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A Modified Technique for Crack Formation on Nuclear Steam Generator Tubing

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Abstract

For the safety and life assurance of nuclear power plants, the management of steam generator (SG) tube integrity receives increasing attention. Non-destructive examination, leak rate measurement and burst pressure evaluation constitute key elements in the effort. SG tubes containing environment assisted cracks with physical and microstructural characteristics similar to those of actual cracked tubes in SG's are needed for the effect. In the paper, a radial dent loading method has been explored to produce axial intergranular cracks using sensitized alloy 600 tubes. We showed based on three-dimensional finite element analysis and preliminary experimental work that the method can be more useful than the internal pressurization method for the production of cracks with high aspect ratio, provided that alloy 600 tubes are severely sensitized. In addition, direct current potential drop (DCPD) method has been implemented for the more accurate control of produced crack size.

1.Introduction

For the SG tube integrity assurance, the accuracy of non-destructive examination – eddy current test (ECT) in this case – is essential. In spite of significant progress in ECT technology and procedures, the nuclear power industry still calls for the higher level of confidence in field inspection campaigns. In order to help meet the demand, both ECT equipments and application personnel need to be trained and tested for an adequate range of realistic degradation modes of SG tubes. For this purpose, it is desired to establish a library of degraded tubes that encompasses a comprehensive range of field damage modes. The acquisition of degraded tubes from operating or retired SG (steam generator) is difficult and expensive due to the limited availability and difficulty in a prior identification of damage nature. Therefore it is necessary to produce Laboratory Degraded Tubes (LDT) that have crack morphology and ECT responses similar to actual degraded tubes in the field.

Several research groups have succeeded in the production of LDT. Both Argonne National Laboratory (ANL) and Korea Atomic Energy Research Institute (KAERI) have established a room temperature cracking procedure using sensitized alloy 600 tubes. [1] For loading, they applied the internal pressure and the direct tension load for the production of axial crack and circumferential crack, respectively. An aqueous solution of 1M sodium tetrathionate ($Na_2O_6S_4.2H_2O$) was used for making the intergranular damage. The internal pressurization method and the tension loading are convenient and inexpensive for the production of cracks on the outer surface of tubes. However both methods lead to more or less semi-circular crack geometry. Actual cracks in SG tubes are often found with high surface length to depth (aspect ratio). Such a long and shallow crack is caused by surface residual stress that decreases rapidly with depth. Furthermore, applications of the internal pressure method to the inner surface is more complicated and less apt for crack size control due to the presence of massive end seals and grips that severely compromise the accessibility of crack monitoring probes.

For the production of a library of LDT, it is desired to improve these methods so that cracks with high aspect ratio can be made and the tube inner surface can be more accessible for both crack monitoring. It is highly desirable to employ on-line crack monitoring techniques such as direct current potential drop (DCPD) if probes are accessible.[2] In addition, finally prepared tubes should contain no excessive plastic deformation that may be used as a clue for crack location by ECT operators. In this study, we explored a tube radial denting method for the production of axial cracks with high aspect ratio. The modified technique also facilitates DCPD instrumentation access to both the outer and the inner surfaces. Finite element analysis and proof of principle experiments have been conducted, as described herein

2.Development of Radial Denting Method

A commercial heat of alloy 600 tubes produced for nuclear steam generators of Korean Standard Nuclear Power Plant (KSNPP) has been obtained for this study. Tubes have 19.05 mm outer diameter and 1.2mm thickness in high temperature mill annealed (HTMA) condition. In order to understand sensitization characteristics of alloy 600 tubes, tube specimens were heat-treated in several different time conditions. Each tube has been subjected to the sensitization treatment by aging at 600°C in 5% hydrogen and 95% argon gas atmosphere, for 24h, 36h, 48h, 60h and 72h, respectively. Modified Huey tests in 25% boiling nitric acid were conducted for 24 hours to measure weight losses by intergranular attack [3]. Table 1 shows a data set on weight loss of sensitized and as-received tubes. As shown in Table 1, alloy 600 tubes can be best sensitized by 48 hours heat-treatment at 600°C and hence actual specimens were sensitized following the schedule. A 0.1 M aqueous solution of sodium tetrathionate ($Na_2O_6S_4.2H_2O$) was chosen for intergranular cracking of tubes at room temperature, based on the earlier work. [4]

Tension test specimens with a reduced section length of 30 mm and width of 6.25 mm were prepared from tubes by electro discharge machining (EDM) without disturbing the curvature of tube in the circumferential direction. ASTM Method E8 has been followed for testing at room temperature with the loading axis in the tube length direction.[5] The tensile test results show that ultimate tensile and yield strengths of the as-received mill-annealed tubes are 660 ± 10 MPa and 280 ± 10 MPa, while the corresponding values for the heat-treated tubes are 660 ± 10 MPa and 270 ± 10 MPa, respectively. Yield strength is only slightly affected by the sensitization treatment.

For the production of a long-shallow axial crack, the radial denting method is explored in this work. The radial denting method does not require end seals and therefore instrumental access can be made for crack monitoring at the inner surface. Figure 1 shows a schematic of the radial denting method applied for the cracking at the inner surface. When an axial crack is to be produced at the inner wall, the end openings allows for DCPD instrumentation for crack monitoring.

A three-dimensional finite element analysis(FEA) was performed for the radial denting method in order to check the adequacy of stress state using ABAQUS 5.7. Figure 2 shows a mesh structure employed for the tube, taking into account a four-fold symmetry. Figure 3 (a) shows a mesh structure for the tube cross-section. Figure 3 (b) shows the resultant stress distribution in the tube under the dent loading.

Earlier studies with sensitized alloy 600 showed that intergranular crack could be obtained, if tensile stress equal to 90% of yield strength is applied. Figure 4 shows predicted circumferential stress as function of applied dent load. It is shown that dent loading of 18.6kN/m and 35.6kN/m is required per one meter of axial length to obtain 90% of yield strength at Point 1 and Point 4, respectively. The highest tensile stress is expected at Point 1 where 90% of yield strength can be achieved without inducing any significant plastic deformation in a tube. Therefore the radial denting method is shown to be suitable for axial crack production at the inner wall.

At the outer wall, the tensile stress reaches a maximum at Point 4. Figure 4 shows that finite plastic deformations are inevitable at Points 1~4 when 90% of yield strength are applied at Point 4. The extent of plastic deformation is predicted based on FEA, as shown in Figure 5. Diametral changes are predicted for loading up to 35.6 kN/m and subsequent unloading. Displacements at Points 1 and 3 are negative whereas those at Points 2 and 4 are positive. After the complete unloading, residual plastic deformation is limited to about 5 μm on the diameter that is too small to be detected by ECT, as shown in Figure 5. Therefore the radial denting method is expected to be applicable to produce axial crack at the outer wall as well. However, when the applied load is increased to obtain 100% of yield strength at Point 4, the plastic displacement is found excessive, as shown in Figure 6. Therefore the maximum load should be limited to that corresponding to 90% of yield strength at Point 4.

At both Point 1 and Point 4, tensile stresses are expected to decrease rapidly in the thickness direction compared with changes in the axial direction. As the crack grows in the thickness direction, the grow rate can be reduced due to the stress decrease. Therefore a long axial crack with shallow depth is expected from this method. Such a high aspect (length-to-depth) ratio would represent typical field cracks that can be attributed to high surface residual stress of tubes.

3. Results and Discussion

Based on the supporting conclusion from FEA, a dent loading experiment was performed to produce an axial crack and succeeded in the crack production at room temperature. As shown in Figure 7, the tube specimen was compressed by a pair of denting jigs and a direct current potential drop was applied with about 2mm wide probe spacing. In parallel, the crack evolution was checked using a traveling microscope installed at the front of the tube. Except for the front rectangular opening area that is predicted to have high tensile circumferential stress, all other surfaces were masked with a chlorine-free paint to avoid spurious crack initiation.

No crack was detected at the design test load corresponding to 90% of yield strength. After waiting for about 48 hours, the load was increased stepwise until a crack was observed. Figure 8 shows a surface crack that occurred in the specimen but at a load in excess of 100% of yield strength. The crack has about 1mm axial length on the surface. A significant crack opening was evident due to excessive loading.

Direct current potential drop (DCPD) method was applied in order to monitor crack length. To detect an axial crack evolution, the direct current was applied at the loading Points so that the current flows along the circumference. Five sets of probe wires were attached with 2mm spacing across the rectangular opening area. In order to assure that the probe arrangement provides DCPD signal in proportion to the crack depth, a penny-shape notch was produced on the tube by a diamond saw cut, DCPD signal at each probe set was measured as shown in Figure 9. For the range of experiment, there appears a good correlation between the local crack depth and DCPD. When DCPD technique was applied to the axial cracking experiment that led to about 1mm crack length, the measured signal was too small to recognize the crack formation. The non-detection of crack by DCPD is attributed to shallow crack depth as predicted by FEA. A prolonged test under this condition may increase crack depth but at the expense of excessive plastic deformation.

Although the radial dent loading method explored in this work can initiate long surface crack, it alone may not be adequate to produce adequate crack depth exceeding the detection threshold of ECT (about 40% of wall thickness). Therefore it is necessary to grow the initiated crack by the internal pressurization method. The two-step cracking process is expected to be capable of producing cracks with a desired aspect ratio. In order to allow DCPD instrumentation access to the inner wall, it is planned to explore a mechanical expansion method for the internal loading, as a future work.

4. Conclusions

In order to produce a library of mock up steam generator tubes with intergranular cracks, a radial dent loading method has been explored by three-dimensional finite element analysis and experimental demonstration. It is confirmed that the radial dent loading can lead to long and shallow axial cracks that are more typical of actual degraded tubes in SG’s. However it was difficult to grow the axial crack into desired depths exceeding detection threshold of ECT by the method without allowing excessive plastic deformations. Therefore a two-step loading, the radial dent loading followed by an internal expansion loading, has been proposed as a more versatile method for the control of crack aspect ratio and depth. DCPD technique is expected to be applicable with the new scheme and capable for monitoring a crack at such a significant depth.

Acknowledgments

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References

[1] D. R. Diercks, et al., Steam Generator Tube Integrity Program, Annual Report, October 1996-September 1997, NUREG/CR-6511, Vol. 4, ANL-98/15, U.S. Nuclear Regulatory Commission, Washington, DC (March 1999).

[2] M.P. Landow and C.W. Marschall, "Experience in Using Direct Current Electric Potential to Monitor Crack Growth in Ductile Metals", Elastic-Plastic Fracture Test Methods: The User's Experience (Second Volume), ASTM STP 1114, J.A. Joyce, American Society for Testing and Materials (1991) pp. 163-177

[3] I.S. Hwang, S.U. Kwon, S.G. Lee and J. H. Kim, “An Intraspecimen Method for the Statistical Characterization of Stress Corrosion Crack Initiation Behavior”, Corrosion 57(2001), pp.787-793.

[4] I.S. Hwang, “Embrittlement Mechanisms of nickel-base Alloys in Water,” MIT Ph. D. Thesis (1987)

[5] ASTM Standards E8, ASTM (1996)

Table 1. Weight loss of sensitized and as-received tubes as measured by Modified Huey tests

Heat-treatment duration (hr) at 600 ℃	As-received	24	36	48	60	72
Weight loss [g/cm^2 day]	0.0142	0.01682	0.07325	0.1401	0.04021	0.03923

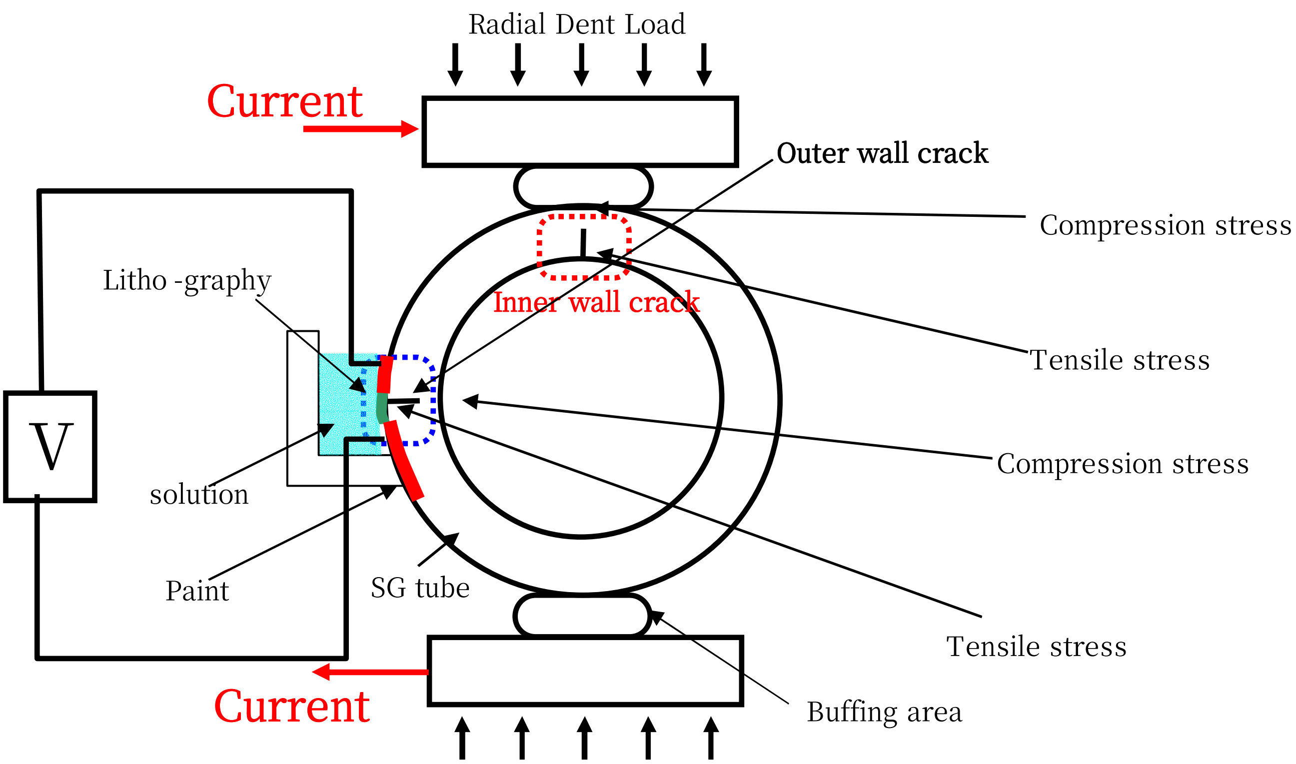


Fig.1. Schematic for axial crack production by radial dent loading method with DCPD.

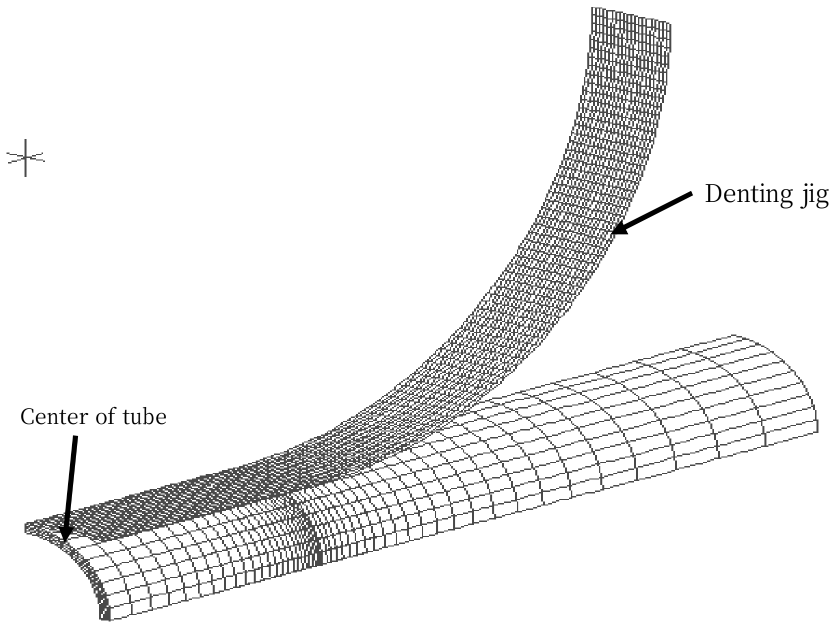
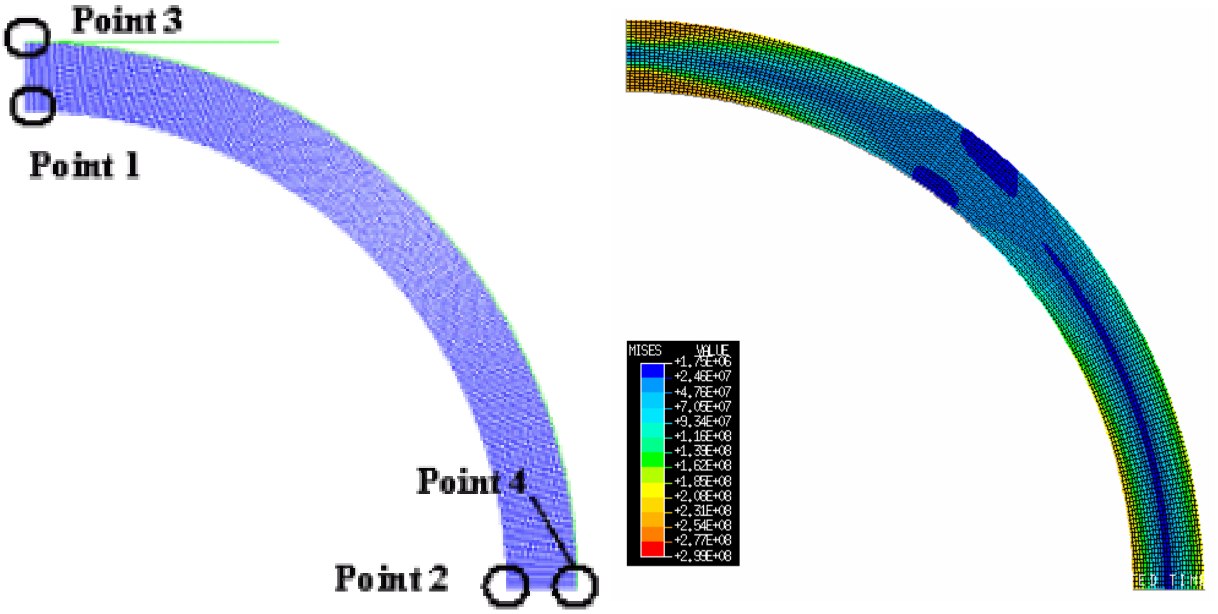


Fig 2. Meshing for three dimensional finite element analysis



(a) Meshing for cross section (b) Stress distribution in cross-section

Fig. 3. Stress distribution in the cross section of a dent loaded tubes

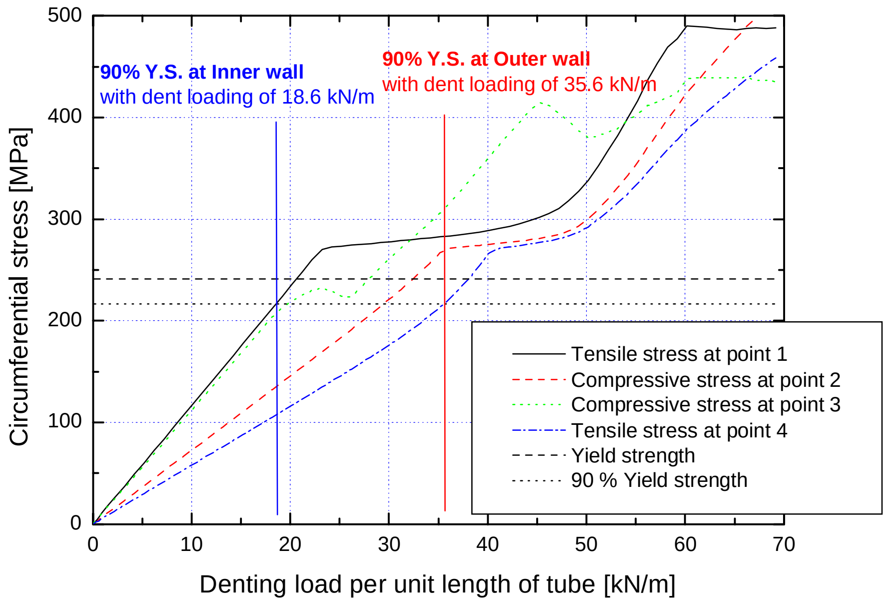


Fig. 4 Circumferential stress distribution at each position as a function of denting load per unit axial length (location of each Point is defined in Figure 3 (a))

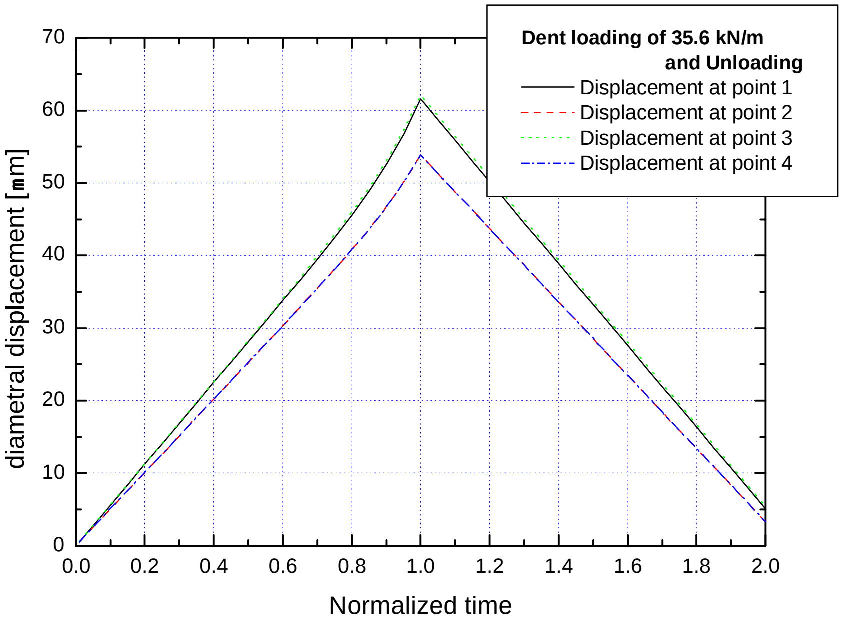


Fig. 5. Diametral displacements corresponding to initial position with loading to 35.6 kN/m followed by unloading (location of each Point is defined in Figure 3 (a))

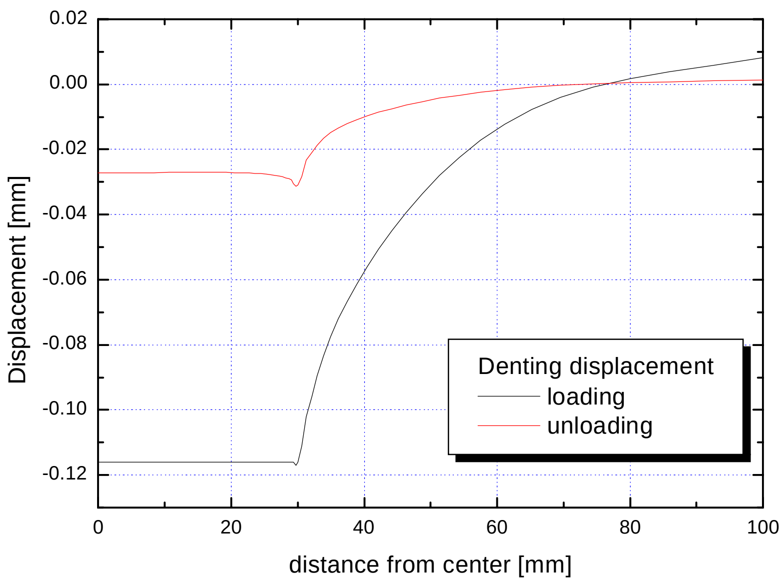


Fig. 6. Diametral placement predicted by three dimensional finite element analysis with loading to 40.0 kN/m followed by unloading

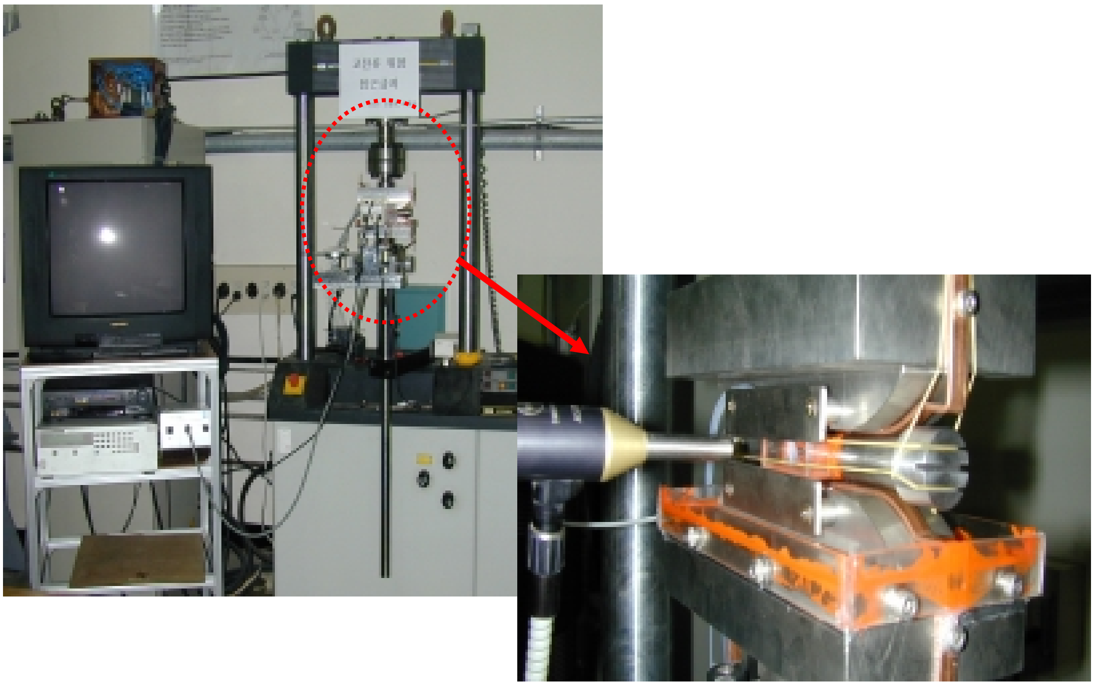


Fig. 7. Dent loading test apparatus with DCPD and observation microscope.

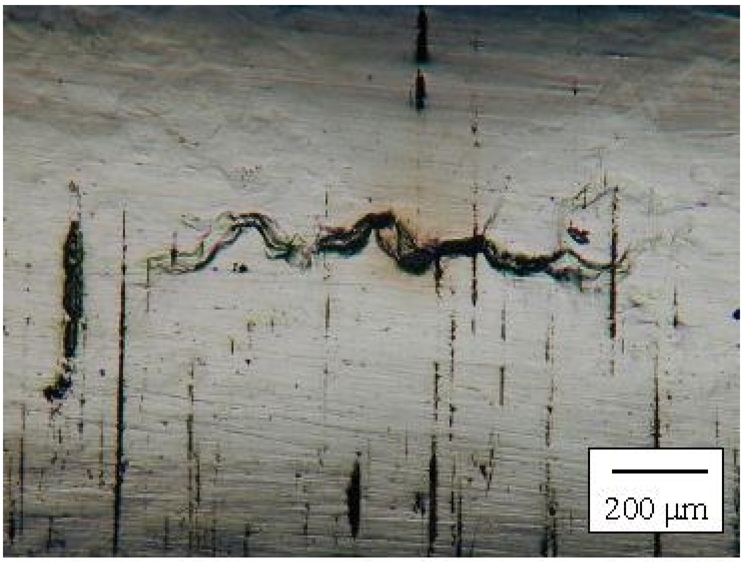


Fig.8. Surface axial crack produced on the tube outer surface by the radial dent loading.

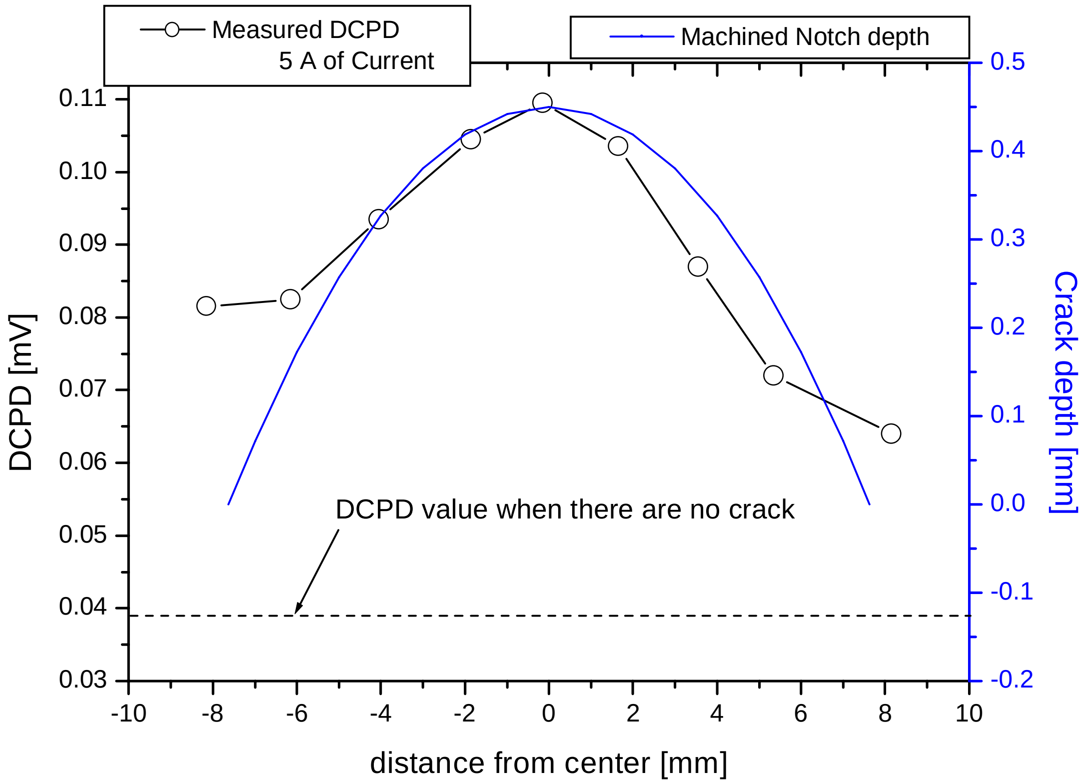


Fig. 9. Measurement DCPD signal and depth of mechanical notch made by a diamond saw cut as a function of axial distance from the specimen center.