

Deformation Mechanism of ERW Tubes in Newly Developed Bending Method “PRB”

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ABSTRACT

For the newly developed tube bending method termed “PRB,” finite element analyses (FEA) with solid elements were carried out to clarify the tube deformation mechanism in comparison with that in conventional rotary draw bending. The following results were obtained.

1. In the investigation of the strain and stress states both outside and inside the bend, it was found that plastic deformation in PRB was almost completed before the tube material entered the bend area. In rotary draw bending, plastic deformation developed in the bend area.
2. Regarding the effect of tube reduction in diameter by the pressure die in deformation of tubes, circumferential compressive deformation involving longitudinal tensile deformation is enhanced outside the bend. Protrusion of the bending die toward the tube facilitates longitudinal compressive deformation inside the bend.
3. In PRB, the tube material inside the bend tends to be compressed along the longitudinal direction in a large area as a result of the protrusion of the bending die toward the tube inside the bend. This eases circumferential compressive stress and reduces wrinkling, even though a mandrel and wiper are not used in PRB.
4. The stress in the thickness direction is not negligible inside the bend for a detailed investigation of deformation behavior.

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INTRODUCTION

Recently, weight reduction and improved strength have become important requirements in the technical field of fabricating automotive structural parts. One method of meeting both requirements simultaneously is application of steel tubes to closed-sectional automotive parts. For this purpose, tube hydroforming (THF) has been the focus of intense attention.

THF, in the narrow sense, has been well known for many years as a technique of bulging metal tubes by hydraulic pressure. The type of THF which is now receiving attention can be understood as a complex technology including pre-forming, such as pre-bending and crushing, prior to the hydroforming step [1]. Hence, tube bending is one very important technology for manufacturing closed-sectional parts, and should be investigated with the aim of improving formability and other features.

In many cases of applying tubes to actual automotive parts, the rotary draw bending is used for the tube bending operation. In the tube bending, a fracture due to thinning outside the bend and wrinkling due to thickening inside the bend are the main problem to be solved. Therefore, many studies were carried out to eliminate these defects such as the studies of bending limit curve [2], bending conditions [3, 4] and new design of tools [5].

PRB is a newly developed tube bending method with slight reduction in tube diameter by Push with a pressure die and use of a Rotation of Bending die [6]. In PRB, a tube is bent while applying compressive force in the circumferential direction with the pressure die, making it possible to bend high strength and/or thin-walled steel tubes in a small radius without a mandrel and wiper, which are often required in conventional rotary draw bending. Because the PRB machine does not use a mandrel and wiper, it is also possible to reduce skilled maintenance work such as die adjustment, which

requires considerable training. This contributes to high productivity.

In the point of view on deformation behavior, PRB can reduce occurrence of wrinkling inside the bend without the mandrel and wiper. PRB can also reduce thinning outside the bend compared with conventional rotary draw bending by the effect of reduction in diameter during bending. However, investigation of the tube bending mechanism in PRB is insufficient. Clarification of the mechanisms will be helpful for the successful of tube bending operations in manufacturing actual automotive.

FEA is useful in investigation of the deformation mechanism and is also widely used for prediction of formability [7]. Especially for the wrinkling elimination, FEA is helpful for the investigation of limiting bending conditions [8]. Usually, shell elements are used for these purposes. However, because shell elements premise the plane stress condition, the effect of the stress in the thickness direction is not clarified. The use of solid elements is necessary to consider the effect of stress in the thickness direction.

In this paper, the mechanisms of the thinning, thickening and wrinkling in PRB are described in comparison with those in rotary draw bending. In this investigation, the effect of stress along the thickness direction was also clarified with solid elements for both PRB and rotary draw bending.

TECHNICAL FEATURES OF “PRB”

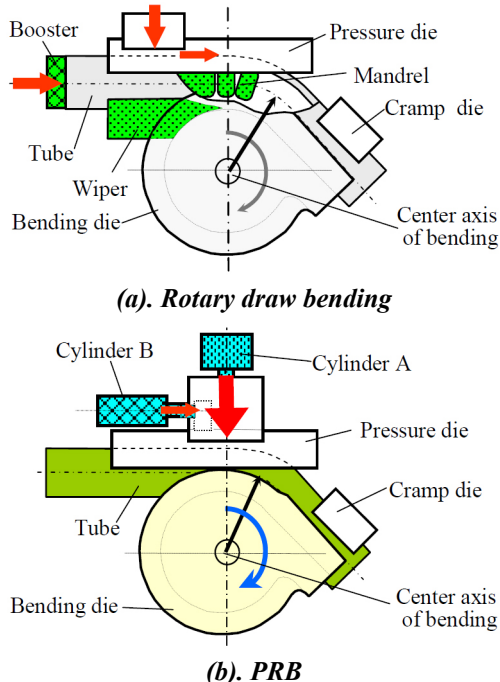


Figure 1. Schematic diagram of rotary draw bending and PRB

Figure 1 (a) and (b) show schematic diagrams of rotary draw bending and PRB, respectively. There are some differences between rotary draw bending and PRB in tool

placement, as shown in Figure 1. In particular, in rotary draw bending, the position of force application with the pressure die is set so as to support bending moment efficiently, whereas, in PRB, it is set on a line which passes through the rotation axis of the bending die and is orthogonal to the tube axis before bending, as shown in Figure 1 (b). This makes it possible to apply a comparatively larger force which can reduce the tube diameter slightly.

Figure 2 shows a schematic diagram of the principle of PRB. First, pressure at a level where the tube is not compressed is applied to the tube through the pressure die before bending.

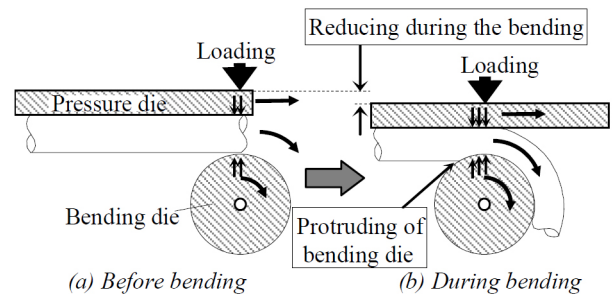


Figure 2. Schematic diagram of bending behavior in PRB

This pressure die applies compressive force to the tube along the circumferential direction so as to reduce the tube diameter and circumferential length. Next, the tube is bent in a way that reduces the circumferential length at the bending portion. In the reduction in circumferential length, the cross-sectional shape of the bent tube is flattening, leading to reduction in the diameter of the tube. This reduction increases tube formability, and the mandrel and wiper which are often required in rotary draw bending can be eliminated.

EXPERIMENTAL AND FEA CONDITIONS

The mechanical properties of the tube used in this study are shown in Table 1. The bending conditions in the experiments and FEA are shown in Table 2. 780MPa class ERW thin walled tubes with a thickness/diameter ratio of about 3.7% were used. In both rotary draw bending and PRB, the bending angle in the experiment was 90° and the bending radius was 140mm.

In rotary draw bending, a 2-ball type mandrel and wiper were used to eliminate wrinkling, but were not used to cause wrinkling. In PRB, the pressure die force was varied to change the result as to whether wrinkling occurred or not. Namely, the limit of the force at wrinkling was investigated.

Figure 3 (a) and (b) show the FEA models for rotary draw bending and PRB, respectively. Table 3 shows the FEA conditions. LS-Dyna ver.971 was used in the study. Solid elements are used for the tube in the FEA. In addition to the solid elements, shell elements are also used and were compared with the solid elements for study of the impact of

stress in the thickness direction. The divisions of the mesh modeling with solid elements in the longitudinal and circumferential directions were set to the same configurations as with the shell elements, which were the same in the previous study by the authors [6]. In this paper, FEA with solid elements are mainly used for the investigation of the deformation mechanism. FEA with shell elements are used for further discussion of the effect of stress in the thickness direction.

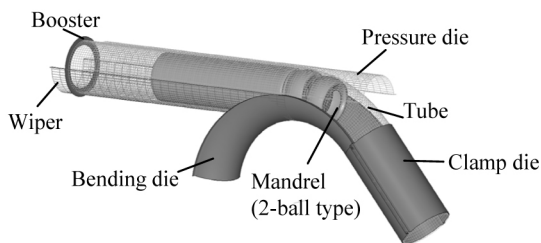
Table 1. Mechanical properties of a tube used in the study

YS (MPa)	TS (MPa)	EL (%)	r - value		
			r_ϕ	r_D	r_θ
757	803	17.0	0.51	1.47	0.67

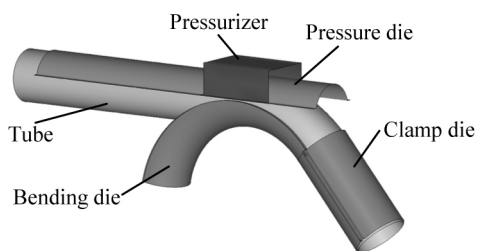
Tube Diameter 70mm, wall thickness 2.6mm, length 600mm

Table 2. Conditions of bending

Common conditions	
Bending angle & radius	90° & R=140mm (R/D=2.0)
Pressure die motion	Synchronized to bending die motion
Conditions for rotary draw bending	
Axial force with booster	98kN
Lubricant	Molybdenum disulfide (for tube-mandrel & wiper)
Mandrel diameter	63.4mm (Clearance 1.4mm)
Condition for PRB	
Pressure die force	78.4 ~ 147kN



(a). Rotary draw bending



(b). PRB

Figure 3. Models of FEA in rotary draw bending and PRB

Table 3. Conditions of FEA

FEM solver	LS-Dyna(Ver.971)
Element type	Solid(8-nodes) and Shell(4-nodes)
Numbers of element division	175 – longitudinal (ϕ) direction: 64 – circumferential (θ) direction 5 – thickness (t) direction : (for Solid)
Number of integration points	Solid: 1 (in one-element) Shell: 7 (Thickness), 1(In-plane)
Friction coefficient	0.06: Tube – mandrel & wiper (for rotary draw bending) 0.10: Others

Figure 4 (a) and (b) show the coordinate systems in the longitudinal and circumferential directions of the bent tube in the study. As shown in Figure 4 (a), the position of the bending end was defined as 0° and the clamping end was defined as 90° in 90° bending. The area before 0° was defined as “no bend area” and the area from 0° to 90° was defined as “bend area.” Therefore, the longitudinal coordinate was defined as a combination of position x in the no bend area and the angle ϕ in the bend area. The directions ϕ , θ and t were denoted as the longitudinal, circumferential, and thickness direction, respectively, in this paper.

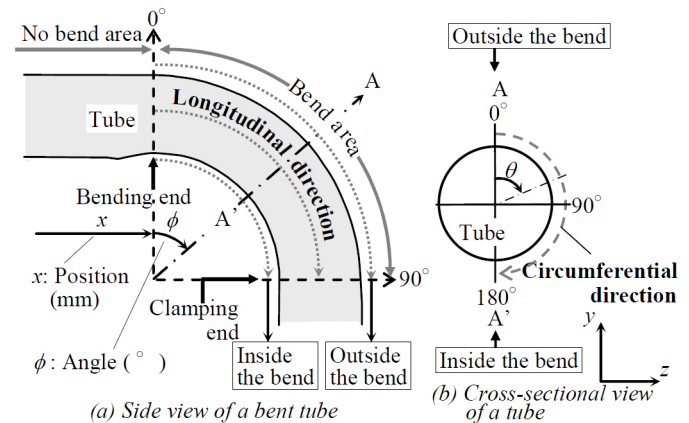


Figure 4. Definition of coordinate systems in longitudinal and circumferential direction of bent tube

EXPERIMENTAL AND FEA RESULTS

For the study of the mechanisms of bending in rotary draw bending and PRB, bending experiments and corresponding FEA were carried out. In the FEA investigations, thinning distributions were examined and compared with the experimental results. The histories of strain in bending were also examined for the investigation of deformation behaviors.

Appearance of Bent Tube

Figure 5 and Figure 6 show comparisons of the appearances of the bent tubes in rotary draw bending and PRB in the experiments and FEA, respectively.