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A new schedule-free mandrel-less bending method for straight/pre-shaped long tubes

Takashi Kuboki [a,*], Kazuhito Takahashi [a], Kazuhiko Ono [b], Kozo Yano [b]

[a] Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, Tokyo, Japan
[b] Komatsu Ltd., Osaka, Japan

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ABSTRACT

The objective is to propose a new schedule-free mandrel-less draw-bending method to achieve high cross-sectional precision for straight and pre-shaped long tube, for which conventional methods lacking innovation are useless. The proposed method applies side compression on the tube. Analyses and experiments verified excellence of the method and the new method successfully reduced the error index of circularity under the severe conditions of conventional methods. The method would bring significant flexibility in manufacturing as the method is able to bend arbitrary portions of tubes and be placed in arbitrary positions of the process line.

1. Introduction

Bent tubes are used as diversified components of structures, machines, liquid and gas delivery systems [1], heat exchange tubings [2] and so on. When bent tubes are used, they need designed bending radius, circularity of cross-section, uniform or designated wall thickness, smooth outer/inner surfaces and total geometrical precision of bent portions.

This paper will present a newly developed bending method and machine that make it possible to bend arbitrary portions of long tubes, not only straight tubes but also pre-shaped or assembled shaped tubes, and obtain high precision of geometrical shape and dimension of the bent portion.

Recent machines and vehicles have been requesting precise and complex-shaped long tubes for realizing their high performance. General conventional bending methods with bending die, including mandrel or booster bending methods, cannot give solutions to the request any more. Insertion of a mandrel inside the tube during bending was once known as a proper method to improve precision [3]. However, the mandrel cannot be used for either pre-shaped or long tubes because of difficulty of insertion and positioning. Booster bending might be an alternative method [4]. However, booster bending also has difficulty, because axial compressive stress leads to wrinkle or buckling. As mandrel and booster bending methods require the tube-end portion to be straight, the flexibility of the process line is strictly limited, resulting in limited variation of the manufactured tube shape. Although a new bending method was developed to respond to these requirements by utilizing overlaid moment by 3 sets of rolls [5], the composition and controlling method are slightly complicated. Therefore, a new process has been desired which realizes cross-sectional precision for straight/pre-shaped long tubes while bending arbitrary portions in flexible order on the process line.

The authors proposed side compression bending (S.C. bending) which applies side compression for a short tube [6]. This paper presents its efficiency for straight/pre-shaped long tubes compared with booster bending, and demonstrates the application concepts to the industry. A series of finite element analyses and laboratory experiments was carried out comparing S.C. bending with booster bending with emphasis on the precision as well as three types of defects: wrinkle, buckling at clamp and buckling at straight part. The results show the excellence of the proposed method in terms of precision and forming limit in addition to significant flexibility for the order of process lines.

2. Bending methods

2.1. Side compression bending

The presented side compression bending (S.C. bending) is shown in Fig. 1. The bending die rotates, while the side compression die pushes the tube into the bending-die groove. The side compression die is composed of upper and lower dies. The upper and lower dies have slopes, which are fit to the slopes on the bending die. When the side compression die is pushed towards the bending die, the upper and lower dies clamp the tube in the vertical direction to shrink the vertical diameter d_v. Side compression δ_C, which is the total displacement of the upper and lower dies, is regulated by the spacer between the dies. Bending radius R_0 is defined at the centre axis of the tube. The tube is clamped at the position L_C, which is set to be equal to bending radius R_0.

* Corresponding author.

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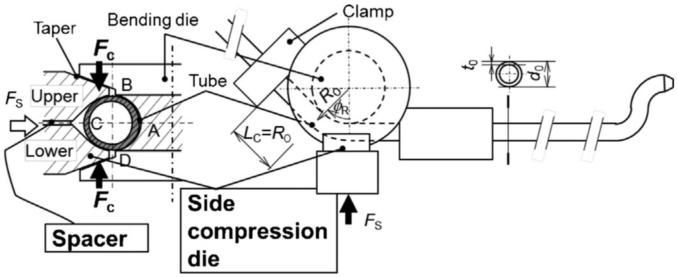

Fig. 1. Side compression bending.

As S.C. bending does not need a straight tube tail, it is applicable for pre-shaped long tubes. An example of a process which uses S.C. bending is shown in Fig. 2. In conventional methods, including mandrel or booster bending, the forming of the tube ends should be conducted after all bending processes, and the series of bending processes should be conducted from the head [H] to the tail [T] in order. On the other hand, S.C. bending is able to bend tubes in an arbitrary order, and even modify tube-bend shape after total assembly as seen in Fig. 2(e). The processing of tube ends or other parts is able to be placed at arbitrary positions of the process line, at the beginning of the line for example. As a result, S.C. bending gives flexibility to process design that would realize the most suitable, intelligent and the most productive manufacturing.

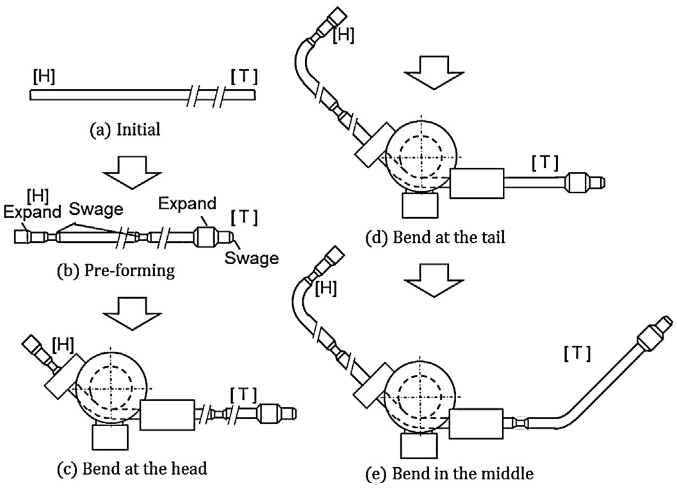

Fig. 2. Application of S.C. bending in process line. (a) Initial, (b) pre-forming, (c) bend at the head, (d) bend at the tail, and (e) bend in the middle.

An experimental example of tube cross sections obtained by S.C. bending is shown in Fig. 3. When side compression δ_C was 0 mm, the tube wall of extrados [C] moved towards the centre of the tube and extrados [B–C–D] flattened. The error index of circularity was evaluated by flatness, defined by the following equation:

$$D_F = \frac{d_v - d_H}{d_0} \quad (1)$$

where d_v and d_h are diameters in vertical and horizontal directions, respectively.

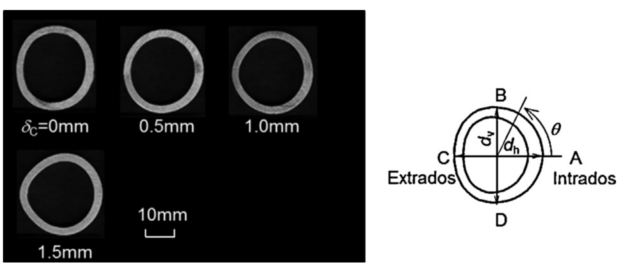

Fig. 3. Effect of side compression bending on circularity (5056 aluminium alloy, thickness t_0 = 3.2 mm, radius ratio R_0/d_0 = 3).

The vertical diameter d_v decreased with increase of side compression δ_C. As the peripheral length was not affected by δ_C, the horizontal diameter d_h expanded, resulting in improvement of circularity. Excessive δ_C led to over-expansion of d_v at δ_C = 1.5 mm.

2.2. Booster bending

The efficiency of S.C bending was compared to booster bending, which is one of the conventional methods and is schematically shown in Fig. 4. The axial compressive stress σ_a should be imposed for improvement of circularity of the tube. However, axial compressive stress often causes defects as shown in Fig. 5. Wrinkle generally tends to occur at the intrados when bending radius is small. Axial compressive stress would increase this tendency. When the axial compressive stress is too large, buckling phenomena would be observed at [P] and [Q] as shown in Fig. 5(b). The excessive axial compressive stress would cause buckling at clamp [P], followed by secondary buckling at [Q]. Furthermore, if the tube is long, buckling would occur at the straight part as shown in Fig. 5(c).

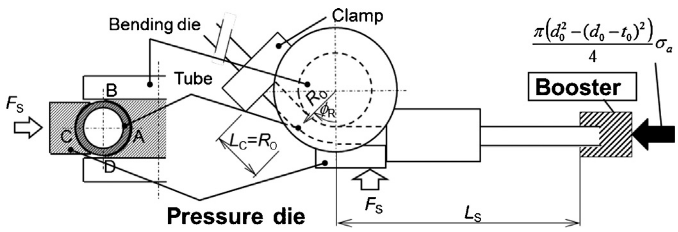

Fig. 4. Booster bending.

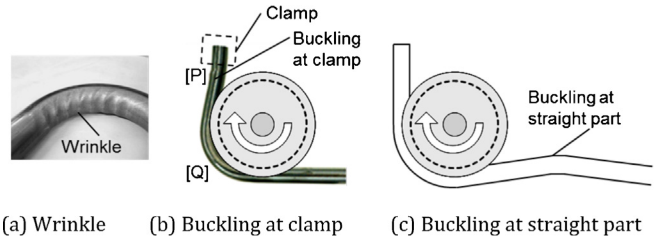

Fig. 5. Defect in booster bending. (a) Wrinkle, (b) buckling at clamp, and (c) buckling at straight part.

On the other hand, S.C. bending does not need any axial compressive stress, which causes or propels defects. In order to verify the excellence of S.C. bending a series of analyses and experiments were carried out. Table 1 shows the details of tubes for bending and Table 2 shows bending condition. Carbon steel for general structural purposes STK 490 (JIS) was used.

Table 1
Specimen for tube bending.

Material		Medium carbon steel STK490 (JIS)
	Tensile strength σ_B/MPa	490
	Hardening exponent n	0.15
	Yield stress σ_y/MPa	327
Dimension	Outer diameter d_0/mm	27.2
	Thickness t_0/mm	2.0–3.2

Table 2
Bending conditions.

Common	Bending radius R_0/mm	1.5 d_0–3.0 d_0
	Rotate angle ϕ_R/mm	90
	Pressure force F_S/kN	30 in experiment Pressure die position was fixed in FEM
Side compression bending	Side compressive displacement δ_c/mm	0–2.0
Booster bending	Axial compressive ratio σ_a/σ_B	0–40%