INTERNAL MAGNETIC ABRASIVE FINISHING FOR
AUSTENITIC STAINLESS STEEL TUBES BENT
USING HIGH FREQUENCY INDUCTION BENDING

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Abstract

This paper examines the applicability of magnetic abrasive finishing to the internal finishing of large–sized bent tubes produced by high frequency induction bending. Finishing equipment was developed for large–sized bent tubes. The finishing experiments using austenitic stainless steel tubes bent by both cold–drawing and high frequency induction bending demonstrate the finishing characteristics and reveal the differences in the finishing mechanism between the two types of elbows. The elbow made by cold–drawing required only one finishing process to achieve a 0.03 µm Ra surface. In contrast, high frequency bent elbow, which is covered with an oxide film, required two–stage finishing using two different sizes of ferrous particles for a smoothly finished surface, 0.05~0.13 µm Ra.

Keywords: Internal finishing, Magnetic abrasive finishing, Austenitic stainless steel bent tube, Finishing characteristics, High frequency induction bending, Two stage finishing

1. Introduction

High frequency induction bending is a hot bending process for pipes and shaped steels using high frequency induction heating. The process has the advantage of three–dimensional flexibility in bend radius and angle within the limits of the bending machine. Complex–shaped tubes, which consist of both bent and straight sections, produced by high frequency induction bending, are used for piping systems to minimize the number of welded joints, thereby reducing the production and installation costs and improving the quality of the piping system. The tubes are required to have smoothly finished inner surfaces to prevent the contamination of gas and liquid. However, the complexity of the tube shapes and the oxide film generated on the tube surface during high frequency bending considerably increase the difficulty of internal finishing of the tubes with conventional technologies.

An internal magnetic abrasive finishing process was proposed for producing precisely finished inner surfaces of nonferromagnetic tubes used for piping systems [1]. This paper examines the applicability of the magnetic abrasive finishing to the internal finishing of large–sized bent tubes produced by high frequency induction bending. Finishing equipment was developed for large–sized bent tubes, and the performance of the equipment was examined through finishing experiments using SUS316 and SUS304 austenitic stainless steel elbows made by both cold–drawing and high frequency induction bending. They demonstrate the finishing characteristics, including surface roughness and material removal, and reveal the differences in the finishing mechanism between the two types of elbows.

Fig. 1 External photograph of experimental setup
2. Processing principle and experimental setup

The poles, which consist of small permanent magnets, placed outside the bent tube generate the magnetic field needed for attracting the magnetic abrasive to the finishing area by magnetic force. When the poles rotate around the bent tube, the magnetic abrasive, driven by magnetic force, rotates along the inner surface of the bent tube along with the poles, and removes material from the surface. Manipulating the rotating poles along the tube axis causes the magnetic abrasive to follow the poles' motion, finishing the entire inner surface of the tube [2].

Previous research developed the finishing equipment and demonstrated the process applicability to nearly uniform internal finishing of SUS304 stainless steel tubes bent by a cold-drawing process (16~21 mm outer diameter, 30~80 mm radius of curvature) [2]. Finishing equipment for large-sized bent tubes, shown in Figure 1, was developed based on the previous equipment. The robot has 6 axes of motion to accommodate tubes of various configurations, and the finishing unit is connected to the arm of the robot.

3. Finishing Characteristics

3.1 Cold-drawing processed elbows

Before the internal finishing of the tube processed by high frequency induction bending, the performance of the equipment was examined through the internal finishing of cold-drawn elbows. Table 1 shows the experimental conditions. A mixture of ferrous particles and WA magnetic abrasive was introduced with lubricant into the elbow at the beginning, and lubricant was supplied into the mixture at every stroke of the finishing unit. It took 5 min for one stroke. The magnetic field measured at the finishing area is shown in Fig. 2, the intensity of which was more than 20% greater than in the case of the previous equipment.

Figure 3 shows the changes in surface roughness at outside, inside, lateral (upper), and lateral (lower) regions and material removal with finishing time. Both the lateral regions show almost same value. The surface was uniformly finished; which is also shown in Fig. 4. This demonstrated both the process applicability to the large-sized elbow and the efficiency of the equipment.

3.2 High frequency induction processed straight tubes

The process applicability to bent tubes made by hot bending and specifically large-sized tubes remained unknown to this point. To reveal the fundamental finishing characteristics, finishing experiments were initiated with straight tubes.
processed by high frequency induction processing (Ø89.1×Ø83.1×400 mm). Figure 5 shows SEM microscopy and oxygen distribution by EPMA of the cross section of the tube. The oxide film, about 3 µm thick, is obvious on the inner surface, and needs to be removed in order to obtain smooth surface.

Figures 6 and 7 show the experimental results with 330, 510, and 1680 µm in mean particle diameter. The conditions with 330 µm iron particles are the same as those for the cold–drawn tube, shown in Fig. 3; this produced the least material removal of the three conditions. According to Fig. 7 (a), the relatively longer wavelength components of the roughness profiles remain on the surface after the finishing process. This resulted from the accumulation of the small cutting operations sustained by a small finishing force. The magnetic force acting on the ferrous particles, controlling the finishing force of the magnetic abrasive, is a function of the particle volume. This resulted in greater material removal in the cases of 510 and 1680 µm iron particles than in the case of 330 µm iron particles. Deep cutting marks resulted from the greater finishing force are observed on the finished surfaces in Fig. 7 (b) and (c). However, these conditions were inappropriate to obtain a smoothly finished surface. Accordingly, two stage finishing was proposed to the tube finishing with a combination of larger iron particles for coarse finishing in the first stage and smaller iron particles for fine finishing in the second stage.

Figure 8 shows the finishing characteristics by two stage finishing with 1680 µm iron particles for the first 40 min and 330 µm for the final 80 min. While the first stage shows similar characteristics to those in Fig. 6, the material removal dropped in the second stage and resulted in the fine surface finish, 0.04 µm Ra. This demonstrates the feasibility of two stage finishing for internal finishing of elbows made by high frequency bending and covered with an oxide film.

3.3 High frequency induction processed elbows

Figure 9 shows the changes in surface roughness and material removal with finishing time for an elbow finished by the two stage finishing with 1680 and 330 µm iron particles.

[Conditions] Workpiece: SUS304 stainless steel tube: Ø89.1×Ø83.1×400 mm, Electrolytic iron particles (330, 510, 1680µm in mean dia.): 56 g, Pole-pole distance: 93.4 mm, other conditions: see Table 1.
The unevenness of the finished surface is seen in the first stage, outside: 6.49 to 4.70 µm $Ra$, inside: 10.2 to 6.06 µm $Ra$, lateral (upper): 8.22 to 3.74 µm $Ra$, and lateral (lower): 9.21 to 4.42 µm $Ra$. After the second stage, the surface regions were finished to 0.13, 0.11, 0.05, and 0.05 µm $Ra$, respectively. Although there remains some surface quality unevenness, this study proves the process applicability to internal finishing for not only fine finishing but also coarse finishing for a wide variety of complex–shaped tubes made by high frequency induction bending.

4. Conclusions
While obtaining uniformly smooth finished surfaces in cold–drawn elbows, the same finishing conditions scarcely removed the oxide film generated by high frequency induction bending. This resulted in the necessity for different finishing conditions to remove the work–hardened layer including an oxide film and primary material. Greater magnetic force acting on the magnetic abrasive was required to remove the work–hardened layer than that for merely removing primary material, and this force was controlled by the size of the ferrous particles mixed with the magnetic abrasive. Accordingly, two stage finishing using two sizes of ferrous particles achieved the fine finish for elbows made by high frequency bending.

Acknowledgement
The authors would like to express their gratitude to Mr. Takato Koshi of Sumikin Stainless Steel Tube Co., Ltd. for his support.

References