Equivalent creep strain of internal pressure specimen*

From the beginning of loading to the end of stress redistribution, the circumferential stress, von Mises equivalent stress, and TF have high values at a distance of about one-third of the thickness from the outer surface of the specimen with the slit, but there is no difference elsewhere regardless of the presence or absence of the slit. The circumferential and the von Mises equivalent stresses are high on the inner surface at the start of loading regardless of the presence or absence of the slit. When there is a slit, after stress redistribution, the circumferential stress is maximum at a position slightly inside from the outer surface, but the von Mises equivalent stress is almost constant in the thickness direction. On the other hand, when there is a slit, TF is highest at a position slightly inside from the outer surface, both at the start of loading and after stress redistribution. Figure 8 shows the equivalent creep strain in the thickness direction at the center of the bottom of the slit. When the slit is present, the creep strain is high at a distance of about one-quarter of the thickness from the outer surface, but no significant difference in strain due to the presence of the slit is observed elsewhere. The highest creep strain in the thickness direction is at the inner surface regardless of the presence of the slit.

From the above results, it is clear that for the specimens targeted in this work, the concentration of stress and creep strain occurs near the slit.

## CONCLUSIONS

In this work, internal pressure creep tests were performed at 650 °C on samples with a slit, which simulate taking a miniature sample, to investigate the effect of taking miniature samples on the creep life of ASME Grade 91 steel pipes. The following findings were obtained:

- From the test results obtained in this work, when the depth of the slit was about 5% of the wall thickness, no creep life reduction due to the slit was found in the virgin material or the service exposed material. When the slit depth was 8.0% or 10.8% of the thickness, the creep life was affected. The creep lives of test pieces with slit depth ratios of 8.0% and 10.8% were 85% and 80% of that of smooth materials without slits, respectively.
- According to the results of FE analysis, the effect of stress and creep strain was observed near the slit.

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