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Assessment of Profile Change and Acceptance Criteria of Cold-worked Elbow of ICI Guide Tubes

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***Abstract*—In tubing or piping systems, tubes carries fluids and the inner profile of elbow is not much of concern, but the in-core instrumentation (ICI) guide tubes used in reactor is a special exception. The ICI guide tubes carry ICI probes and cables that can be able to travel inside of the tube. Hence, the inner profile is utmost importance to maintain clearance. One of the most troublesome problems is change of tube profile change and after bending process. In the outside of bend, the tube wall is subjected to tensile stress and it becomes thin, while in the inside wall is subjected to compressive stress resulting in thick wall. Moreover, the uneven deformation of cross section of bent tube also occurs, which is not perfectly circular and uniform but a significant deviation of circularity can result in from the fabrication process. A crucial factor in reducing cost and increasing product quality of bent tubes or pipes will be in the ability to predict and minimize fabrication variations. For view of the above issues, a study on imperfection prediction for bend tube is necessary in reality. In this study, the deformation profile of bent tube such as wall thickening/ thinning and cross-sectional distortion in cold bending process was studied. The finite element method to assess bending deformation using ANSYS V.15 was performed. The wall thinning and thickening in the bend region were investigated and the deviation from the circularity in the bend region was investigated to give the fabrication tolerance of ICI tube elbows.**

Keywords—Tube bend; Pipe bend; Pipe bend profile change; Pipe elbow wall thining

I. INTRODUCTION

In the manufacturing process of tube bends, it is very difficult to control thickening at the intrados and thinning at the extrados. In addition, the cross section of the bend becomes non-circular due to bending process resulting in ununiformed deformation. Ovality phenomenon can occur at the cross section of bend region. The acceptability of tube bends will be based on the induced level of these shapes imperfections. For example, in the case of pipe or tube bend used for fluid is concerned about wall thinning at the extrados of bend. These applications do not require stringent bend cross-sectional profile requirement. However, in-core-instrumentation (ICI) probe and cable guide tube used for nuclear reactor as shown in Fig. 1 required strict internal tolerance. Hence, it is very important to maintain the circularity of internal surface of ICI guide tube bend [1].

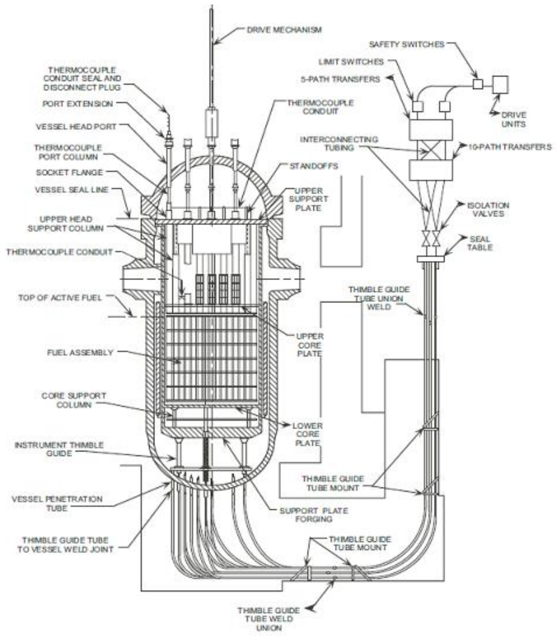

Figure 1. ICI arrangement in reactor vessel [1]

So far many studies have been performed for the above problems. It depends on the function of its required equipment or system. In this study, the cold bending process was performed including large plastic deformation, large displacement, nonlinear contact analysis, etc. We use the ANSYS V.15 software and its nonlinear methods to build tube bending simulation system to predict some imperfection phenomena of bending tube[2][3]. In this study, cold press bending method was used and simulated. Various failures are undesired deformation, wall thinning, wall thickening, and ovality. Thus optimization of process for cold bending of metal tubes plays a very important role.

The deviation of the tube bend cross section for circularity can be calculated from software data for any ovality using equation and hence the maximum and minimum tube bends diameters. Thinning at the extrados is assumed to be equal to thickening at the intrados, and accordingly the dimensions of the geometry are calculated and created in a major commercial finite element analysis software code[4]. The sketch of pipe bending methods are shown as Fig. 2. A typical bending

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method of 4 different cases are shown in Fig. 2. Depending on the size of pipe and the stiffness of pipe, one of the methods are selected. If pipe diameter is too big then this kind of bending is not feasible and need separate fabrication of elbow.

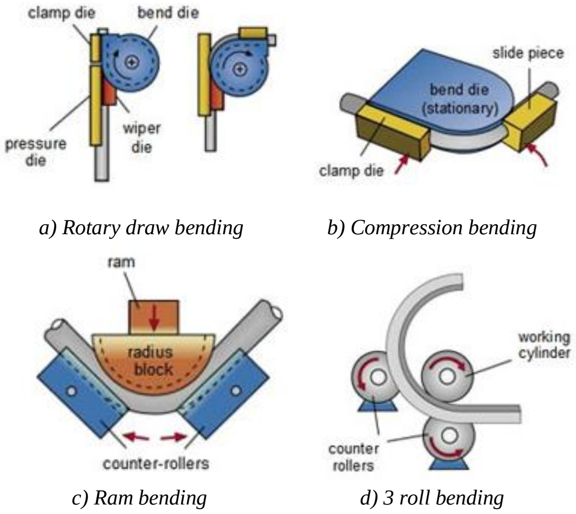


Figure 2. Pipe bending methods for elbow fabrication

Four different bending methods are shown in Fig.2, in which rotary draw bending, compression bending, ram bending and 3 roll bending. The rotary bending method is the most accurate methods and the 3 roll bending method is the most simple method to make an elbow of piping or tubing system.

II. TUBE BENING METHODS

A. General descriptions of tube bending

When tube system consists of elbows, it is constructed either by assembly of straight tube and elbow or by bending of straight pipe. Bending of straight tube give smooth connection in the elbow region and may reduce construction cost. When tube bends to a desired shape or geometry, the applied force on the bend wheel must exceed the “yield point” of bend tube material. In order to make a tube bend, different bending methods are used depends upon the tube or pipe diameter, wall thickness, minimum bend radius required, and part complexity.

When a tube is bent, two phenomena happen in the bend region. The outside wall of the tube collapses and thins out, and the inside of the tube compresses and wrinkles. Besides these issues, there is different deformation at the cross section of bent tube resulting in change of ovality of tube.

There are several types of tube bending method adapted to manufacturers’ purpose. In fact, press bending or rotary draw bending method is commonly used to form bend of pipe or tube.

B. 3 Roll bending method

Press bending is simplest and cheapest method of bending cold tube and pipe. This method is almost the first bending process used on cold tubing and pipes. In this process, a die (roller) is pressed against the tube forcing the tube into desired shape.

The principle of press bending method is shown in Fig. 3. The bending mechanism consists of three rollers of which rollers 2 and 3 are stationary and work as fixed support throughout the fabrication process. While the roller 1 is fixed to the battering ram and moves up or down depending on the required bend radius of tubes.

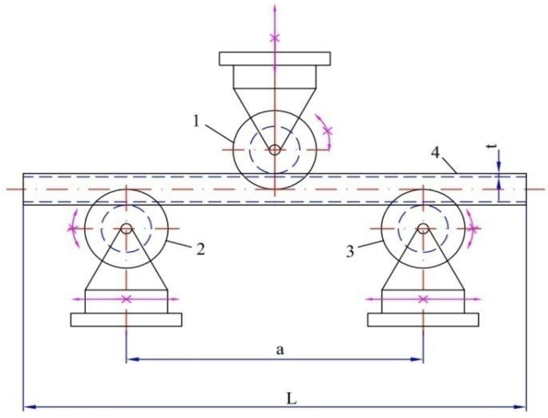
In order to make desired bend radius, tube 4 is placed on rollers 2 and 3, while roller 1 moves vertically on the tube causing plastic deformation. The bending radius is adjusted by changing horizontally distance a between two rollers 2 and 3 and vertically stroke b of roller 1, see Fig. 2.

Depending on the thickness of the pipe or tube material, this process will deform the tube or pipe into an elbow. This is the easiest and least expensive bending process comparing to other methods. This process can be used when the shape of elbow is not important.

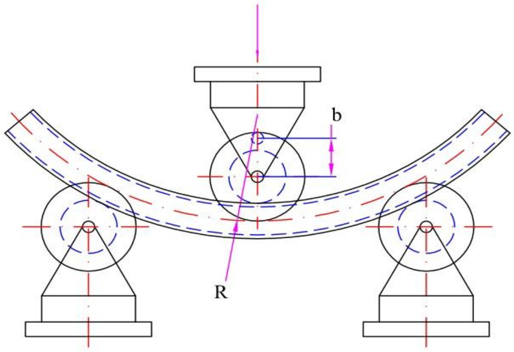
C. Rotary draw bending method

This method is common, useful and flexible bending method among the types of tube bending processes. It is the most widely used approach to achieve relative high efficiency and precision bending forming. The tooling of this method includes four components: a bend die, a pressure die, a clamp die and a wiper die as shown in Fig. 4.

Rotary draw bending is precise in that they bend using tooling or die which have a constant centerline radius. The die set consists of two parts. The bend die creates the shape to which the material will be bent. The pressure die does the work of pushing the straight material into the bend die while traveling the length of the bend.



1-upper roller; 2, 3-lower rollers; 4-tube



b: travel distance; R: bending radius

Figure 3. Sketch of principle of 3 Roll Bending Method

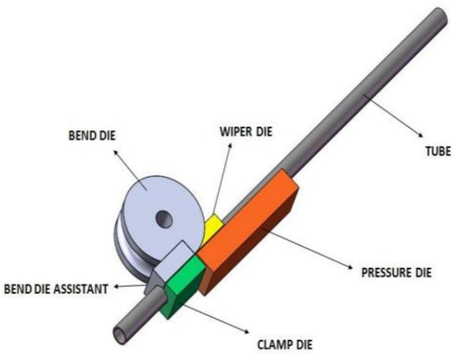


Figure 4. Components of rotary draw tube bending

The basic steps of rotary draw of bending process are as follows:

- The clamp die presses the tube tightly against the bend die to prevent the tube sliding during the bending process.

- The pressure die then rotates together with tube until desired rotation angle, i.e. 90°, 60° or 45°.

- The wiper die pushes the tube at the inside so that the tube will not buckle during the bending operation. It also reduces the thinning of the tube and assist to completing the bend by supporting the tube during the bending operation.

D. Common defects of bend tube

Some terminologies are used in this study such as thinning, thickening, and ovality will be described below and indicated in Fig. 5.

Thinning, which occurs at extrados of the pipe bend, is defined as the ratio of the difference between the nominal thickness and the minimum thickness to the nominal thickness of the pipe bend and is expressed in percentage as given in Eq. (1) [5][6].

$$C_{th} = \frac{t - t_{min}}{t} x100 \qquad (1)$$

Thickening, which occurs at intrados of the tube bend, is defined as the difference between the maximum thickness and the nominal thickness divided by the nominal thickness of the tube bend. The percentage thickening is given in Eq. (2).

$$C_t = \frac{t_{max} - t}{t} x100 \qquad (2)$$

Ovality is determined by the difference between the major and minor diameters divided by the nominal diameter of the tube as given in Eq. (3).

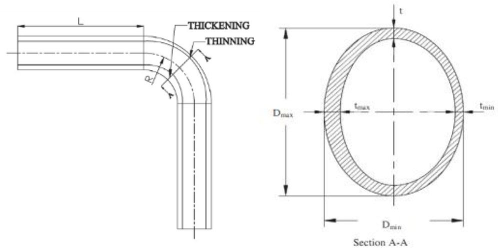


Figure 5. Tube bend and cross-section of the elbow

$$C_0 = \frac{D_{max} - D_{min}}{D} x100 \qquad (3)$$

Where $D = \frac{D_{max} + D_{min}}{2}$ (4)

III. FEM MODELING

The aim of this study is to predict the deformation characteristics of a fine tube with several sizes in the bending process. Simulation of tube bending using FEA was performed to observe the deformation characteristics such as wall thinning, wall thickening, and ovality of the bent tube at cold-working temperature of 370°C.

A. Modeling

The ANSYS-Workbench is used to create geometric model of tube bend of tubes given in table 1. In this study, a simplified model was created which includes three rollers and one tube. The tube is arrested by two lower rollers, while upper roller against the tube and perform vertical stroke during bending process adapting with desired bending radius.

Finite element simulations were used to evaluate the thickness distribution of the tube, the distortion of the cross section in bend region during the bending process. All simulations were carried out by using Finite Element Analysis (FEA) software ANSYS/WORKBENCH version 15 with large plastic deformation, large displacement, and nonlinear contact analysis options.

To reduce the size of FEM model and simulation time, the symmetric model is created as shown in Fig. 6. It consists of three rollers and one tube where contact between tube and rollers were defined to reflect actual contact condition. In this study, a whole tube was divided into two equal parts. The purpose of that work is to get more convenience in checking process of imperfections of bent tubes.

Table 1. Dimensions of stainless pipe used for analysis

Nominal Pipe Size, (in)	OD (mm)	Nominal Wall Thickness (mm)		
		Schedule 10SCH	Schedule 40SCH	Schedule 80SCH
3/8	17.1	1.65	2.31	3.20
1/2	21.3	2.11	2.77	3.73
1	33.4	2.77	3.38	4.55

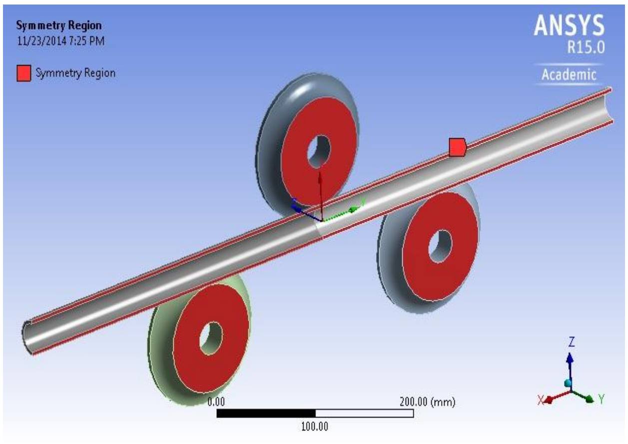


Figure 6. Symmetric model of tube bending process

The tube is defined as a deformable body, while three rollers are assumed as solids have absolute stiffness by using "RIGID" option. For the accurate simulation of bending operation, the multilinear relationship of material is used in the analysis. This will give more accurate result than simply assuming elastic perfectly plastic relationship of deformation.

Contact between various pairs of surfaces: tube 4 and the rollers 1, 2, and 3 were all defined by "Frictional Contact" to simulate the real situation in their normal direction as shown in Figure 7. In the tangential direction, sliding occurs only when the shear exceeds the value multiplying the normal stress by a friction coefficient, which is input as a contact property. The analysis was performed using friction coefficient of 0.1.

The "PROBE DEFORMATION" option in ANSYS-Workbench was used to get information of every node at the circumference of the mid-cross section in bend region as shown in Fig. 8, and then determine the trend of deformation of tube such as wall thickness, ovality, thinning ratio, thickening ratio.

Geometry nonlinearity is due to large deformation of structures, each element stiffness is a function of the element's material properties as well as geometry. To include geometry nonlinearity, during the modeling operation, simply turn on "Large Deflection" in "Analysis setting".

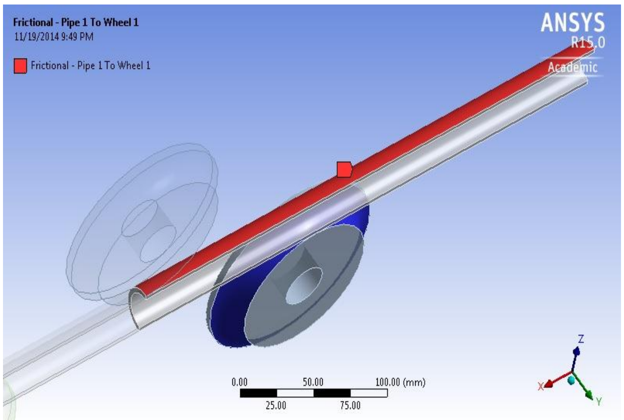


Figure 7. Friction contact surface of roller and tube

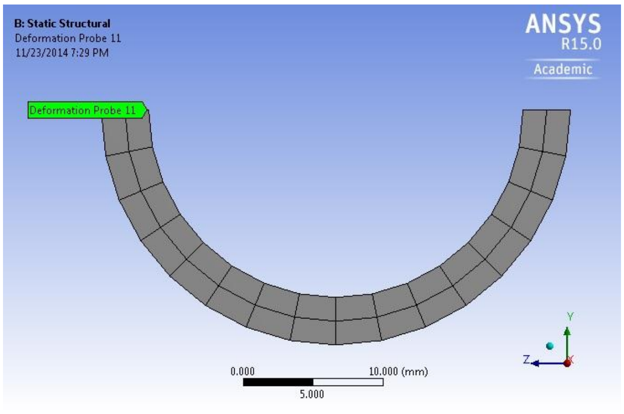


Figure 8. Measurement of deformation at the mid-section using probe tool

B. *Engineering Data Preparation*

For the material of bending tubes, austenitic stainless steel SS182 type-F316L was selected which is used in the nuclear power plant broadly, with mechanical properties of Young's modulus E=2.83x107 psi and Poisson's ratio v=0.3.

In this study, the material is assumed multilinear elastic-plastic. So the stress strain relationship is not a linear relationship, hence, we need to specify the multilinear relationship of material properties which is shown in Fig. 9 [6].

C. *Mesh Generation and Mesh Improvement*

Besides, nonlinear problems require much more computational resource than linear problem, and poor mesh quality may aggravate the situation and result in a not so accurate solution. In order to improve solution accuracy and improve computing time at the same time, symmetry of the problem can be used without losing the accuracy of solution and using appropriate element for mesh.

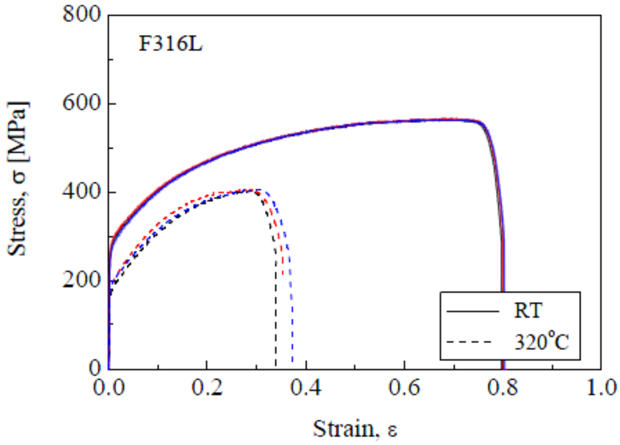


Figure 9. Multilinear material properties of tube material [6]

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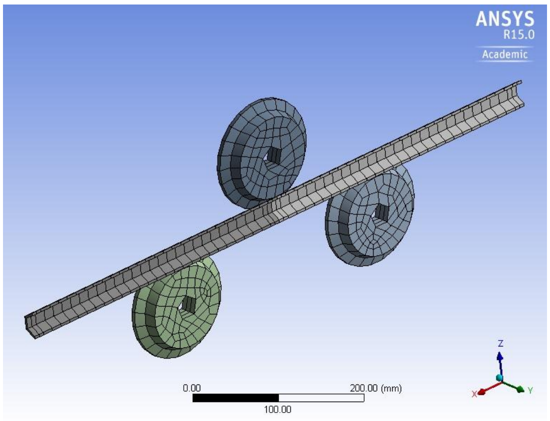
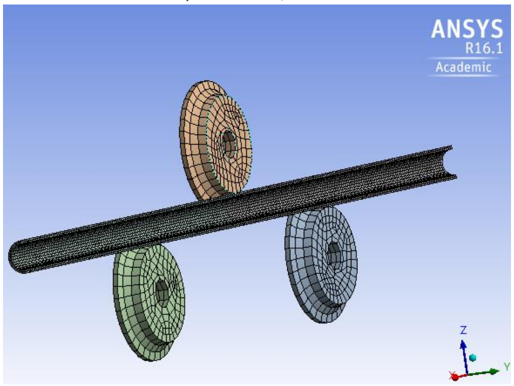


a) Initial default mesh



b) After mesh refinement

Figure 10. Meshing of the tube bend model

The ANSYS workbench allows performing automatic meshing, but its quality is not expected. Fig. 10 shows the initial default mesh and after mesh refinement.

D. Boundary Conditions

The supports of the two lower rollers were used by “Frictionless Support”, which expressed the connection between the two directional rollers of bending system and rotating shafts. The upper roller was imposed a displacement boundary condition by using “displacement” option that the stroke b of roller 1 is defined to produce displacement resulting in required bending radius.

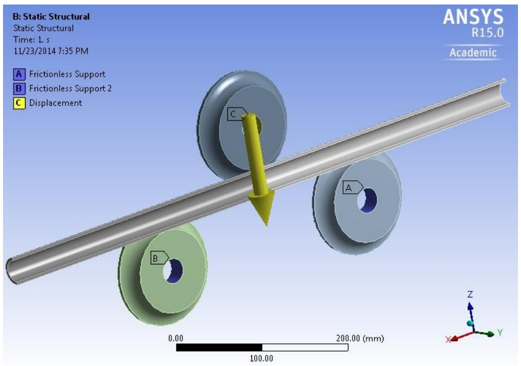


Figure 11. Displacement boundary condition of the upper roller

Table 3. Upper roller displacement of tube size of OD=25.4mm (NPS 1in)

Bending radius (mm)	150	180	200	300	500	800	1000
Stroke of upper roller (mm)	60.3	50.8	46	32.29	20.18	13.2	10.6

Table 4. Upper roller displacement of tube size of OD=21.3mm (NPS 0.5in)

Bending radius (mm)	150	180	200	300	500	800	1000
Stroke of upper roller (mm)	62.5	52.32	47.3	32.68	20.45	13.2	10.7

Table 5. Upper roller displacement of tube size of OD=17.1mm (NPS 0.375in)

Bending radius (mm)	150	180	200	300	500	800	1000
Stroke of upper roller (mm)	63.5	53.2	47.9	32.94	20.5	13.2	10.8

The value of stroke of upper roller was calculated and shown in Tables 3, 4, and 5 for each different tube sizes, where L is distance between two lower rollers, b is stroke of the adjustment of the upper roller and t is outside diameter of considering tube.

IV. RESULTS AND DISCUSSIONS

A. Distribution of mechanical strain

Distribution of total strain of bent tube is presented for bending radius R=300mm and diameter OD=33.4mm. As shown in Fig. 12 the extrados region becomes thinner, and intrados wall thickens. The maximum total mechanical strain occurs at the mid-cross section of bend region.

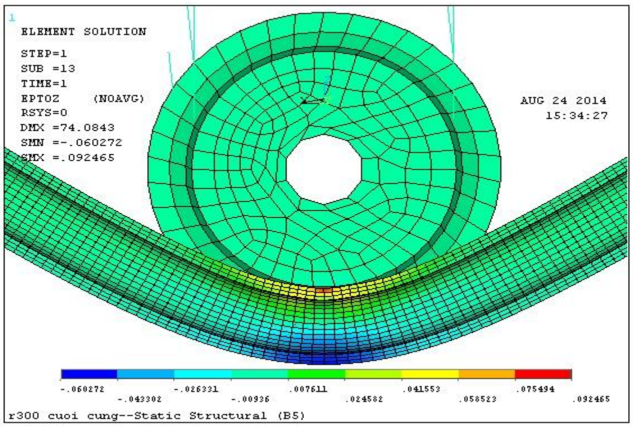


Figure 12. Distribution of total mechanical strain of bent tube wall

B. Wall Thickening and Thinning Change

The bent tube becomes thicker at the intrados and thinner at the extrados as shown as Figure 13. The thickening of wall is greatest at the inside bend and thinning is greatest at the outside of bend. Fig. 13 shows the effect of thickening and thinning of bent tube wall cross section. The effect of thickening and thinning is evaluated to the selected tubes. Figs 13 and 14 show the thickening and thinning of tube bends of NPS 1” tube, NPS 1/2” tube, and NPS 3/8” tube.

From the figure, as the bending radius becomes smaller the wall thickening and thinning grow larger showing inverse relationship. This thickening and thinning becomes prominent as the bending radius becomes smaller. It would indicate at some point tube collapses due to plastic instability [7][8].

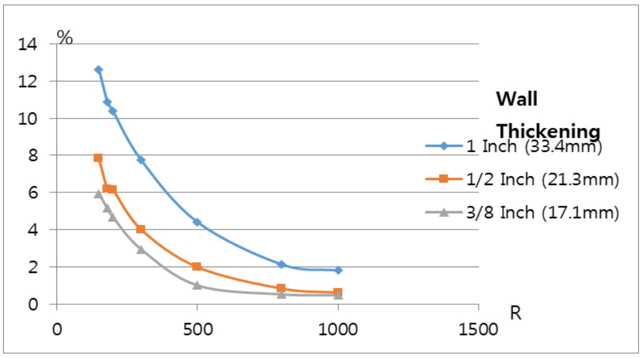


Figure 13. Effect of bending radius for wall thickening of tubes

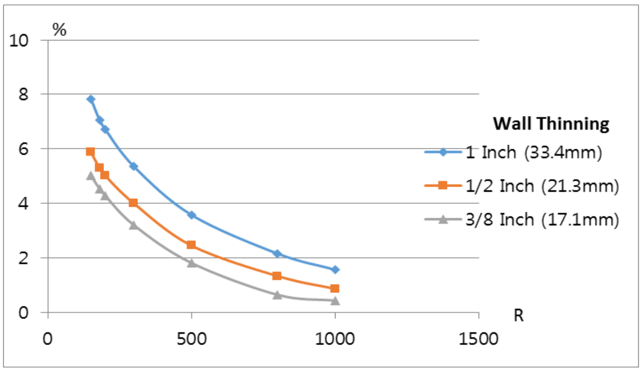


Figure 14. Effect of bending radius for wall thinning of tubes

C. *Ovality.*

The cross section of bent tube becomes oval shapes. The deviation from circular shape to oval shape depends on the size of bending radius and bend tube diameter. As shown in Fig. 15, 16 and 17 shows the profile of bend cross section for different size of tubes.

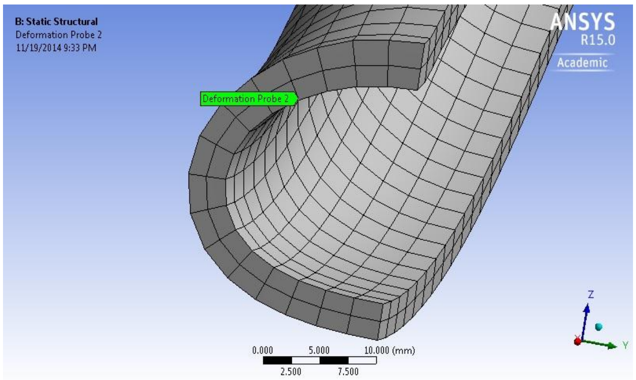


Figure 15. Cross section of bend for tube 1in for bending radius R=150mm

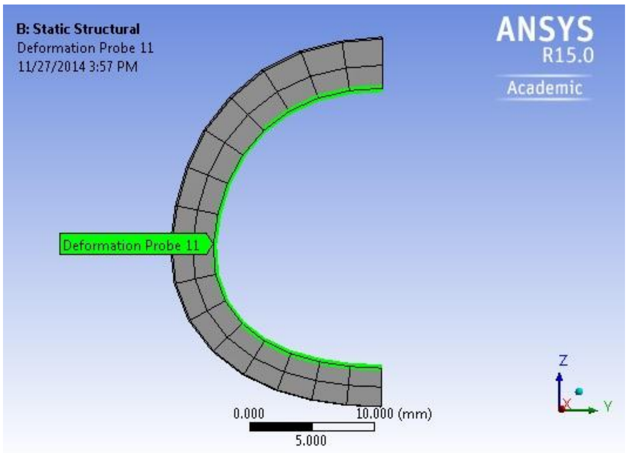


Figure 16. Change of ovality of bend tube 1in for bending radius R=150mm

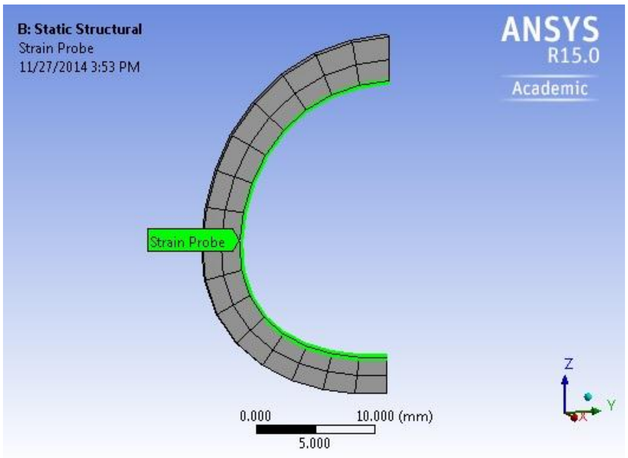


Figure 17. Change of ovality of bend tube 1 in for bending radius R=180mm.

Figure 18 presents the ovality change according to the tube diameter. It shows that the larger diameter of tube causes the larger change of ovality. This results show that the tolerance of tube inner diameter should be carefully specified if ICI probe is to be inserted through the tube

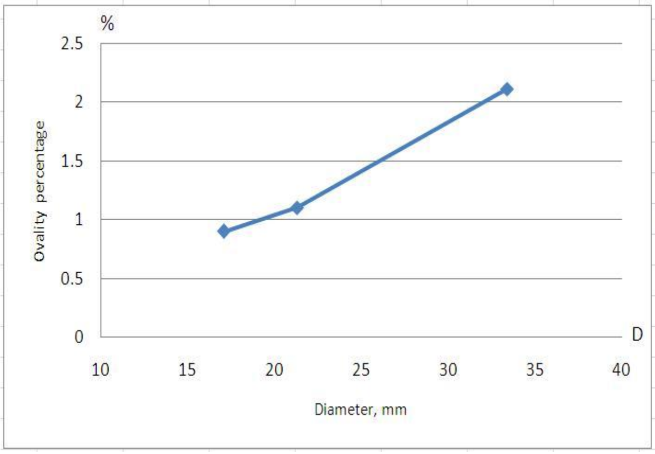


Figure 18. Change of ovality for bending radius R=300mm

The reduction of inside diameter of tube 1in. for several bending radius is shown is Table 6. It indicated that the small bending radius causes large reduction of inside diameter. The reduction of diameter can be used as a criterion for designing ICI guide tube.

Table 6. Reduction of inside diameter for bending radius for tube size of 1in

Items	Bending Radius						
	150	180	200	300	500	800	1000
Reduction of ID (mm)	2.88	2.136	1.881	1.204	0.474	0.042	0.008
Reduction of ID %	21.7	16.1	14.17	9.07	3.57	0.32	0.06

V. CONCLUSIONS

This paper concerned about tube bending process of deformation of bending region shape change. The bending process was assumed a simple bending setup with 2 support rollers and a single push roller are used to make bends. This is the simplest setup of bending process. The multi-linear material properties were used in the analysis.

The analyses showed that the change of wall thickness of tube occurs in bending process. Consequently, the bent region of tube wall appears thicker at intrados and thinner at extrados. Moreover, bending process affects the ovality of tube cross section at bend region.

From these results, wall thinning and cross-sectional ovality change need to be considered in the application and design of tube. In case of ICI guide tube, the inner circularity is very important since ICI probe and cable has to pass through the bend elbow, and any deviation from the tolerance causes stuck of ICI probe in the bend region. This is one of special importance where geometric deviations need to be carefully monitored. The simulation presented in this paper is focused on the estimation of geometric variation resulted in bending process of tube with typical bending process.

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