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A Study on the Profile Change Measurement of Steam Generator Tubes with Tube Expansion Methods

Young Kyu Kim*, Myung Ho Song** and Myung Sik Choi***

Abstract Steam generator tubes for nuclear power plants contain the local shape transitions on their inner or outer surface such as dent, bulge, over-expansion, eccentricity, deflection, and so on by the application of physical force during the tube manufacturing and steam generator assembling and by the sludge (that is, corrosion products) produced during the plant operation. The structural integrity of tubes will be degraded by generating the corrosive crack at that location. The profilometry using the traditional bobbin probes which are currently applied for measuring the profile change of tubes gives us basic information such as axial locations and average magnitudes of deformations. However, the three-dimensional quantitative evaluation on circumferential locations, distributional angle, and size of deformations will have to be conducted to understand the effects of residual stresses increased by local deformations on corrosive cracking of tubes. Steam generator tubes of Korean standard nuclear power plants expanded within their tube-sheets by the explosive expansion method and suffered from corrosive cracks in the early stage of power operation. Thus, local deformations of steam generator tubes at the top of tube-sheet were measured with an advanced rotating probe and a laser profiling system for the two cases where the tubes expanded by the explosive expansion method and hydraulic expansion. Also, the trends of eccentricity, deflection, and over-expansion of tubes were evaluated. The advanced eddy current profilometry was confirmed to provide accurate information of local deformations compared with laser profilometry.

Keywords: Steam Generator Tube, Profilometry, Advanced Eddy Current Probe, Explosive Expansion, Hydraulic Expansion, Eccentricity, Deflection

1. Introduction

Cracks, wears, pits, inter-granular attack, etc. occurred on the inner and outer surfaces of steam generator tubes in operating nuclear power plants. The eddy current test as a method of non-destructive tests was used to detect these defects[1,2]. Except these defects, various local tiny profile changes as dent, bulge & protrusion, over-expansion, eccentricity, deflection, and so on were made on both sides of tubes. For these profile changes, the traditional bobbin type probe merely provided general information such as the location of profile change and the average size of diametral change for the dent and the bulge and could not give detailed information including the occurrence of eccentricity and/or deflection, the circumferential location and distributional angle, the real size of the diameter, etc. These profile changes resulted in crack-like defects by inducing of local stresses and increasing of total residual stresses.

In order to fix the steam generator tube to the tube-sheet in the nuclear power plant, the mechanical expansion method, explosive expansion method, and hydraulic expansion method were used[3]. In domestic plants, explosive expansion method and hydraulic expansion method were applied, based on the operating experience, tubes expanded by the

[Received: April 21, 2011, Revised: July, 21, 2011, September 23, 2011, Accepted: October, 7, 2011] *Hongik Univ. School of Materials Science and Engineering, **Korea Institute of Nuclear Safety, Engineering Research Department, ***Korea Atomic Energy Research Institute, Materials Research Division, †Corresponding Author: k084smh@kins.re.kr

hydraulic method had few cracks like a defect, but tubes which expanded by the explosive method had lots of cracks on the inner and outer surface of tubes in the early operating stage[4,5].

In this paper, the profile variation measurement of steam generator tubes was performed using the advanced eddy current probe, which can detect circumferential locations and distribution angles as well as the abnormal profile of tube roll transition areas and their tube longitudinal locations. After that, previous results of eddy current test were compared with those of laser profilometry, quantitatively.

2. Advanced Eddy Current Probe

At first, the advanced eddy current probe used in this work uses the non-surface riding method[6]. This probe produces profile information that presents the profile as a correlation between the distance from the inspected substance and the magnitude of signal amplitude which is induced from probe coils. Secondly, this probe also produces the continuous profile information for all circumferences of a tube. Therefore, this probe has the technical characteristic that measures and evaluates the axial location and length of the tube profile change, the circumferential location and distribution angle, and the radial size 3-dimensionally. The difference between the advanced probe and the conventional probe were minutely described in the paper published last year[7].

Fig. 1 illustrates the basic scheme of an advanced eddy current probe. This probe consists of the coils that are wound as the circling type and the cylindrical coil supporting body. The coil part is a non-surface riding and rotating type and is fixed on the outer surface of the supporting body. That is, the inspection coil was designed not to contact the inner surface of the tube and to constantly keep the invariable gap. This probe was designed to have the compatibility to be able to be used in the existing inspection equipment and the analysis software system.

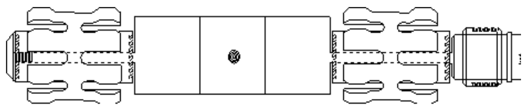


Fig. 1 Schematic of the advanced eddy current probe for measuring the shape transition of steam generator tubes

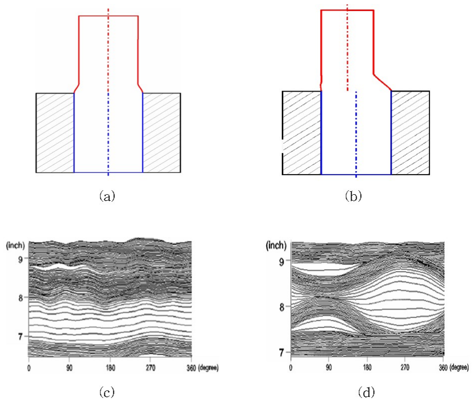
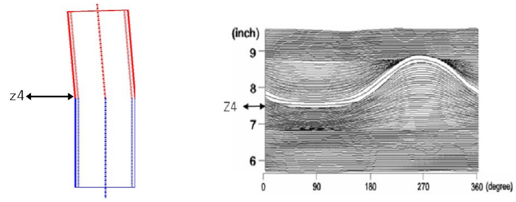


Fig. 2 Eddy current signals of the expanded tubes: (a) tube with a concentric expansion shape, (b) tube with an eccentric expansion shape, (c) advanced probe signal from the concentric expansion shaped tube and (d) advanced probe signal from the eccentric expansion shaped tube

Fig. 2 shows the analysis results of the eddy current signals obtained from an advanced eddy current probe. These signals are divided into two types of the tubes fixed within the tube-sheet. One is the concentric tube with the same central axes of the expanded tube and the non-expanded tube(Fig. 2-a) and the other is the eccentric tube with the different central axes(Fig. 2-b). It is noted that there is a large difference between the shape expanded concentrically(Fig 2-c) and the shape expanded eccentrically(Fig 2-d). In the shape that the tube is expanded concentrically, the area which line interval is wide corresponds to the profile change of the expansion transition area and the signal amplitude of this area is almost constant over all circumferences of a tube. In addition, in the shape that the tube is expanded eccentrically as shown in Fig. 2-d, the plain area which has a constant signal amplitudes circumferentially in the upper part and the lower part corresponds to the non-expanded area of the tube-sheet upper side and the expanded area of the tube-sheet inside, respectively. This plain area represents the area that has normal conditions. The area that has two hills and a valley like amplitude change is the signal produced from the eccentric expansion. When the advanced eddy current probe is used, irregularity of roll transition area, the location of eccentricity, and the direction of circumference as well as the shape of the eccentric expansion can be confirmed. The eccentric size, that is the displacement of the central axis in the radial direction, can be quantified by measuring the magnitude of the signal amplitude in the hills and valleys and consequently the quantity of 3-dimensional eccentric size can be realized.

Fig. 3 shows the analysis results for eddy current signals obtained from the tube with a deflective shape. The deflection as shown in Fig. 3-a represents that the central axes of the expanded tube and the non-expanded tube tilted at the boundary of the expansion transition area at the top of the tube-sheet. In this case, there is no displacement of the central axis in the radial direction. Fig. 3-b clearly shows the signal change corresponding to the shape change of axial and circumferential directions in z4 level (z-4 means the transition line which the deflective change is started.). The generation theory of such deflective signal is same to one of the eccentric signal, but the signal of the tube with deflective expansion has a hill shape of the profile change signal in the terrain plot because the probe movement and the signal sensing



(a) (b)

Fig. 3 Eddy current signals of a deflected tube: (a) tube with a deflection, and (b) signal from the new probe

characteristics of coil in the deflective area are different from those in the eccentric area.

The advanced probe has been partially applied in the pulled-out tube examination of KSNP(Korea Standard Nuclear Power Plant) steam generator practically to find the cause of cracks[5]. In US Ginna plant as the foreign plant, this probe was applied to measure the shape and the size of dents in tubes. That result was reported in 30th EPRI SG NDE Workshop last summer[8]. This inspection method is not recognized as the regular one in respect of the inspection method of the steam generator tube because the purpose of this method is not to detect the defects. So the accept and the reject criteria related to this method was not established. But excellent detect-ability can provide the information with relation to the crack initiation such as the degree of tube deformation. This inspection can be recommended as a good managing strategy in aspect of the proactive aging management instead of the present materials aging management.

3. Experimental Method

3.1 Test Specimens

The expansion specimens are fabricated from the steam generator tubes of KSNP(Korean Standard Nuclear Power Plant) with Alloy 600 HTMA material and the tube-sheet with

Fig. 4 Tube specimens prepared by expanding (a) explosively, and (b) hydraulically

low alloy steel, ASME SA 508 Class 3 material. The outer diameter of the tube is 19.05 mm and its thickness is 1.07 mm. The types of expansion specimens which are fabricated for this work consist of the specimens with the explosive expansion and the specimens with the hydraulic expansion as shown in Fig. 4.

In the specimens with the explosive expansion, according to the standard procedure of the Doosan Heavy Industry for steam generator tube expansion, 12 holes with 19.25 mm hole diameter are machined in the tube-sheet with 20 cm of thickness and the tubes with 40 cm in length are inserted into these holes and explosive wires(Primacord^{TM}) with 20 cm in length connecting to the detonator are inserted into tubes. After that, explosive wires are exploded and the tubes are expanded explosively. At this time, the explosive of 15 gr/ft as the Primacord^{TM} unit and the expansion ratio of 2~6% as standard design values were applied to keep the proper contacting force and to have no crevice between the outer surface of the tube and the inner surface of tube-sheet.

Otherwise, also in the specimens with the hydraulic expansion, according to the standard procedure of the Doosan Heavy Industry for steam generator tube expansion, 12 holes with 19.25 mm hole diameter are machined in the tube-sheet with 53.5 cm of thickness and the tubes with 60 cm in length are inserted into these holes and the mandrel connecting to the Mark Ⅳ Hydroswage^{TM} system of Haskel Co. is inserted into tubes. After that, the mandrel is pressurized up to the hydraulic pressure of ~38,000 psi for 4 seconds and therefore, the tube is expanded. The deviation of the expansion ratio was measured to be about 1.5~2.8% in the range of 34,000~38,000 psi.

3.2 Eddy Current Testing

The advanced probes and the conventional bobbin probes(A-610-ULC) were used in the eddy current signal collection for expanded specimens. Then the technical performance of the advanced probe was confirmed through the comparative evaluation of signals obtained from two types of these probes. In this work, Zetec MIZ-70^{TM} data acquisition system was used. To calibrate the profiling signals quantitatively, the ASME defect standard tube and the EDM notch standard tubes with axial & circumferential flaws were used. Test frequencies for the advanced probe were 10, 100, 300, 400, 700 kHz and 10, 100, 300, 550, 700 kHz for the bobbin probe. The probe running speed and the rotating speed for the advanced probe were 0.2 inch/sec and 300 rpm, and 12 inch/sec for the bobbin probe. On the other hand, the accuracy of the advanced probe was evaluated as 1/100 mm and this value was equal to that of the laser profilometry method.

3.3 Laser Profilometry

To measure the 3-dimensional profile change of the expanded specimens and to compare with the measured results of the advanced eddy current probe quantitatively, the laser profilometry was performed. The LP-2000^{TM} control unit and LP-P-0.75 probes of Laser Techniques Co. were used for this work. The spot size of the laser beam was 0.13 mm and the measuring resolution was 0.013 mm.

4. Results and Discussion

4.1 Bobbin Signal Characteristics

Fig. 5 and 6 show the representative profile change of bobbin signals obtained from the specimens with the explosive expansion and the hydraulic expansion, respectively. The right side of figures from the centerline, TSH line (It means the top of tube-sheet), is the expansion area within the tube-sheet and the left side is the non-expansion area. As mentioned before, because all circumferential signals of the tube are displayed as a single line; the bobbin profile signals shows the average distances between the expansion locations and the central axis of the tube. Therefore, the dent, the bulge, and the over-expansion of the tube can be qualitatively identified by the bobbin probe but the local deformations cannot be quantitatively measured in this case.

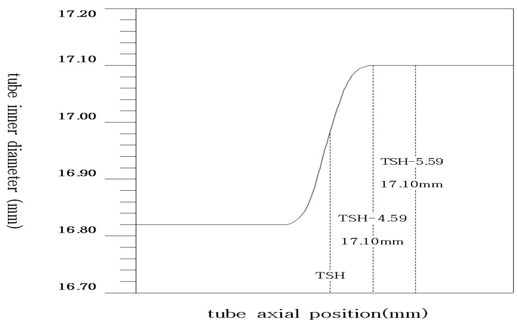


Fig. 5 Profile data of a tube expanded explosively by bobbin probe

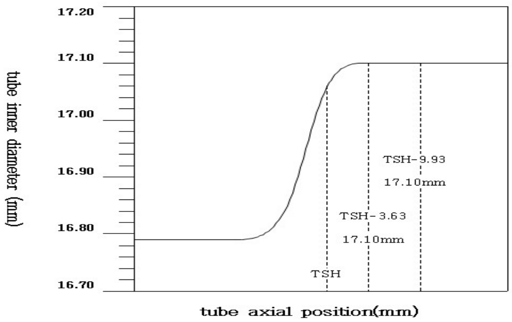


Fig. 6 Profile data of a tube expanded hydraulically by bobbin probe

We can note in both figures that the expansion transition slope of the tube with the explosive expansion is smooth and its length is long but that the slope of the tube with the hydraulic expansion is steep and its length is short. Such results are same to those measuring values of the circumferential profile displayed as a single line of axial direction in a similar way to bobbin profile signals by using the laser inspection system.

4.2 Advanced Probe Signal Characteristics

Table 1 summarizes the profilometry results by using of the advanced eddy current probe and the laser profilometry probe for all specimens with the explosive expansion and the hydraulic expansion, respectively. The advanced eddy current probe is beneficial to detect the eccentric particularity of the tube, but it is noted that the evaluation technique needs to be supplemented for the precise separation and measurement of the different two signals when the tiny deflection and eccentricity exist simultaneously. In this paper, the analysis and the comparison between the quantities of eccentricity by laser profilometry and those by advanced eddy current probe were not performed.

Table 1 Profilometry results of tubes expanded explosively or hydraulically

Specimen No.	Explosive Expansion		Hydraulic Expansion	
	Advanced probe technique	Laser profilometry (Max. ecc. angle, Ecc. mag., Ecc/Def)	Advanced probe technique	Laser profilometry
1	Ecc	237°, 0.089mm, Ecc	G	G
2	Ecc	139°, 0.197mm, Ecc	G	G
3	Ecc	122°, 0.163mm, Ecc	G	G
4	Ecc(Def)	178°, 0.145mm, Ecc(Def)	G	G
5	Ecc	333°, 0.080mm, Ecc	G	G
6	Ecc	120°, 0.094mm, Ecc	G	G
7	Ecc	154°, 0.143mm, Ecc(Def)	G	G
8	Ecc	189°, 0.092mm, Ecc(Def)	G	G
9	Ecc	259°, 0.190mm, Ecc(Def)	G	G
10	Ecc	185°, 0.126mm. Ecc	G	G
11	Ecc(Def)	350°, 0.097mm, Ecc(Def)	G	G
12	Ecc	259°, 0.082mm, Ecc	G	G

Note. Ecc: eccentricity, Def: deflection, G: good expansion

Fig. 7, 8, and 9 show the signals of the advanced eddy current probe obtained from expansion- transition areas of specimens by the explosive expansion and the hydraulic expansion. Fig. 7 shows the best expansion shape of the specimens with explosive expansion and the signal of the strip chart on the left side of the upper figures is considerably clear. It can be concluded that the tube expansion was relatively expanded uniformly. However, a little amplitude change in the C-scan plot of the lower figure appeared circumferentially, therefore, this confirms that there was a tiny eccentricity.

On the other hand, Fig. 8 shows the poor expansion shape of the specimen with both the eccentricity and the deflection by the explosive expansion. The strip chart signals of the expansion-transition area for this tube shows the severe signal noise cluster in the upper and lower areas at the top of the tube-sheet. This fact means that the quantity of the eccentricity increases with the increase of the amplitude of the signal noise cluster as the oscillation phenomena of the signal amplitude responding to the eccentricity. The amplitude change of the two hill and valley shapes in the C-scan plot (see Fig. 8) appears in the boundary of TSH point, where the tube has the eccentricity in the boundary of the top of the tube-sheet. That is, when the advanced eddy current probe with the rotating coil moves along the axial direction in the eccentric tube, the probe body supporting lugs also move along the different central axes within the tube-sheet and out of the tube-sheet. When the rotating coil pass the eccentric expansion-transition area, it continuously detects the distance changes between the coil and the inner surface of the tube and the corresponding changes of the signal amplitude are recorded in the C-scan plot. Consequently the eccentricity of the tube is able to be confirmed and from the circumferential location angle with the maximum amplitude, the direction of the eccentricity is

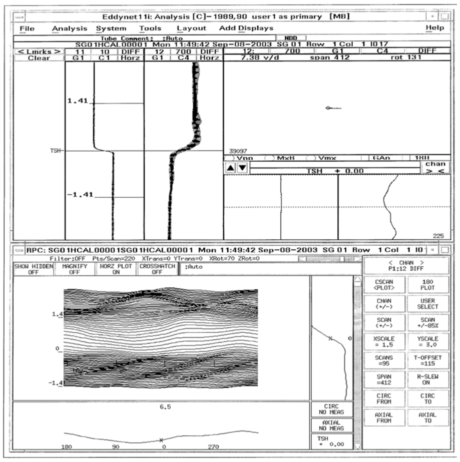


Fig. 7 Profile data of an optimal tube expanded explosively, measured by advanced probe

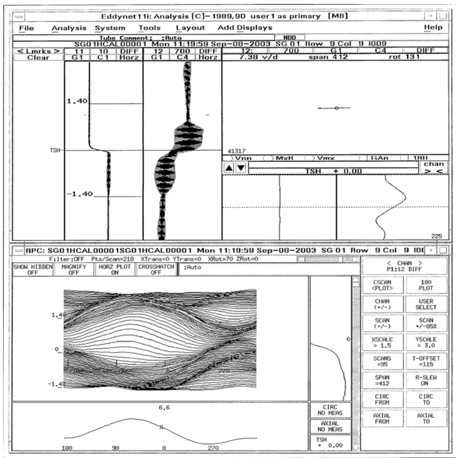


Fig. 8 Profile data of a poor tube expanded explosively, measured by advanced probe

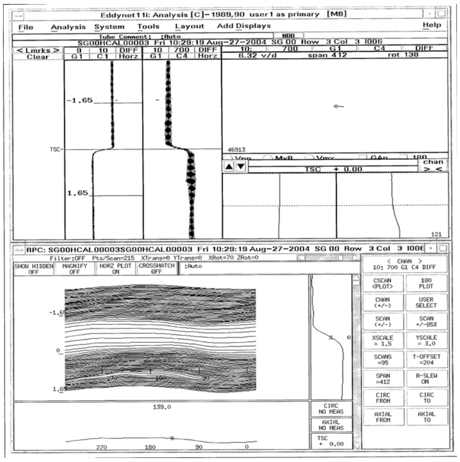


Fig. 9 Profile data of a tube expanded hydraulically, measured by advanced probe

also able to be measured. While the profilometry result of this specimen measured by the laser inspection system shows the eccentricity and the tiny deflection (Table 1, No. 9), the profilometry by the advanced eddy current probe does not show these deformations. Thus, when the large eccentricity and the tiny deflection exist simultaneously, the evaluation technique for the precise separation and measurement of the different two signals has to be supplemented.

Fig. 9 shows the typical characteristics of uniform expansion signal which appears in all specimens with the expansion-transition area formed by the hydraulic expansion. The strip chart signals on the left side of the upper figures as Fig. 7 are fairly clear and without the formation of hills and valleys in the lower C-scan plot, the constant signal amplitude are circumferentially measured. Therefore, it is confirmed that the tube is expanded uniformly.

4.3 Laser Profilometry Results

Fig. 10, 11, and 12 are the schematic drawings of the eccentricity and the deflection of specimens 2-dimensionally. These look like plane figures that all specimens are projected downward. Fig. 10 shows the results for which the same specimen used to obtain the signals as Fig. 7 was observed; 0.089 mm of very small eccentricity in 239° of circumferential location was confirmed. Fig. 11 shows the results for which the same specimen used to obtain the signals as Fig. 8 was observed; 0.089 mm of the maximum eccentricity in 259° of circumferential location was confirmed. And Fig. 12 shows the measuring results of the eccentric potential for the specimen to obtain the signals as Fig. 9 and it was confirmed that this specimen has almost a concentric shape.

Fig 13, 14, and 15 show the eccentricities and the deflections that 3-dimensionally schemed

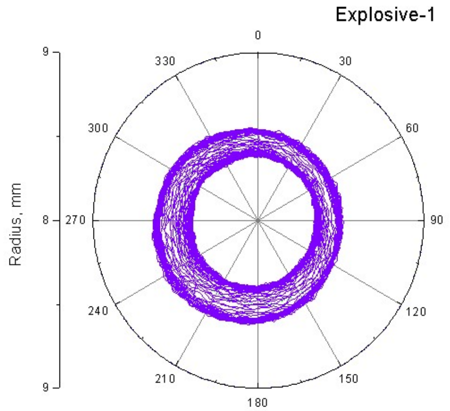


Fig. 10 2-Dimensional data of an optimal tube expanded explosively, measured by laser inspection system

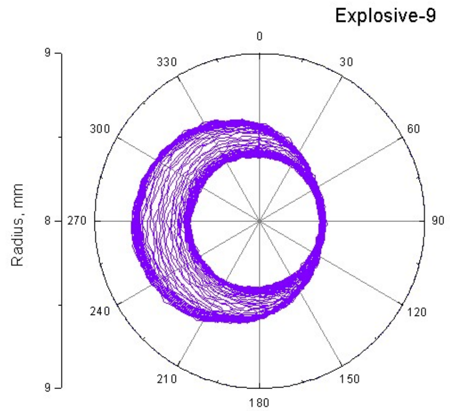


Fig. 11 2-Dimensional data of a poor tube expanded explosively, measured by laser inspection system

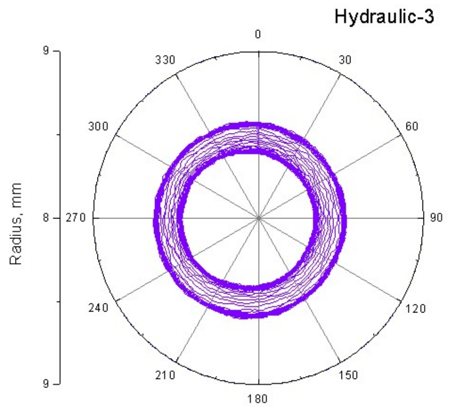


Fig. 12 2-dimensional data of a tube expanded hydraulically, measured by laser inspection system

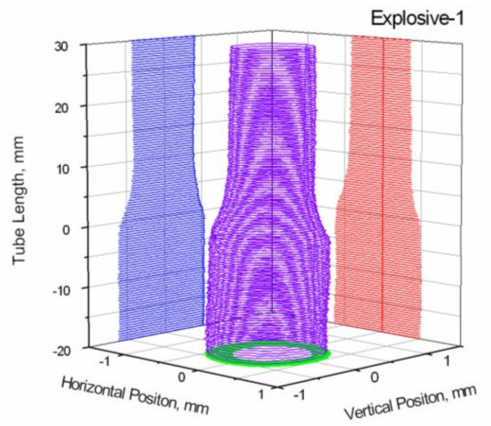


Fig. 13 3-Dimensional data of a optimal tube expanded explosively, measured by laser inspection system

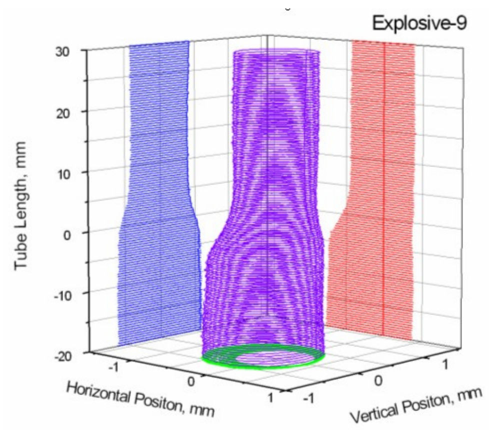


Fig. 14 3-Dimensional data of a poor tube expanded explosively, measured by laser inspection system

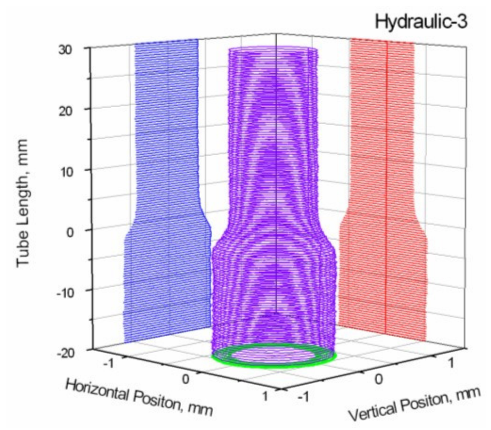


Fig. 15 3-Dimensional data of a tube expanded hydraulically, measured by laser inspection system

for the specimens used to obtain the signals as Fig. 7, 8, and 9. Fig. 13 appears almost like a uniform expansion shape like in Fig. 15, although its expansion method is different from each other. However, Fig. 14 shows the severe eccentricity based on the 3-dimensional tube shape in the middle of the figure and the deflection based on the tilted silhouette of the tube projected on the left side. The circumferential shapes of the circles projected the ground of the central tube shapes from Fig. 13 to Fig. 15 and coincided with the plane figures from Fig. 10 to Fig. 12.

5. Conclusions

In this work, the profilometry of the tube expansion-transition area expanded by explosive expansion method and the hydraulic expansion method was performed by the advanced eddy current probe and the laser inspection system to find the cause of circumferential cracks experienced in KSNPs. The following conclusions are drawn.

1) The hydraulic expansion method resulted in the uniform shape of the expansion-transition area for all specimens. While the explosive expansion method was somewhat different, that resulted in the eccentricity for all specimens and partly with the deflection.
2) The shape particularities detected by the advanced eddy current probe are in better coincidence with the results of laser profilometry for the same specimens.
3) More circumferential cracks in the tube with the explosive expansion may be related to the deformations such as the eccentricity and the deflection in the expansion-transition area.

Acknowledgement

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