Experimental Investigation of Maximum Achievable Convolution Height of Metallic Bellows in Hydroforming Process

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Abstract: The manufacturing of metal bellows with high ratios of crown-to-root diameters is very sensitive to design parameters such as internal pressure inside the tube, axial force and movement, die-stroke length (distance of the dies) as well as the initial tube length. In this paper, hydroforming process of a metallic bellows is investigated experimentally. For this purpose, the effects of internal pressure and die stroke on the maximum achievable convolution height and thickness distribution of hydroformed bellows is studied. The experiments are performed with different internal pressures such as 90, 110 and 130 bars and also in different die strokes such as 10, 12 and 14 mm. The results show that by increasing the die stroke, the range of allowable internal pressure to produce a metallic bellows without wrinkling or bursting decreases and manufacturing of the bellows becomes more difficult. It is extracted from results that with holding the die stroke value, very low internal pressures lead to wrinkling in the hydroformed bellows while very high internal pressures cause the excessive thinning. Also, it is concluded that by increasing both internal pressure and die stroke, the convolution height of manufactured bellows is increased. It is proved that the maximum thickness reduction is occurred at the crown point of hydroformed bellows.

Keywords: Convolution height, Hydroforming process, Metallic bellows

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1 INTRODUCTION

Tube hydroforming is a manufacturing process that consists of placing a tube into a die and pressurizing the tube with fluid until it conforms to the shape of the die cavity. Tube hydroforming offers several advantages over conventional die -stamping processes, which include weight reduction, fewer secondary operations, and improved structural strength and stiffness. Major applications of tube hydroforming can be found in the automotive, home appliance, plant pipe installations, and aircraft industries as well as in the manufacturing of structural components. Bellows are commonly used in piping systems to absorb expansion and mechanical movement. The bellows geometry is an axial symmetric shell, which consists of a thin-walled shell of revolution with a corrugated meridian in order to provide the flexibility needed to absorb mechanical movement. Bellows have widespread application in industrial and chemical plants, power systems, heat exchangers and automotive vehicle parts. The standard material for the circular type metal bellows used in the high temperature and corrosive environment is austenitic stainless steel, that is, AISI 304 and 316.

In addition, other special Nickel based alloy material, Inconel, Incoloy, Monel and Hasteloy, can be applied on the servicing of aggressive fluid. Basically, austenitic stainless steel is resistant to both high temperature and an aggressive media. It has good mechanical properties as well when it comes to the effect of continuous motion in axial, lateral and angular direction. The extent of expansion depends on the temperature difference, the expansion coefficient and the length of the pipe. In recent decades many researches have been performed on tube hydroforming process. In 2017, Je et al. [1] proposed a new manufacturing technology of micro hydroforming using 355 nm ultraviolet (UV)-pulsed laser. The laser was irradiated under water in order to reduce the thermal effects. Their results showed that the proposed method could provide high selectivity, excellent hydroforming efficiency and lower cost to achieve micro grooving pattern on the surface of thin metal sheets in comparison with conventional processing technology.

In 2017, kim et al. [2] developed a multi-scale simulation model of tube hydroforming process for superconducting radio frequency cavities. In order to reduce the computing time, a crystal plasticity model (developed and implemented into ABAQUS using UMAT) was used for determining the flow stress curve under bi-axial loading. In 2015, Hajializadeh and Mashhadi [3] presented a finite element analysis of impulsive hydroforming for sheets and tubes using an explicit scheme. The interaction between the fluid and the shell elements was approximated through the use of the surface based acoustic-structural interaction. In 2014, Ziaei Poor et al. [4] investigated forming of square cups in hydro-Mechanical deep drawing process numerically and FEM results were compared with experimental measurements. Effects of two parameters including punch corner radius and the clearance between punch and die on thickness distribution were studied. The results showed that the fabrication of a cup with uniform thickness distribution by using an optimum pressure profile and with a suitable clearance between die-punch was achievable.

In 2013, Bihamta et al. [5] proposed an approach in which a three-part die was used instead of one with two-halves to produce complex tubes by hydroforming process. The results showed that complex tubes could be manufactured with developed idea while without this idea it was not possible. Also, quality and uniformity in the thickness of hydroformed tube was increased using the proposed die set. In 2012, Li et al. [6] proposed a novel experimental approach to evaluate the formability of tube hydroforming under biaxial stretching through elliptical bulging. Also, based on the deformation theory and the classical Hosford yield criterion, they constructed an analytical model for the elliptical bulging of tube hydroforming. In 2009, Xu et al. [7] studied the effects of friction coefficient, strain-hardening exponent, and anisotropic coefficient on thickness distribution of the tube in a square cross-sectional die by analytical, numerical, and experimental methods. They reported that the increment of friction coefficient increases tube thickness variation, and as a result, the uniformity of the part is reduced.

In 2005, Hwang and Chen [8] examined the corner filling in a square cross-sectional die by analytical, numerical, and experimental methods. They concluded that a higher pressure was required to fill the die corner in case the corner radius was decreased, and doing so would increase the internal pressure to a critical value, so it would cause the tube to be torn. In 2003, Kridli et al. [9] have studied the effects of some materials and die parameters on corner filling and wall thickness distribution of the hydroformed parts. It has been concluded that wall thickness distribution was a function of die corner radius and strain-hardening behavior of material. It has been also stated that the thickness distribution could be reduced if a larger die corner radius was utilized. The literature on fatigue bellows is extensive and fewer papers address the hydroforming process of bellows. In 2006, Wang et al. [10] have developed a new process for manufacturing of expansion joint bellows from Ti–6Al–4V alloys with high degree of spring back. In 2002, Lee [11] has carried out a parametric study on some of the forming process parameters of the metal bellows by finite element method. He has mentioned that, in general, metal bellows are manufactured in four stages: deep drawing, ironing, tube-bulging and folding.

It is concluded from literature review that in spite of many researches that have been reported on tube hydroforming process, there are reported few researches on tube hydroforming of bellows due to complexity. Hence, in this paper a comprehensive study on hydroforming process of metallic bellows is being done. Several parameters affect the process, including tube diameter, tube thickness, die stroke (distance between annular plates), feeding and internal pressure. For a particular bellows tube, diameter and thickness cannot be changed so the latter three parameters can be studied. These parameters have an effect on crown diameter, length of the bellows after spring back and thickness distribution, which determine the quality of the product. In this paper the effects of internal pressure and also die stroke on the thickness distribution and crown height of the hydroformed bellows are investigated experimentally.

2 MATERIALS AND METHODS

The material of the bellows for the current study is chosen as AISI 304 austenitic stainless steel. The chemical composition of AISI 304 is given in the "Table1". The initial thickness of AISI 304 tube is 0.6 mm and its diameter is 51mm.

Table 1 Chemical composition of AISI 304 tube

Component	C	Cr	Ni	Mn	P	Si	S	Fe
Weight (%)	0.08	18-20	8-10.5	2	0.045	1	0.03	66-74

For manufacturing a metallic bellows, the proposed hydroforming process in this paper consists of two steps such as tube-bulging and tube folding. For the tube-bulging step, equally spaced circular plate dies surround the wall of the preform and the internal fluid pressure increases until a specified value is reached. At the contact positions between the preform and the plate dies, the preform is constrained and deformation does not occur at these positions. The tube bulges in the regions between the plate dies, creating several small bulges. During the folding step, an axial force is applied along the longitudinal direction of the bulged tube, while maintaining an internal fluid pressure, in order to complete the final shape of the metallic bellows. These two forming steps are critically important, because the quality of the metallic bellows is strongly influenced by the soundness of these processes. In Fig. 1, various steps of hydroforming process in order to manufacture a bellows from an initial cylindrical tube is shown. Also, in "Fig. 2", the die components installed on a hydraulic press unit are shown.

Fig. 1 Various steps of hydroforming process in order to manufacture a bellows from an initial cylindrical tube (From left to right of picture)

As it was mentioned in the previous section, the tube thickness, tube diameter, die stroke (distance between annular plates), internal pressure, axial displacement and material are the most crucial parameters in the tube hydroforming process. Since in this study a particular bellows is considered, tube thickness and diameter are not taken into consideration as design parameters. However, the effects of internal pressure and die stroke on thickness distribution and crown diameter of hydroformed metallic bellows are studied. "Table 2", shows the design parameters and the values for internal pressure and die stroke.

Fig. 2 The die components installed on a hydraulic press unit

Table 2 Parameters in manufacturing of metallic bellows

Internal pressure (Bar)	Die stroke (mm)
90	10
110	12
130	14

3 RESULTS AND DISCUSSION

"Table 3" shows that by increasing the die stroke, the range of allowable internal pressure to form a metallic bellows without wrinkling or bursting decreases. Therefore, a lower limit of internal pressure, which is determined by wrinkling, increases, and the upper limit of internal pressure, which is determined by bursting, decreases, and manufacturing of the bellows becomes more difficult.

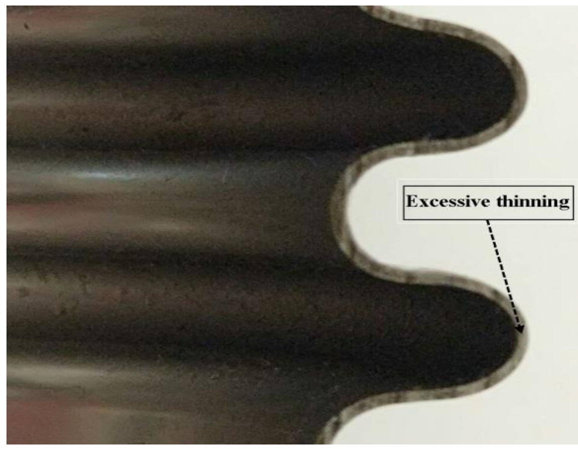
Table 3 Experimental results for different die strokes and pressures

Pressure (bar)	50	90	110	150
Die stroke = 10 mm	Wrinkling	Good quality	Good quality	Excessive thinning (0.30 mm)
Die stroke = 16 mm	Wrinkling	Wrinkling	Good quality	Excessive thinning (0.24 mm)

In "Fig. 3", some of manufactured bellows with wrinkling, good quality and also excessive thinning conditions are shown. It should be noted that in this paper, the criterion for excessive thinning is the thickness reduction of tube more than 50% of initial thickness.

a

b



c

Fig. 3 Some of manufactured bellows with different conditions: (a): Wrinkling, (b): Good quality and (c): Excessive thinning

Also, in "Fig. 4", a path has been defined in a schematic view of a bellows shape. A similar path as same as defined path in "Fig. 4" is considered in order to measure thickness distribution of a hydroformed metallic bellows.

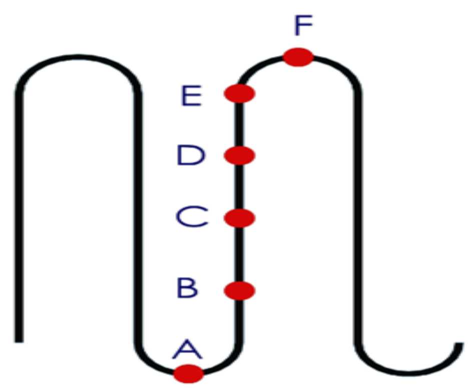


Fig. 4 A defined path for measuring thickness distribution of a hydroformed metallic bellows

In "Fig. 5", the thickness distribution along a path (presented in "Fig. 4") is shown. As it is shown in "Fig. 5", the thickness decreases at the crown point and increases at the inner point of a metallic bellows after hydroforming process.

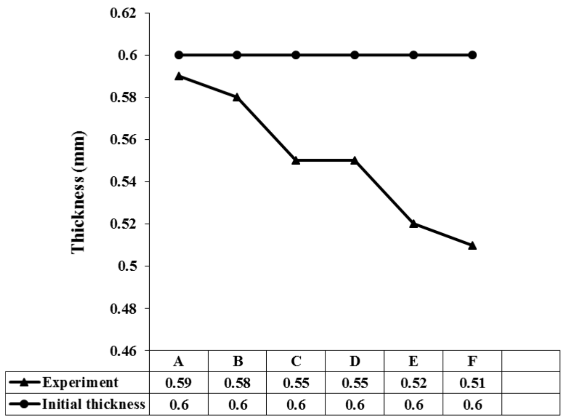


Fig. 5 The thickness distribution along a path (presented in "Fig. 4")

In "Fig. 6", the effects of internal pressure and die stroke on the convolution height of hydroformed metallic bellows are shown. As it is seen in this figure, with increasing in both internal pressure and die stroke, the convolution height is increased due to more material flow in the hydroforming process. It should be noted that in the results of "Fig. 6", the sample point F (that was shown in "Fig. 4") has been selected for measuring the convolution height.

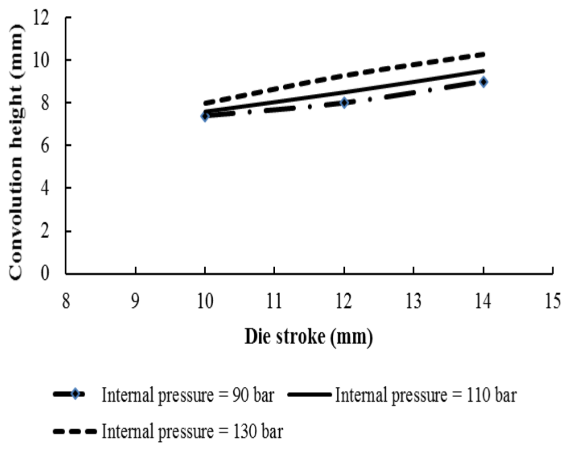


Fig. 6 Effects of internal pressure and die stroke on the convolution height

4 CONCLUSION

In this paper, hydroforming process of a metallic bellows was investigated experimentally. For this purpose, the effects of internal pressure and die stroke on the convolution height and thickness distribution were studied. The material of the bellows for the current study was chosen as AISI 304 austenitic stainless steel. The initial thickness of AISI 304 tube was 0.6 mm and its diameter was 51mm. The results showed that by increasing the die stroke, the range of allowable internal pressure to form a metallic bellows without wrinkling or bursting was decreased. Also, it was concluded that with increasing in both internal pressure and die stroke, the convolution height of metallic bellows was increased due to more material flow in the hydroforming process. It was proved that the maximum thickness reduction is occurred at the crown point of hydroformed bellows.

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