

Development of semi-dieless metal bellows forming process

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ABSTRACT

A novel semi-dieless metal bellows forming process with local induction heating and axial compression without using any conventional dies is proposed. Firstly, the thickening of a tube is induced by local heating and axial compressive force. Secondly, the buckling of the tube occurs, producing a convoluted shape. The seamless tubes used are stainless steel SUS304 with an outer diameter of 5 mm and a thickness of 0.5 mm and 0.3 mm. The effects of compression ratio on the profiles of the bellows such as convolution height, pitch and thickness are investigated experimentally. It is found that convolution height can be controlled by compression ratio. Additionally, the mechanism of this process for fabrication of the metal bellows can be clarified by loading curve during processing. Furthermore, the validity of a two-step compression technique for improving convolution height and pitch is verified. The fundamental of the proposed technique can be confirmed as a basic key processing to fabricating metal bellows with various dimensions and small quantities.

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1. Introduction

Metal bellows are a structural component in which a wavy bellows shape is formed on the surface of circular tubes to induce an elastic property. The metal bellows can be utilized to join tubes to sheets and tubes to tubes. In addition, the metal bellows can absorb the expansion and shrinkage caused by heating and cooling, as well as mechanical vibrations, because of their elastic and airtight properties (Becht, 2000). They are mainly used as piping in air-conditioning equipment, industrial plant equipment, and vacuum systems, and as components of transportation systems such as automobiles, ships, and airplanes. Recently, the demand for metal bellows to be used in medical equipment and small sensors has been increasing (Shapiro et al., 2011). Thus, it is expected that various shapes of metal bellows will be required in the future. However, dies and tools are generally used in the current metal bellows forming methods, such as hydroforming (Kang et al., 2007), combination process of bulging and upsetting (Teramae et al., 2000), and gas bulging at elevated temperature (Faraji et al., 2009). However, complex shape of dies outside tube is required in these processes to form the metal bellows shape. In addition, press working and laser welding process (Lee et al., 2000) and roll type incremental forming (Koyama and Aoyagi, 2008) for manufacturing metal bellows also need dies and tools. Therefore, the shape of the formed metal

bellows largely depends on the shape of dies, and is limited in terms of degree of freedom. In recent years, the demand for metal bellows made of processing-resistant materials, such as titanium alloys and magnesium alloys, has also been increasing. Therefore, the above metal bellows forming methods are not appropriate for forming metal bellows with a high degree of freedom in terms of shape and material.

We have focused on dieless drawing, which is a type of dieless forming and can be used to miniaturize tubes to a predetermined shape by local heating and the induction of tensile deformation without using dies, and examined the fabrication of metal microtubes (Furushima and Manabe, 2007), effective temperature distribution (Furushima et al., 2009), high-speed forming (Furushima et al., 2010a), and shape control (Furushima et al., 2010b). Through these examinations, we have demonstrated a high degree of freedom of dieless forming.

The purpose of this study is to develop a new semi-dieless metal bellows forming process involving local heating and the induction of axial compressive deformation, instead of tensile deformation in the dieless drawing. Concretely, we examined the conditions for forming a bellows shape on tubes using two stainless-steel SUS304 tubes with an initial outer diameter D_0 of 5 mm and initial thicknesses t_0 of 0.3 and 0.5 mm, and verified the validity of our method. In addition, the effects of the forming conditions on the convolution height and convolution pitch were examined to establish a method of controlling the bellows shape without using dies. Furthermore, a Vickers hardness test of the formed metal bellows was carried out to evaluate their mechanical properties. Finally, we propose a

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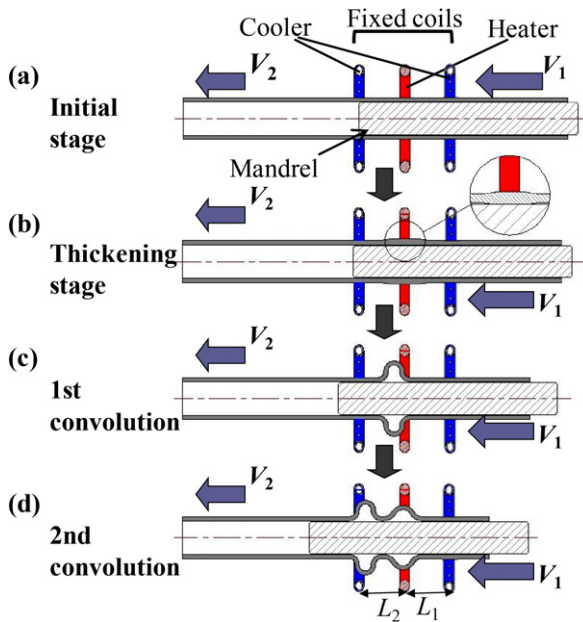


Fig. 1. Schematic illustration of principle of semi-dieless metal bellows forming process (a) initial stage (b) thickening stage (c) 1st convolution (d) 2nd convolution.

method for further increasing the convolution height on the basis of the results obtained in this study.

2. Principle of semi-dieless metal bellows forming process

In this study, buckling that occurs in metal tubes upon the application of axial compression is used to shape bellows by dieless metal bellows forming. In general, various types of buckling deformations, including both axisymmetric and non-axisymmetric buckling deformations, occur in metal tubes upon the application of axial compression (Bardi and Kyriakides, 2006). It is generally difficult to control the area where the buckling occurs, as well as the buckling mode, by inducing the compression deformation alone. Alves and Martins (2012a, 2012b) controlled non-axisymmetric buckling with internal mandrel and tools outside tube in order to produce inclined and out-of-plane metal bellows in tubes. However, the tools depended on target buckling shape were required in their processes. In this study, we developed a method of generating a difference in flow stress between the heated and cooled areas by locally heating the metal tube to induce buckling at the locally heated area with low flow stress without using any tools outside tube. A schematic illustration of the principle of our method is shown in Fig. 1. The metal tube is moved through the local heating region where a heating induction coil is placed while the tube is subjected to compressive deformation to form a bellows shape by continuously inducing buckling. Concretely, one end of the metal tube is moved with compression velocity V_1 and the other end is moved with feeding velocity V_2 . V_1 is set higher than V_2 to induce compressive deformation of the moving metal tube. When buckling occurs at the locally heated area, followed by the already formed convoluted part moving to the cooling region, the deformation at this area stops. Then, another part enters the local heating region and the next buckling occurs in the local heating region. This process enables the generation of continuous buckling through compression and simple continuous movement of the metal tube to form metal bellows. A mandrel was inserted into the metal tube to obtain a uniform compression force and to ensure that metal bellows are steadily form outward because without a mandrel there is a high risk of having both inward and outward material flow. We use the term “semi-dieless” metal bellows forming, instead of

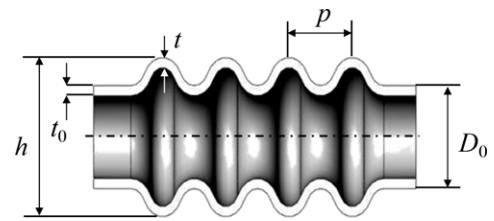


Fig. 2. Metal bellows geometry.

“full-dieless” metal bellows forming, because we used mandrels in this study. After the formation, the mandrel was removed to obtain metal bellows. The ratio of V_1 to V_2 is defined as the compression ratio

$$C = \frac{V_1}{V_2} \quad (1)$$

where $V_1 > V_2$.

In this study, the effects of C on the convolution height, h , convolution pitch, p , and thickness of the tube, t , were determined to clarify the principle of this method (Fig. 2).

3. Metal tubes and experimental method

Two types of seamless stainless-steel SUS304 tubes used for typical metal bellows, were used in this study. Their initial tube dimensions were D_0 of 5 mm, and t_0 of 0.5 (tensile strength = 629 MPa) and 0.3 mm (tensile strength = 620 MPa).

Fig. 3 shows a schematic illustration of the developed experimental apparatus for semi-dieless metal bellows forming. Axial compression was applied to the moving tube by applying V_1 to one end and V_2 to the other end of the tube using actuators driven by servomotors. It was possible to control V_1 and V_2 independently. A high-frequency induction heating device with an output power of 2 kW and a frequency of 2.2 MHz was used as a heating source and the heating induction coil was fixed at an output transformer. The temperature of the local heating region was measured using a thermocouple in a preliminary experiment and was subsequently set at 1150 °C. A water cooling coils were placed on both sides of the heating coil to realize local cooling. The distance between the water cooler and the heating coil was $L_1 = 8$ mm on the compression-velocity side and $L_2 = 10$ mm on the feeding-velocity side. In the experiment, V_2 was fixed at 0.3 mm/s and V_1 was varied to examine the effects of C on h , p , and t . After the forming process, the mandrel was removed using a tensile test machine.

A Vickers hardness test of the cross section of the formed metal bellows was carried out to evaluate its mechanical properties.

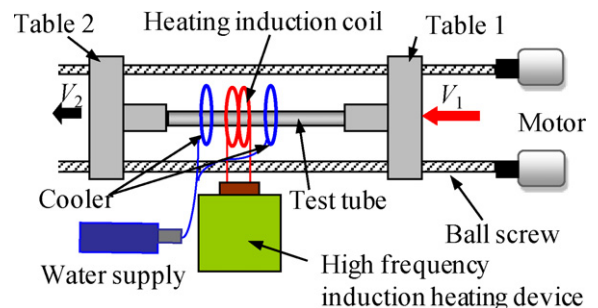


Fig. 3. Schematic illustration of experimental apparatus for semi-dieless metal bellows forming process.

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