Effect of Bending Method on Tube Hydroforming^{*1}

Masaaki Mizumura^{*2,*3} and Yukihiisa Kuriyama^{*4}

Steel Research Laboratories, Nippon Steel Corporation, Futtsu 293-8511, Japan

We studied the effect of the bending method on the hydroforming of a tube in a subsequent process, using experiments and the finite element method. Two bending methods, rotary draw bending and intrusion bending, were investigated. A tube was bent into an S-shape by each bending method, and a hydroforming test was carried out with the same hydroforming die. The wall thickness distribution was measured after the hydroforming. The wall thickness of the tube is smallest on the compression side when it is bent by the rotary draw bending method and on the tension side or the intermediate side when it is bent by the intrusion bending method. In both bending cases, burst occurs on the intermediate side during axial feeding. In rotary draw bending, a burst occurs on the compression side or at the R stop nearby, however, in intrusion bending, burst does not occur on the compression side but occurs on the R stop nearby during the final increase of internal pressure. Intrusion bending leaves a larger hydroforming allowance than rotary draw bending. This is because the wall thickness after intrusion bending is greater than that after rotary draw bending. [doi:10.2320/matertrans.P-M2019866]

(Received September 11, 2019; Accepted November 11, 2019; Published January 20, 2020)

Keywords: tube forming, bending, forming property, bulge forming, deformation behavior, finite element method, tube hydroforming, process design

1. Introduction

The tube forming method with both internal pressure and axial feeding has been used for bicycle parts¹⁾ and tube fittings.²⁾ This method has been known as bulge forming since long ago. However, the shapes formed are T-shapes and other simple forms. Recently, this forming method has been applied to a wide range of purposes, from integration of parts to weight reduction in automobiles.^{3,4)} The name was changed to hydroforming and more complex shapes were able to be formed.^{5,6)} Hydroformed parts made of straight tube as well as bent tube are increasing, as shown in Fig. 1.

Deformation behaviors in hydroforming processes after bending have been the subject of past research. Lei, *et al.*⁷⁾ researched deformation of actual parts and Sato, *et al.*⁸⁾ and Ishigaki, *et al.*⁹⁾ investigated fundamental shape. In addition, the authors investigated strain behavior during hydroforming at bent portions and found suitable forming conditions without fractures or wrinkles,¹⁰⁾ even with an expanding ratio of 30% or larger.

There are many kinds of tube bending methods employed processes before hydroforming, but investigation into the effect of the bending method on hydroforming behavior has not been conducted thus far. In this paper, we explored two bending methods, rotary draw bending,¹¹⁾ which is the most common method performed, and intrusion bending,¹²⁾ which enables the forming of various shapes. We investigated the effect of the bending method on deformation behavior in the hydroforming process after each bending process through experiments and the finite element method (FEM).

Fig. 1 General hydroforming processes.

2. Procedures for Experiment and Analysis

2.1 Specimens

For specimens, we used tubes made from interstitial free steel plates¹³⁾ for deep drawing that were laser welded after being pressed several times into a round shape. Table 1 shows their sizes and representative mechanical properties. The mechanical properties in this table are the values in longitudinal direction obtained by tensile tests with arc shape specimens.

2.2 Final forming shape and processes

The final shape after forming is an S-shape with 2 bent portions, as shown in Fig. 2. In this paper, the portion that was bent first is called Bend No. 1 and the second is called Bend No. 2. This forming shape was selected for the following two reasons. The first, as previously reported,¹⁰⁾ is that the shape of the hydroforming die is simpler than the single bend shape in previous papers because both axial feeding directions are parallel to each other. The second reason is that deforming state can be observed both near the tube ends where axial feeding is readily effective and between the two bending portions where there it is more difficulty in effectiveness. In the two bent portions, the radius of the bend in the neutral axis was 152 mm, the angle was 42

^{*1}This Paper was Originally Published in Japanese in J. JSTP **60** (2019) 175–181.

^{*2}Corresponding author, E-mail: mizumura.4hb.masaaki@jp.nipponsteel.com

^{*3}Present address: Futtsu Unit, Nippon Steel Technology, Futtsu 293-0011, Japan

^{*4}Present address: Department of Systems Innovation, The University of Tokyo, Tokyo 113-8656, Japan

Table 1 Sizes and mechanical properties of tube.

Outer diameter	Wall thickness	Yield stress	Tensile strength	Total elongation	n value	r value
D_0 /mm	t_0 /mm	σ_y /MPa	σ_B /MPa	ε_{el} /%		
63.5	1.4	175	292	50	0.219	1.63

Fig. 2 Shape of hydroformed part.

degrees and the length between the two bent portions was 247 mm. The cross sections at and between the bent portions were rectangular with a 37% expanding ratio. In this paper, the expanding ratio is defined as the ratio of the elongation length after expanding to the original length in a circumferential direction.

2.3 Bending procedure

We used two bending methods, rotary draw bending and intrusion bending. An outline of each of these methods is shown in Fig. 3.

In rotary draw bending, a tube end is held with a clamping die and bent by rotating the bending die to obtain a bent tube with the same radius as the bending die. There are other tools used for restraint, such as pressure dies, wipers, mandrels and

balls. These restrain the inside and outside of tubes to prevent the formation of defects such as wrinkles and ensure an accurate forming shape. Because of this, this bending method is most commonly used in industrial production. However, flexibility of the shape is limited because it is determined by the die shape.

In intrusion bending, a tube is bent through the movement and rotation of a gyro set in front while pushing the tube from the back. Gyro movement enables several kinds of shapes to be produced, so this method boasts more flexibility in shape than rotary draw bending. However, forming defects such as wrinkles occur more readily and the process is less repeatable because of lack of restraint. Intrusion bending methods are divided into two types by control method and tool conditions. One method was developed by Murata, *et al.*¹⁴⁾ In this type, gyro movement is controlled to advance only the length of tube, and the gyro, set by spherical support according to movement, is rotated automatically. The mandrel is not inserted into the tube. Another method was researched by Naoi, *et al.*¹²⁾ In this type, both the movement and the angle of the gyro are controlled, and the mandrel is inserted into tube. The wall thickness of the tubes used in this paper was thin, which causes flatness and wrinkles to occur more readily, so the latter type (using a mandrel) was selected.

Now, we will discuss the general differences in shape after application of the two bending methods. In rotary draw bending, a constant bending radius is obtained. However, in intrusion bending, the bending radius shape inevitably changes at the beginning and end of gyro movement. An example of intrusion bending conditions and bending shape is shown in Fig. 4. The parallel translation and rotation of the gyro occur simultaneously, but a constant radius cannot be obtained at the beginning and ending of gyro movement. Therefore, it is necessary to determine gyro movement conditions in consideration of transient areas in order to obtain the target bent shape.

The distribution of thickness also differs between the two bending methods. Figure 5 shows the distribution of thickness increase and decrease ratio at the compression and tension sides for a bending radius 3 times the original diameter (3DR) and a 90-degree bending angle made using STKM11A electric resistance welded steel tubes with a 60.5 mm outer diameter and a 2.0 mm thickness.¹⁵⁾ STKM11A is one of Japanese industrial standard (JIS) for carbon steel tubes for machine structural purpose. The increase and decrease ratio is defined as the ratio of change in thickness after bending compared to the original thickness. In intrusion bending, the constant ratio is 3 times the original tube's diameter. From these figures, we can see that the thickness increase ratio at the compression side is almost the

Fig. 3 Schematics of bending method. (a) Rotary draw bending, (b) Intrusion bending.

Fig. 4 Example of intrusion bending conditions and bending shape.

Fig. 5 Distribution of thickness increase and decrease ratios after bending ($\phi 60.5$, t2.0, STKM11A).¹⁵⁾ (a) Rotary draw bending, (b) Intrusion bending.

same as the thickness decrease ratio at the tension side for rotary draw bending. On the other hand, the thickness increase ratio at the compression side is much larger than the

Fig. 6 S-shape made by each bending method to fit hydroforming die. (a) Rotary draw bending, (b) Intrusion bending.

thickness decrease ratio at the tension side for intrusion bending. Because it is bent with compression from the end of the tube, the thickness increases overall. In addition, the thickness increase/decrease ratio is constant in rotary draw bending, but is not in intrusion bending.

Now we will discuss S-shape. The final radius of 152 mm is the hydroformed shape, as shown in Fig. 2, but the radius during the bending process need not be 152 mm. As previously reported,¹⁰⁾ a bending shape that fits the hydroforming die at the compression side is desirable because the tube is pushed by axial feeding during the hydroforming process. As a result of that, the bent shape is set as shown in Fig. 6. In rotary draw bending, the bending radius was 254 mm, which was larger than the radius of the hydroforming shape. Thickness reduction at the thinnest areas could be suppressed by this bending design more than with a bending radius of 152 mm. On the other hand, intrusion bending enabled a larger bending radius through utilization of the aforementioned transient bending range in the beginning and end of the constant bending radius. The constant bending radius could be realistically set at 311 mm. As described above, and from the viewpoint of the bending shape formed before hydroforming, in this study, intrusion bending could suppress thickness reduction more than rotary draw bending due to the ability to set a larger bending radius.

2.4 Hydroforming procedure

S-shape bent tube made by each bending method was set in a hydroforming die with the same cavity shape as that shown in Fig. 2, then hydroformed. In the hydroforming process, internal pressure p and axial feeding from both ends δ are controlled while being subjected to load. This loading path is shown in Fig. 7. First the pressure was increased to the specified pressure with short axial feeding for sealing. Next, axial feeding was performed while maintaining the pressure and stopped at the specified stroke. Finally, only pressure was increased until burst occurred. In this loading path, the holding pressure and final axial stroke are defined as p_H and δ_F , respectively. In general hydroforming paths, the

Fig. 7 Loading path of hydroforming.

pressure is increased during axial feeding.¹⁶⁾ However, we adopted the loading path shown in Fig. 7 because the later discussed hydroforming range in this loading path is expressed by only two parameters, p_H and δ_F .

The reason that the pressure is increased until burst occurs is because the corner R limit and the wrinkle limit can be obtained by seeing if the corner R is less than the target size or if wrinkles have been removed when the tube has been subjected to enough pressure to cause this burst. Additionally, the burst limit is the holding pressure limit during axial feeding and the buckling limit is the limit of excessive thickness at tube ends. Those included, the authors developed 4 kinds of forming limits that are all expressed with holding pressure p_H in the vertical axis and final axial stroke δ_F in the horizontal axis in a previous paper.¹⁷⁾ A typical example is shown in Fig. 8. The area surrounded by the 4 forming limit lines is the hydroforming range, and the hydroforming allowance can be evaluated by comparing area size. Through this method, many comprehensive tests under a matrix of changing conditions are necessary to obtain the 4 forming limits. To simplify this process, the final axial stroke δ_F was fixed at 60 mm, and the burst, corner R and wrinkle limits were obtained at this axial stroke. The range of holding pressure p_H is expressed as 2 arrows (dashed and dotted), as shown in Fig. 8. For the long dashed left arrow with the low pressure corner R limit, the range of the original hydroforming range has expanded to the left. On the other hand, the long dotted arrow with the low wrinkle limit means that the hydroforming area has expanded to the right. The buckling limit was not apparent in these tests, as the tubes

Fig. 8 Hydroforming allowance.

Fig. 9 FEM models of bending and hydroforming.

were a thin 1.4 mm. As described above, we conducted simple evaluation of hydroforming allowance by using the 2 forming ranges of holding pressure p_H obtained by burst limit, corner R limit and wrinkle limit at a 60 mm final axial stroke δ_F .

2.5 Finite element method procedure

We conducted analysis of the results of this experiment using the finite element method (FEM). Dynamic explicit analysis software, PAM-STAMP, was used for this FEM analysis. As shown in Fig. 9, S-shape bent tube with the thickness and strain calculated by analysis of each bending process was inserted in a hydroforming die and analyzed. Shell elements of about 2.5 mm were used. The mechanical properties of the tube were approximated with the Swift formula.

3. Results and Discussions

3.1 Effect on distribution of thickness

The FEM result of thickness distribution after each bending process is shown in Fig. 10. In rotary draw bending, thickness was decreased at the tension side and increased at

Fig. 10 Distributions of wall thickness after bending (FEM). (a) Rotary draw bending, (b) Intrusion bending.

the compression side. However, in intrusion bending, there was almost no decrease in thickness at the tension side and extreme increase at the compression side. In draw bending, S-shape Bends No. 1 and No. 2 were independent of each other, so the thickness distributions were almost the same. On the other hand, in case of intrusion bending, it was expected that Bends No. 1 and No. 2 are dependent upon each other because the tube is bent continuously, but there was no difference in the distribution of thickness. The distance between the guide cylinder and gyro was 25 mm during zero gyro movement and rotation. The distance between Bends No. 1 and No. 2 is 65 mm, as shown in Fig. 6(b), which is longer than the distance between the guide cylinder and gyro. Bends No. 1 and No. 2 are regarded to be considerably independent of each other in this intrusion bending.

Figure 11 shows the results of the experiment and FEM for distribution of thickness strain in the center section of Bend No. 1 after bending and hydroforming. The hydroforming conditions after each bend were different. This will be described in 3.3, but the holding pressure p_H of intrusion bent tube must be higher than that of rotary draw bending. To ensure conditions where the tube does not burst, the holding pressure p_H selected was 15 MPa for rotary draw bending and 18 MPa for intrusion bending. In rotary draw bending, the thickness strain was negative at the tension side, positive at the compression side and these absolute values were almost the same. In intrusion bending, however, the thickness strain was positive at the compression side, but was almost zero at the tension side. These trends and absolute values corresponded well in the results of the experiment and the FEM.

Fig. 11 Circumferential distributions of wall thickness after bending and hydroforming (experiment and FEM). (a) Rotary draw bending, (b) Intrusion bending.

Next, we'll discuss the thickness strain distribution after hydroforming. In rotary draw bending, the thickness strain at the compression side changed from positive to negative, but was almost constant at the tension side from the time of bending. Our previous report¹⁰⁾ mentioned that thickness at the tension side did not decrease due to axial feeding after contact with the hydroforming die, but during the final pressure increase, a gap developed between the tube and die at the compression side due to decreased thickness. On the other hand, the gap did not grow in intrusion bending due to a holding pressure p_H that was higher than in rotary draw bending. As a result, thickness strain did not progress at the compression side, which was comparatively thicker after bending, and negative strain progressed at the intermediate and tension sides. Trends and absolute values for strain at the compression side in the experiment and FEM corresponded, but strain at the tension and the intermediate sides was higher in the experiment and FEM, respectively. It is assumed that these differences are due to the timing of contact with the die influencing strain at the tension and intermediate sides.

3.2 Effect on fracture position

Figure 12 shows the test samples that burst during axial feeding of hydroforming. Burst during axial feeding occurred due to excessive high holding pressure p_H . This occurred in rotary draw bending at 16 MPa or higher and in intrusion bending at 20 MPa or higher. These bursts occurred at the intermediate side in all cases. These results corresponded to cases with 1 bend as mentioned in our previous report.¹⁰⁾ The FEM results in Fig. 13 show that the most extreme decrease in thickness was at the intermediate side during axial feeding no matter the bending case.

Next, we'll discuss the positions where burst occurred during final pressure increase. Some examples are shown in Fig. 14. As indicated in the previous report,¹⁰⁾ burst occurred at the compression side or near the R stop of the compression side because the position at which the gap increased by axial feeding expanded further during final pressure increase. Particularly in rotary draw bending, cases were observed where increased strain on the compression side resulted in burst (Fig. 14(a) below). In all cases of intrusion bending, burst occurred at the R stop near the compression side along

Fig. 12 Examples in which bursts occurred during axial feeding. (a) Rotary draw bending, (b) Intrusion bending.

Fig. 13 FEM results in which bursts occurred during axial feeding. (a) Rotary draw bending, (b) Intrusion bending.

Fig. 15 FEM results in which bursts occurred during final raising of pressure. (a) Rotary draw bending, (b) Intrusion bending.

Fig. 14 Examples in which bursts occurred during final raising of pressure. (a) Rotary draw bending, (b) Intrusion bending.

the area between the two bent parts due to the low progression of strain at the compression side, as described in the section above. This is because the thickness in the straight area is generally less than that at the bent positions. It is estimated that the straight area between the two bent parts was more easily burst because effective axial feeding was more difficult. Figure 15 shows the FEM results for thickness distribution after hydroforming. It is observed that the thickness decreased significantly at the same positions where burst occurred in the experiments.

3.3 Effect on hydroforming allowance

The effect of the bending method on hydroforming allowance was investigated using results above. As

Fig. 16 Hydroforming allowance in rotary draw bending and intrusion bending.

mentioned in 2.4, the authors evaluated the allowance by comparing the length of the two arrows (dashed and dotted) for holding pressure p_H . The dashed arrow means the area from the burst limit to the corner R limit and the dotted arrow means the area from the burst limit to the wrinkle limit under a 60 mm final axial stroke δ_F . The results are shown in Fig. 16. For the burst limit, the pressure was higher in intrusion bending due to relatively higher thickness, so the allowance tended to be larger. For the lower limit, however, the corner R limit pressure was lower in intrusion bending, while the wrinkle limit pressure was lower in rotary draw bending. As mentioned above, the corner R became smaller because intrusion bent thickness enabled load to be withstood until final application of high pressure. However, this was believed to make wrinkles develop more readily during intrusion bending. Generally speaking, this is because of lower die restraint. Sharp wrinkles were not observed in any kind of bending, however small wrinkles grew during the hydroforming process. Figure 17 shows FEM results of deformation in Bend No. 1 at the beginning of axial feeding. From this figure, we can see that wrinkles appeared to develop more easily at the compression side of intrusion bending.

To summarize the findings above, rotary draw bending is advantageous to the wrinkle limit, however the total allowance of intrusion bending is greater. In addition, we found that high internal pressure is necessary for the

Fig. 17 Forming shapes at compression side of 1st bending under the conditions of 15 MPa holding pressure and 20 mm axial feeding (FEM). (a) Rotary draw bending, (b) Intrusion bending.

hydroforming loading path in intrusion bending. This is because thickness reduction during bending process is suppressed in intrusion bending.

4. Conclusion

In order to investigate the effect of bending method on hydroforming in subsequent processes, S-shape tubes were hydroformed with the same die after application of two kinds of bending methods, rotary draw bending and intrusion bending. We made the following conclusion from the results of experiments and FEM.

- (1) Regarding distribution of wall thickness after hydroforming, wall thickness of the tube is thinnest on the compression side for rotary draw bending and on the tension or intermediate sides for intrusion bending.
- (2) Regarding burst position, burst occurs at the intermediate side during axial feeding no matter the bending method. In rotary draw bending, burst occurs at the compression side or at the nearby R stop, however, in

intrusion bending, burst does not occur at the compression side, but occurs at the nearby R stop during the final increase of internal pressure.

- (3) Intrusion bending results in a larger hydroforming allowance than rotary draw bending. In addition, higher internal pressure is necessary for intrusion bent tube. This is because the wall thickness after intrusion bending is greater than that after rotary draw bending.

REFERENCES

- 1) R. Takagi: J. JSTP **12**(120) (1971) 59–66.
- 2) S. Fuchizawa: J. JSTP **30**(339) (1989) 473–480.
- 3) M. Hamada: Nikkei Mechanical **539** (1998) 32–46.
- 4) K. Nasu: J. JSTP **46**(531) (2005) 321–325.
- 5) Y. Kuriyama: J. JSTP **45**(524) (2004) 715–720.
- 6) M. Mizumura: J. JSTP **53** (2012) 193–198.
- 7) L.P. Lei, J. Kim and B.S. Kang: Int. J. Mech. Sci. **44** (2002) 1411–1428.
- 8) K. Sato and S. Ito: J. JSTP **44**(515) (2003) 1189–1193.
- 9) K. Ishigaki, N. Sakaguchi, N. Kaneda and M. Kojima: Proc. 61st Jpn. Jt. Conf. Technol. Plast., (2010) pp. 447–448.
- 10) M. Mizumura and Y. Kuriyama: J. JSTP **53** (2012) 225–230.
- 11) S. Fuchizawa, K. Manabe, K. Ichinose, J. Endo, I. Ochiai, N. Takada and M. Nakamura: *Tubefforming*, (Corona Publishing Co., LTD., Tokyo, 1992) pp. 39–40.
- 12) H. Naoi, N. Kitakami, M. Mizumura and Y. Kuriyama: J. Mater. Eng. Perform. **17** (2008) 376–381.
- 13) K. Kishida: Bull. Iron Steel Inst. Jpn. **2**(9) (1997) 679–683.
- 14) M. Murata, S. Yamamoto and H. Suzuki: J. JSTP **35**(398) (1994) 262–267.
- 15) M. Mizumura: Ph.D. thesis, The University of Tokyo, (2006) pp. 99–108.
- 16) S. Fuchizawa, K. Manabe, H. Abe, K. Kato, Y. Kuriyama and H. Hamano: *Tube Hydroforming*, (Morikita Publishing Co., Ltd., Tokyo, 2015) pp. 108–111.
- 17) M. Mizumura and Y. Kuriyama: J. JSTP **44**(508) (2003) 524–529.