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Dimensional accuracy of tubes in cold pilgering

Hideaki Abe*, Tetsuya Iwamoto, Yoshiaki Yamamoto, Satoru Nishida, Ryosuke Komatsu

ZircoProducts Co., Ltd., 1-13 Chofu Minatomachi, Shimonoseki 752-0953, Japan

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ABSTRACT

The effects of process conditions on the dimensional accuracy of tubes in cold pilgering were studied. The dimensions included the ovalities of the outer and inner diameters and the eccentricity ratio of the wall thickness. The permissible variations of the dimensions on the objective tubes were of 10 μm order. The process conditions included the feed rate (1.0, 1.5, 2.0, and 2.5 mm/stroke), stroke speed (140, 180, and 200 strokes/min), and turn angle (40, 60, and 80°). The materials tested were type 316L stainless steel and the zirconium alloy Zircaloy-4. The dimensions of the tubes were measured by ultrasonic and laser equipment, and the characteristics of the tubes were determined, such as their hardness, tensile properties, residual stress, and crystallographic texture. The dimensions of the tubes being subjected to cold pilgering were continuously measured by ultrasonic equipment. Strong effects of the feed rate and turn angle on the ovality were observed; the ovality increased with the feed rate. The increase in ovality was thought to be caused by springback. The mechanism underlying the increase in ovality with the feed rate is described by considering the inhomogeneous springback after releasing the tubes from the constraint of the tools. The effect of the turn angle on the ovality was proved to be related to the asymmetric deformation of the tube from the numerical analysis results of cold pilgering. The effect of the springback on the ovality was confirmed by the measurement results for the residual stress. The eccentricity ratio of the wall thickness was unaffected by the process conditions; it was mainly determined by the eccentricity ratio of the mother tube. The eccentricity ratio of 316L tubes decreased after cold pilgering, whereas that of Zircaloy-4 tubes increased. The change in the eccentricity ratio was explained by a self-centering mechanism based on the combined effect of the roll dies and mandrel, and the eccentricity ratio of Zircaloy-4 tubes was proved to be related to the mechanical anisotropy owing to their crystallographic texture. These findings are expected to assist the selection of manufacturing conditions for tubes with close tolerance.

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1. Introduction

In general, high-quality seamless tubes, such as those made of stainless steel, titanium alloys, and zirconium alloys, are manufactured by cold working followed by a heat treatment. Cold pilgering is a common cold working process for such tubes. Stinnertz (1988) reported that it is widely applied to tube manufacturing. The tubes usually require good mechanical properties, high surface quality, and close dimensional tolerance. For the zirconium alloy tubes used for nuclear reactor fuel cladding and the titanium alloy tubes used for aircraft hydraulic lines, the permissible variations in the outer and inner diameters and wall thickness are of 10 μm order. It is critical for tube manufacturers to select appropriate fabrication conditions to meet the dimensional requirements. The objective of the present study is to investigate the effects of process conditions on the dimensional accuracy of tubes subjected to cold pilgering, including the feed rate, stroke speed, and turn angle.

Fig. 1 shows a schematic view of the cold pilgering process. The tools used consist of a pair of roll dies and a mandrel. The roll die has a decreasing caliber from the inlet to the outlet. In the working zone, the caliber and the mandrel diameter are changing, whereas in the sizing zone they are almost constant to obtain dimensional precision. The roll dies are rotated and simultaneously reciprocated, and the rate of reduction of the outer diameter depends on the caliber. The mandrel, which is stationary inside the tube, has a tapered shape in the rolling direction. The diameters and wall thickness of the tube are reduced with increasing number of rolling steps, and the tube is axially elongated. In each rolling step, the mother tube is advanced and rotated in the idle zone at a preset feed rate and turn angle, respectively. A large cross-sectional reduction of more than 70% is possible in cold pilgering.

* Corresponding author. Fax: +81 83 246 8921.
E-mail addresses: abe-hide@jcom.home.ne.jp (H. Abe), iwamoto@zpc.co.jp (T. Iwamoto).

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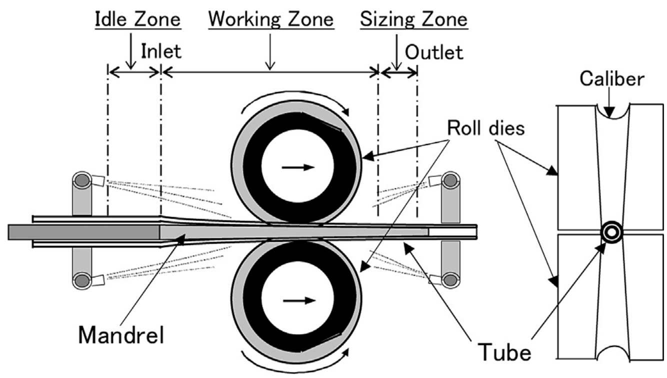

Fig. 1. Cold pilgering process.

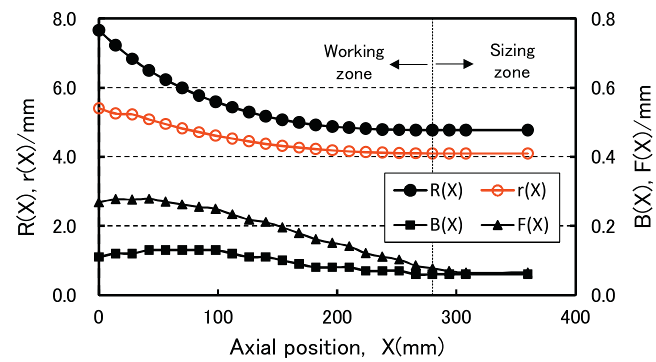

Fig. 3. Design dimensions of tools.

The working zone in the tool design is illustrated in Fig. 2(a) and the roll die caliber and mandrel diameter are shown in Fig. 2(b). The caliber is described by three basic parameters, R(x), B(x), and F(x), at axial position x, which are the radius of the groove, the offset, and the side relief, respectively. The mandrel diameter $r(x)$ and groove radius $R(x)$ generally follow power-law functions. The tool design is well known to significantly affect the quality of the finished tubes, such as the surface quality, dimensional variations, and microstructures.

To investigate the surface quality of tubes, Bembenek et al. (1981) conducted cold working tests on austenitic stainless-steel tubes and quantitatively discussed inner fissure formation. Montmitonnet et al. (1992) reported a theoretical study of the lubrication state on the inner surface of zirconium alloy tubes in cold pilgering. Abe and Furugen (2010) reported the cold workability of zirconium alloy tubes. Also, Abe et al. (2014) reported a new method of evaluating the lubrication state of tubes.

In contrast, few studies on the dimensional accuracy of tubes in cold pilgering have been reported. Randall and Prieur (1967) discussed the effects of the side relief on the dimensional accuracy of finished tubes. The tool design, particularly the side relief, has been thought to be critical for dimensional accuracy. However, in actual operation, tube manufactures have struggled to achieve the process conditions required for high dimensional accuracy. In the present study, the effects of the process conditions on the dimensions of finished tubes in cold pilgering are systematically studied. Cold pilgering tests are performed on stainless-steel and zirconium alloy tubes under a variety of process conditions. The mechanism underlying the dimensional changes in the tubes during cold pilgering is discussed on the basis of the test results together with characterization results for the materials.

2. Experimental

2.1. Materials

The materials tested were type 316L austenitic stainless steel and the zirconium alloy Zircaloy-4 (Zry4). Table 1gives their chemical compositions and mechanical properties. The mother tubes used in the cold pilgering tests were 14.6 mm in outer diameter (*OD*) and 1.65 mm in wall thickness (*WT*), and were fabricated by hot extrusion followed by cold working and heat treatment three times. The final heat treatment was annealing at 1100 °C for 1 min in a bright furnace for the 316L tubes and recrystallization at 650 °C for 2 h in a vacuum furnace for the Zry4 tubes.

2.2. Cold pilgering pass schedule and caliber design

Table 2 gives the parameters of the cold pilger mill used in the present study. The mill has the ability to set variable values for the feed rate, stroke speed, and turn angle. The caliber design of the roll dies and the diameter of the mandrel in the present study, which are described by standard power-law functions, are shown in Fig. 3. The actual dimensional deviations were less than 10 and 5 μm for the roll-die caliber and mandrel ovality, respectively.

2.3. Test conditions

Table 3 gives the conditions of the cold pilgering tests. The mother tubes were 14.6 mm in *OD* and 1.65 mm in *WT*, and the finished tubes were 9.53 mm in *OD* and 0.66 mm in *WT*. The reduction in area was 73% and the elongation rate was 3.6. The feed rate was set to 1.0, 1.5, 2.0, or 2.5 mm. The stroke speed, which is the reciprocation speed of the roll dies, was set to 140, 180, or 200 strokes/min (spm). The turn angle was set to 40, 60, or 80°. The standard conditions for the feed rate, stroke speed, and turn angle were 1.5 mm, 180 spm, and 80°, respectively.

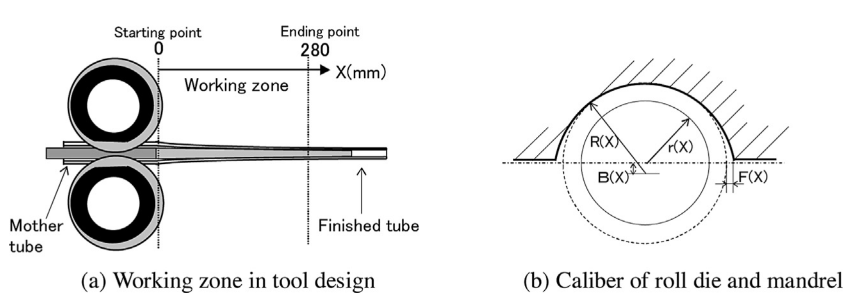

Fig. 2. Tool design in cold pilgering (a) working zone in tool design, (b) caliber of roll die and mandrel.

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