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ORIGINAL ARTICLE

Extending the forming of thin-walled metal circular rings with corrugated meridians to a process without axial compression

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Abstract In order to avoid the highly complex process sequences and the potential instable metal flow in the manufacture of thin-walled metal circular rings with corrugated meridians, a forming method without use of axial compression on blank end is developed specially. A highly viscous polymer, i.e., the viscous medium, is utilized as pressure carrying medium in the proposed method. Since the lack of axial feeding leads to the insufficient metal flow into the die cavity, which finally causes severe wall thickness thinning, the tangential adhesive stress at blank/medium interface is used to promote metal flow. The limit of diameter variation of thin-walled metal circular rings produced by employing different types of viscous medium is predicted by finite element analysis (FEA) and resulting strain-based FLD. The numerical results show that employing viscous medium with proper strain rate sensitive exponent (m) will be feasible to extend the limit of diameter variation. Based on the evaluation on the achievable diameter variation in compression forming and expansion forming, a multistep forming process was presented. Accordingly, nickel-based superalloy parts with one and two convolutions were manufactured successfully. The end displacement of ring-shaped blank is considerable and the resulting wall thickness reduction is relatively small (9 %), which demonstrates the metal flow is promoted effectively. The proposed forming method is considered to be simple and convenient for the fabrication of ring-shaped parts with extremely thin wall and complex shapes.

Keywords Thin-walled metal circular rings · FLD · Viscous medium · Nickel-based superalloy

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1 Introduction

Thin-walled tubular parts meet with the increasing requirements of lightweight components in industrial systems nowadays, thus have widespread applications in plant equipments, vacuum systems, aerospace industry, and so forth. Conventionally, the tube hydroforming (THF) process is adopted to produce these parts. The principle of this process is summarized by Koc and Altan as follows: high-pressure liquid is introduced into the inner side of tubular blank enclosed by a tool and axial compressive load is applied on tube ends simultaneously, then tubes are formed [1].

Forming methods based on this principle has been extensively investigated. Lee studied the forming parameters, such as wall thickness of tubular blank, internal pressure, and die stroke, in the metal bellows hydroforming process numerically [2]. On the basis of Lee's investigation, Faraji et al. produced CuSn6 thin-walled metal bellows by THF process and discussed the effects of internal pressure, die stroke length, and initial tube length on the forming process [3, 4]. They stated

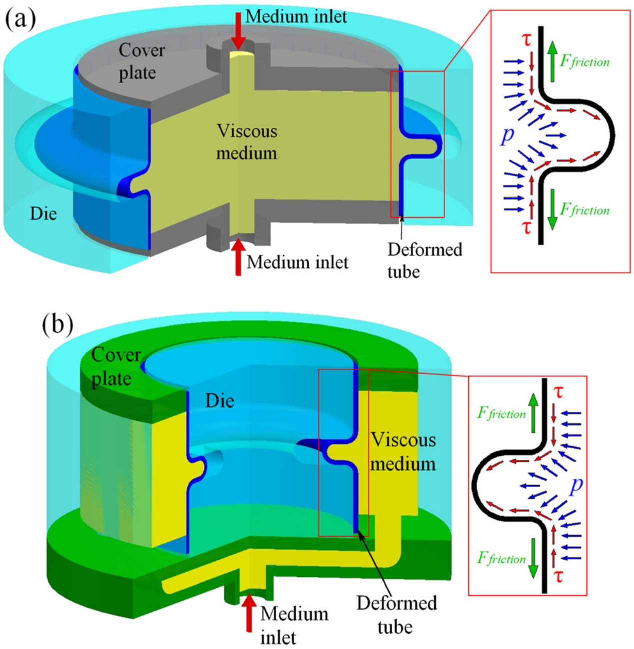


Fig. 1 Principle of viscous pressure forming process for tubular parts: **a** expansion forming and **b** compression forming

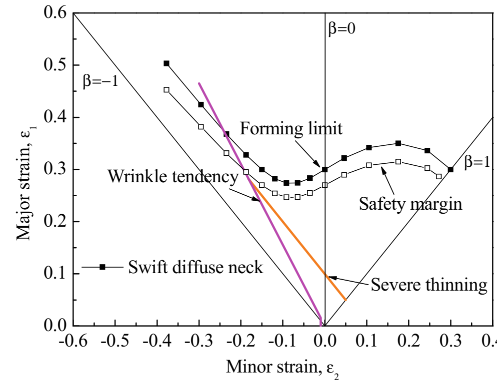


Fig. 3 Analytical models in FLD

that increasing the axial feeding, die stroke, and internal pressure all leads to excessive thinning and the allowable variation range of design parameters is relatively small. Bakhshi-Jooybari et al. studied the effect of pressure path on forming SS316L bellows [5]. They presented a comprehensive forming window for bellows to predict the occurrence of bursting or wrinkling defects. Besides, a single-step tube hydroforming process is proposed by Kang et al. to make tubular bellows with simultaneous control of internal pressure and axial feeding [6]. Similarly, Wang et al. developed a superplastic forming method of applying gas pressure and axial compressive load at elevated temperature to form bellows expansion joints [7].

However, abovementioned processes involve highly complex process sequences with lots of material parameters, geometry parameters, and process parameters [8]. For a certain product, process parameters, which consist of the loading path of internal pressure and axial force, the amount of axial feeding and lateral expansion, and so forth, show more significance. Since axial compressive load probably causes wrinkle [9], the accurate control of hydraulic pressure and axial compressive load is necessary to restrain the inward material flow

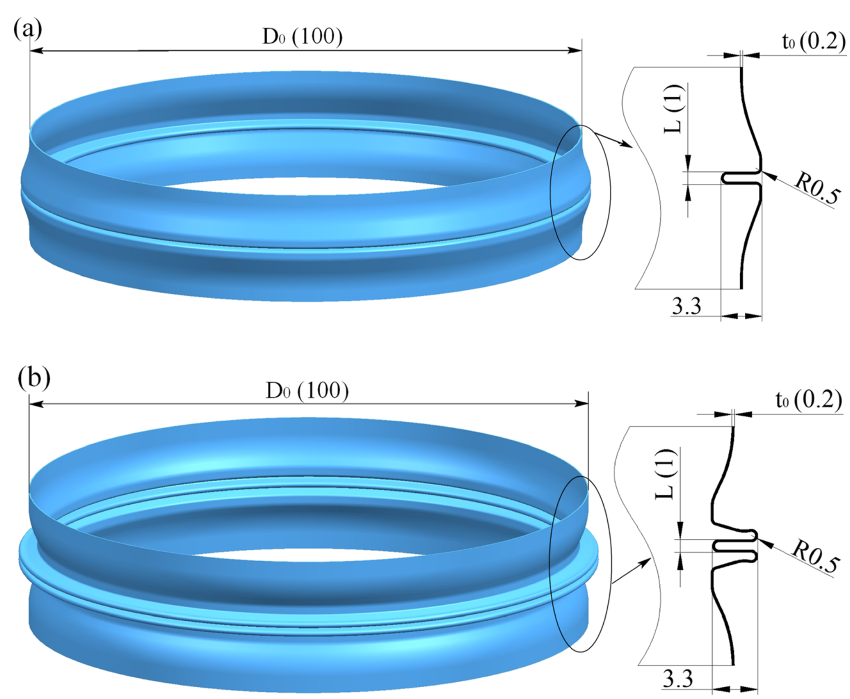


Fig. 2 Typical thin-walled circular rings with corrugated meridians: **a** type 1 and **b** type 2 (unit: mm)

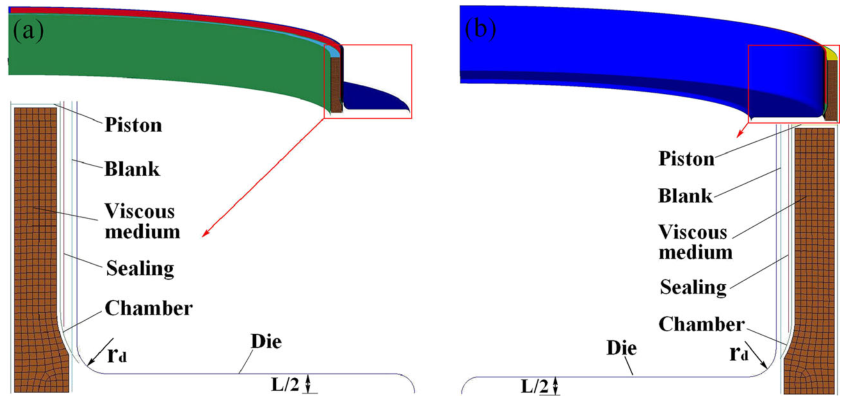


Fig. 4 Finite element models: **a** expansion forming for circular ring and **b** compression forming for circular ring

of tubular blank. Thus, there is a risk of failing of the forming processes due to the incorrectly adjusted process parameters [10]. Besides, for tubular parts with extremely thin wall or large diameters (i.e., ring-shaped parts), it is not easy to impose well-proportioned axial load on the tube ends. That is to say, in order to facilitate the fabrication of specific tubular parts and avoid failures in forming procedures, forming processes without use of axial compressive load will be advantageous. However, if no axial compressive load is applied, severe thinning or even fractures may occur due to the unstable metal flow of tubular blank [6]. Therefore, only if the wall thickness reduction is restrained, the forming process without use of axial compressive load will be feasible to make sound tubular parts.

The role of axial compression is to push tube material into the die cavity. In the case that axial compression is removed, some substitutional methods should be found out to promote metal flow and to prevent excessive wall thickness reduction. A forming method employing viscous medium as pressure-carrying medium will be a promising choice. To be specific, viscous medium, a flowable semi-solid polymer with high viscosity [11], is introduced into the inner side of tubular blank and is pushed by piston to raise the forming pressure. Material of tubular blank is forced into the die cavity under the combined action of normal pressure and tangential adhesive stress as illustrated in Fig. 1a (p and τ respectively refer to the normal pressure and tangential adhesive stress). The high viscosity of viscous medium results in tangential adhesive force, which assists the metal flow of tubular blank. Thus, excessive thinning is probably avoided. It is the main characteristic of this forming method to be distinguished with others. Similarly, the expansion forming process is extended to compression forming as illustrated in Fig. 1b. The tangential adhesive force has been testified by Niehoff et al. [12] through introducing viscous fluid which flows in the opposite direction of tensile direction in uniaxial tensile test. Then, the wall thickness reduction in the middle region of tensile specimens decreases, which is due to the action of tangential adhesive force. Besides that, since viscous medium has good fluidity and filling ability, the viscous pressure forming (VPF) process employing viscous medium as pressure-carrying medium is suitable to produce parts with regional surface of small radius of curvature [13].

The adhesive attraction at tube/medium interface directly influences the metal flow in the condition that no axial compressive load is applied. However, it is rarely investigated that to what degree the tangential adhesive force influence the metal flow and the limit of diameter variation in the forming of tubular parts. For the forming of thin-walled tubular parts with complex shape, it is essential to get clear inspection to these issues so that the process is designed reasonably to avoid the unstable metal flow which probably leads to process failures.

The purpose of this paper is to develop a simple forming process of thin-walled circular rings with complex shapes, in which the axial compression is not involved. Therefore, the limit of diameter variation of thin-walled circular rings in the proposed process was evaluated and appropriate approaches were found out to extend the forming range of thin-walled metal circular rings. Concretely, the strain-based FLD was employed to predict the limit of diameter variation at first. The effect of mechanical properties of viscous medium, especially the strain rate sensitive exponents, on the limit of diameter variation was examined. Then, a two-step forming process was proposed to form thin-walled circular rings with one convolution. Forming experiments of nickel-based superalloy parts were conducted to examine the validity of the proposed method. Finally, thin-walled circular rings with two convolutions were formed on the basis of the results obtained in this work.

Table 1 Parameters in FEA

Initial blank diameter, D_0 (mm)		100
Initial wall thickness, t_0 (mm)		0.2
1/2 of axial distance of the die cavity, $L/2$ (mm)		0.5
Die radius, r_d (mm)		1.0
Coulomb friction coefficient	Blank/viscous medium interface, μ	0.2 [19]
	Blank/die interface, μ_s	0.05

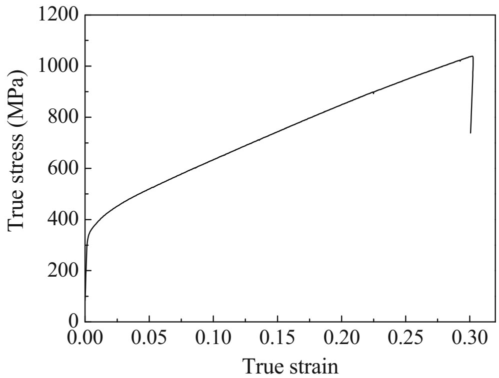


Fig. 5 True stress versus strain curve of GH4169 sheet

2 Analytical models

Figure 2 shows two types of thin-walled circular rings with corrugated meridians. They are characterized by thin wall (t_0=0.2 mm), large diameter-thickness ratio (D_0/t_0=500), and large diameter variation per unit axial length ($\Delta D/L$=6.6). Material of initial ring-shaped blank is GH4169, which has similar nominal composition and mechanical properties as Inconel 718 in US [14]. To achieve a diameter variation of 6.6 mm in 1-mm axial length without excessive thinning of wall thickness is the main difficulty in the fabrication. Since fractures probably occur when metal blank fills into the die cavity with narrow axial distance.

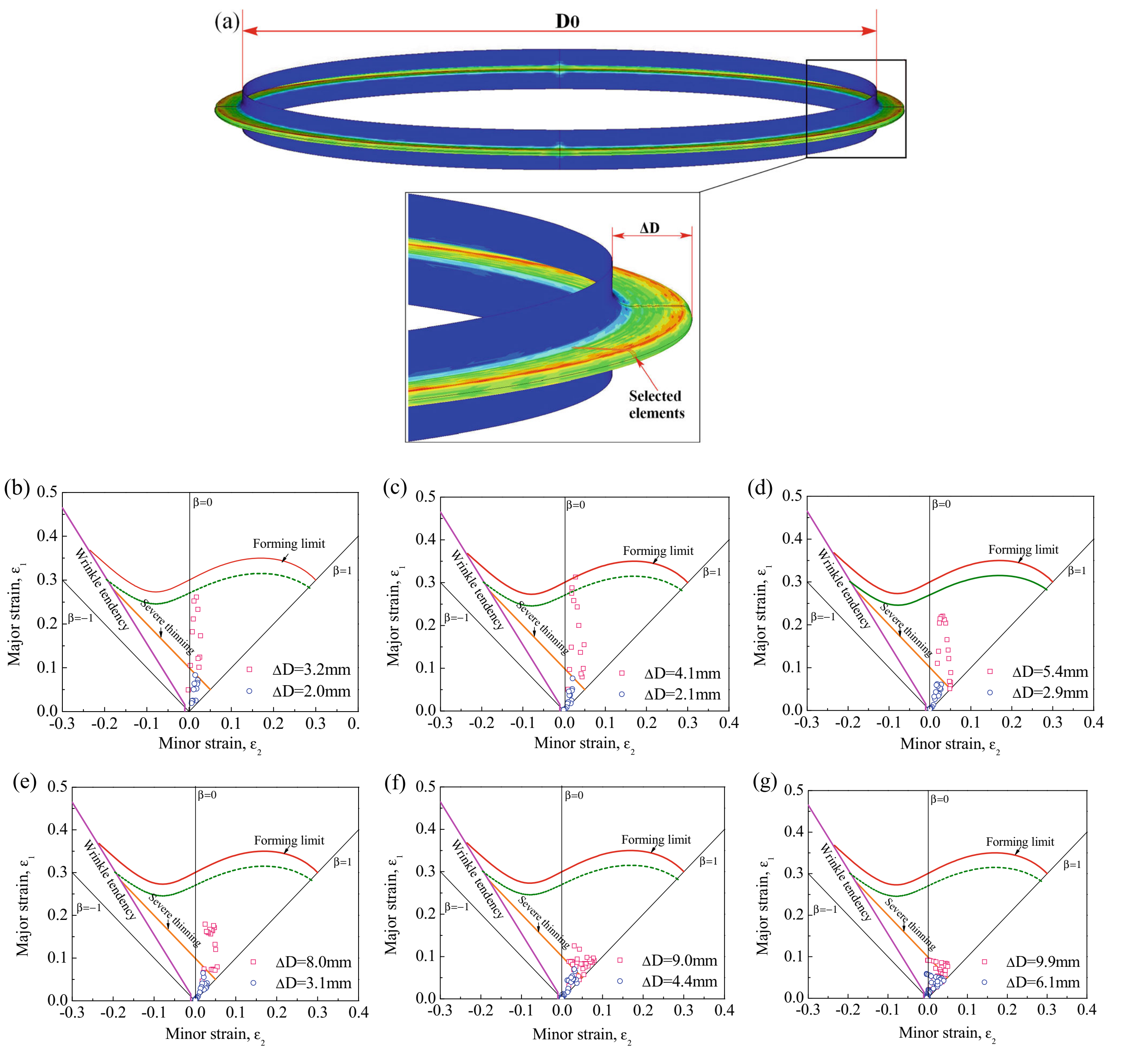


Fig. 6 Forming limit curves corresponding to different strain rate sensitive exponents in expansion forming: **a** simulated contour, **b** m=0.5, **c** m=0.4, **d** m=0.3, **e** m=0.25, **f** m=0.2, and **g** m=0.1

In order to deal with abovementioned problems, the forming limit of thin-walled circular rings should be evaluated at first. Conventionally, the strain-based forming limit diagram (FLD) is used as an empirical estimation of forming limit. Here, the forming limit refers to a state without necking and fracture and is a natural characteristic of metal regardless of forming processes or shapes of parts. To describe the initial necking of sheet metal in FLD, some analytical models were proposed, such as the diffuse neck (Swift, 1952), through-thickness neck on the left-hand side of FLD (Hill, 1952), and through-thickness neck on the right-hand side of FLD (Storen and Rice, 1975). The proportional loading is assumed and the constitutive relationship of materials is combined to define a locus of points in strain space, namely the forming limit [15]. Based on analytical models, Song et al. evaluated the forming limit of bulged tubes in THF process [16]. They derived the forming limit of rolled-formed tube based on Swift's diffuse necking criteria, Hill's local necking criteria, and tube bulge test results. Faraji et al. used FLD and FLSD based on the well-known M-K model to predict the initiation of necking in metal bellows forming processes [17]. Results from FEA and experiments show good agreement. In general,

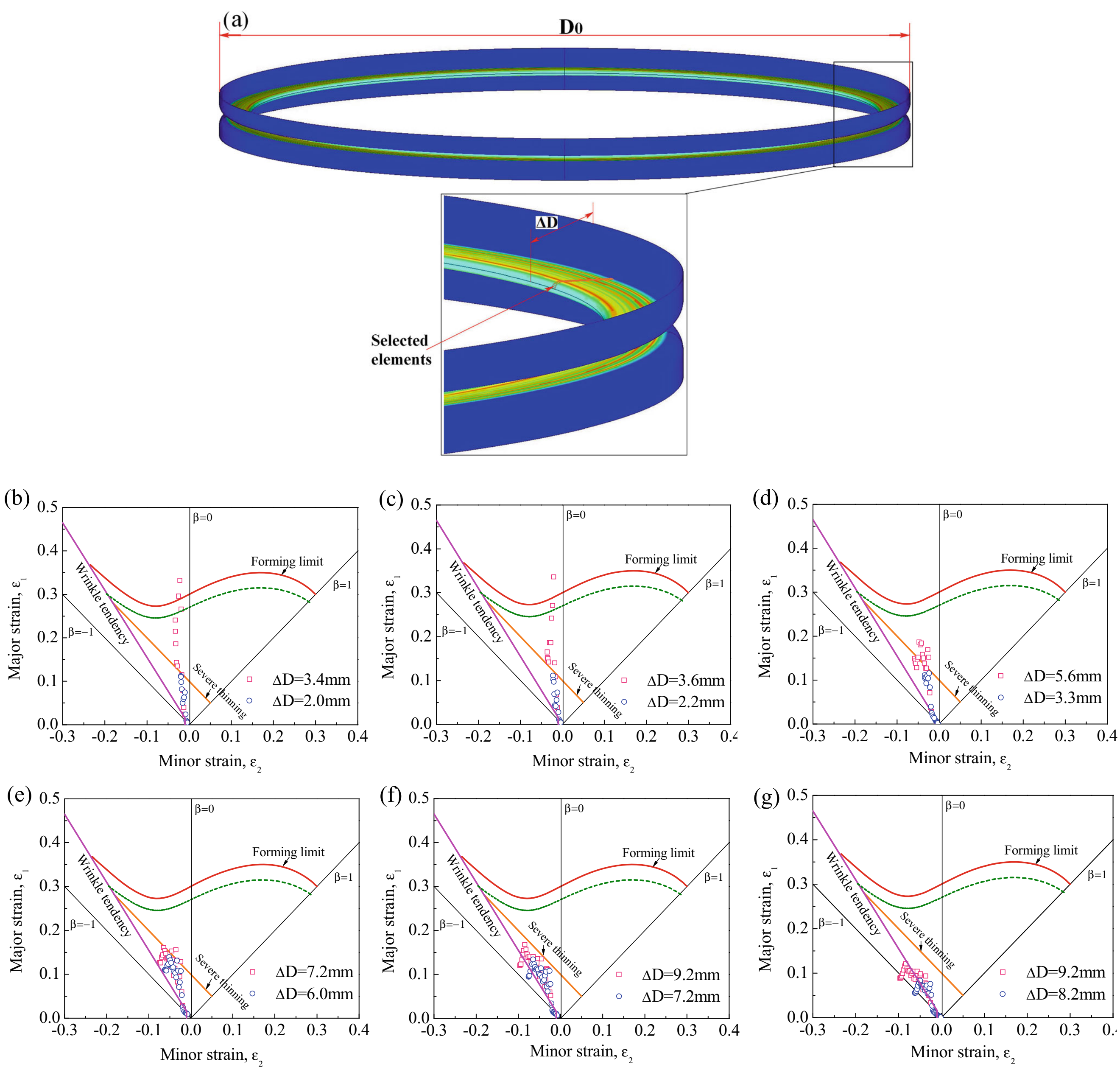


Fig. 7 Forming limit curves corresponding to different strain rate sensitive exponents in compression forming: **a** simulated contour, **b** m=0.5, **c** m=0.4, **d** m=0.3, **e** m=0.25, **f** m=0.2 and **g** m=0.1

the analytical approaches such as Swift's diffuse necking criteria provide simple and useful guidelines for the avoidance of failure within conventional industrial purpose [18].

Thus, Swift's diffuse neck model was applied to predict the forming limit of thin-walled circular rings in this work. Swift indicates that a diffuse neck is satisfied when the load reaches a maximum along both principle directions. Based on the assumption of proportional loading, Eq. (1) was used to define the instability for a Von Mises material [15].

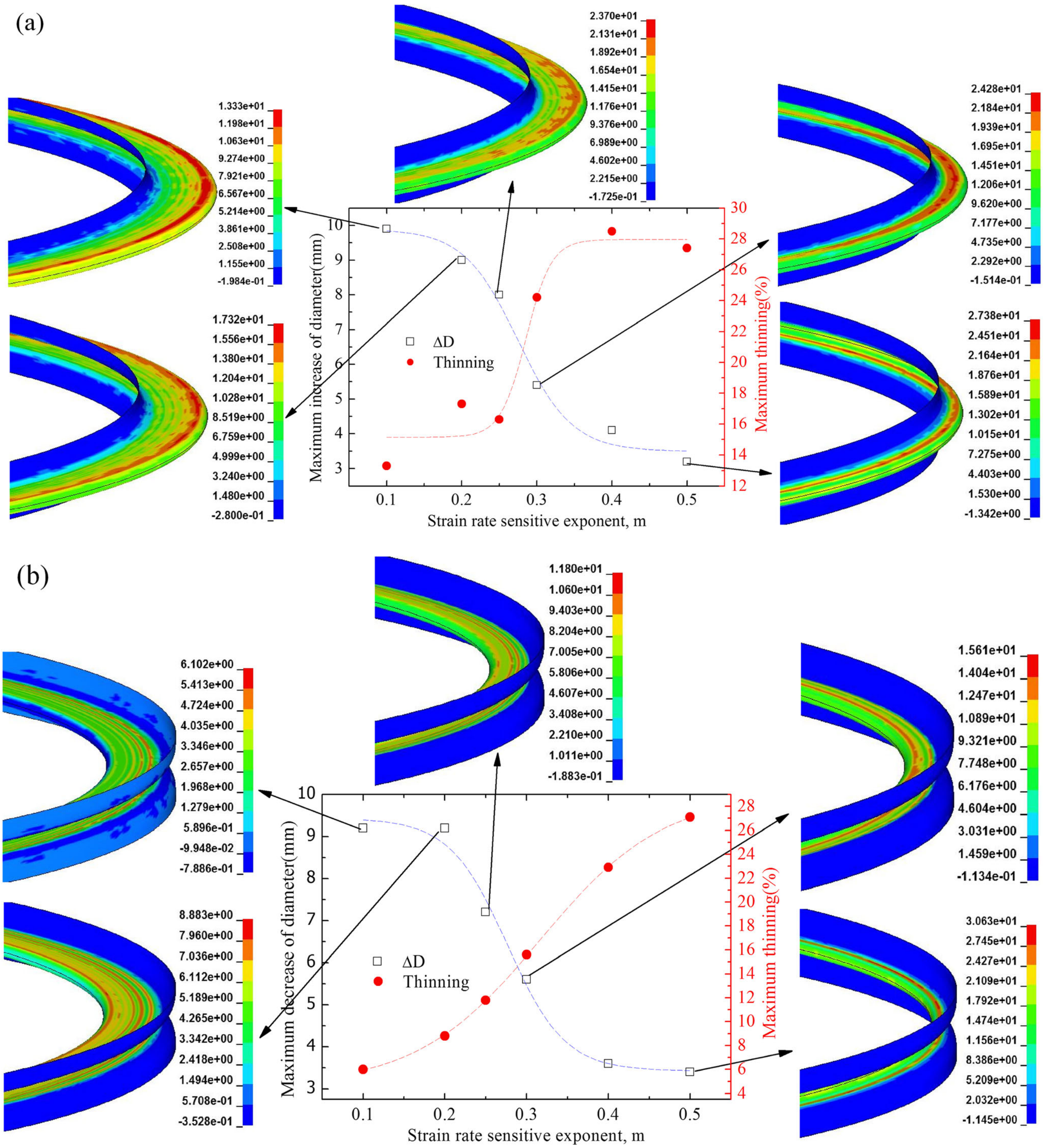


Fig. 8 Change of maximum diameter variation and thinning of wall thickness with strain rate sensitive exponents: **a** expansion forming for circular rings and **b** compression forming for circular rings

Table 2 Maximum diameter variation of formed circular rings without excessive thinning

m	Expansion forming		Compression forming	
	ΔD (mm)	Maximum thinning (%)	ΔD (mm)	Maximum thinning (%)
0.5	2.0	11.1	2.0	9.7
0.4	2.1	10.4	2.0	8.2
0.3	2.9	11.0	3.3	9.8
0.25	3.1	8.3	6.0	9.7
0.2	4.4	10.4	–	– (wrinkle)
0.1	6.1	8.9	–	– (wrinkle)

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \end{pmatrix} = \begin{pmatrix} \dfrac{2n(2-\alpha)(1-\alpha+\alpha^2)}{4-3\alpha-3\alpha^2+4\alpha^3} \\ -\dfrac{2n(1-2\alpha)(1-\alpha+\alpha^2)}{4-3\alpha-3\alpha^2+4\alpha^3} \end{pmatrix}, \quad (1)$$

where ε_1 and ε_2 are, respectively, the major strain and minor strain; n is the hardening index of material; and α is the stress ratio, $\alpha=\sigma_1/\sigma_2$.

Finite element analysis was used to evaluate the forming limit of thin-walled circular rings shown in Fig. 2 to save time and cost caused by experiments. The major strain and minor strain of formed parts were derived from numerical results. Then Swift's diffuse neck model was introduced to predict the initial necking, namely the forming limit. Conventionally, a safety margin curve shown in Fig. 3 was used as a maximum strain criterion in process design. The major strain and minor strain of circular rings with different diameter variation was introduced into the strain space to examine whether necking or fracture occurs or not. However, merely checking the initiation of necking is not enough for the process design. Because thin-walled metal circular rings are rather sensitive to wall thickness reduction, which is prone to cause failures of parts during repeated use. Thus, thinning of 10 % was taken as the critical boundary of excessive thinning. Meanwhile, wrinkle must be evaluated and thickening of 1 % was taken as the critical boundary of wrinkling. Based on these criteria, the maximum diameter variation of thin-walled metal circular rings without excessive thinning and wrinkle can be determined.

3 Finite element analysis

3.1 Modeling conditions

Commercial finite element software ANSYS/LS-DYNA was used. Both expansion and compression forming processes for thin-walled metal circular rings are simulated, and the finite element models are illustrated in Fig. 4. Dimensions of models and friction coefficients are shown in Table 1. The section thickness of viscous medium was set to be small in the modeling in order to save computing time. The lateral expansion of the die cavity is large enough so that the ring-shaped blank expands along lateral direction freely. Ring-shaped blank was modeled with Belytschko element. The sealing was modeled with Blatz-ko element, a nonlinear elastic element. Viscous medium was meshed with eight-node hexahedron elements (solid164).

Uniaxial tensile test at room temperature was conducted to get material properties of GH4169 sheet (see Fig. 5). Then, the

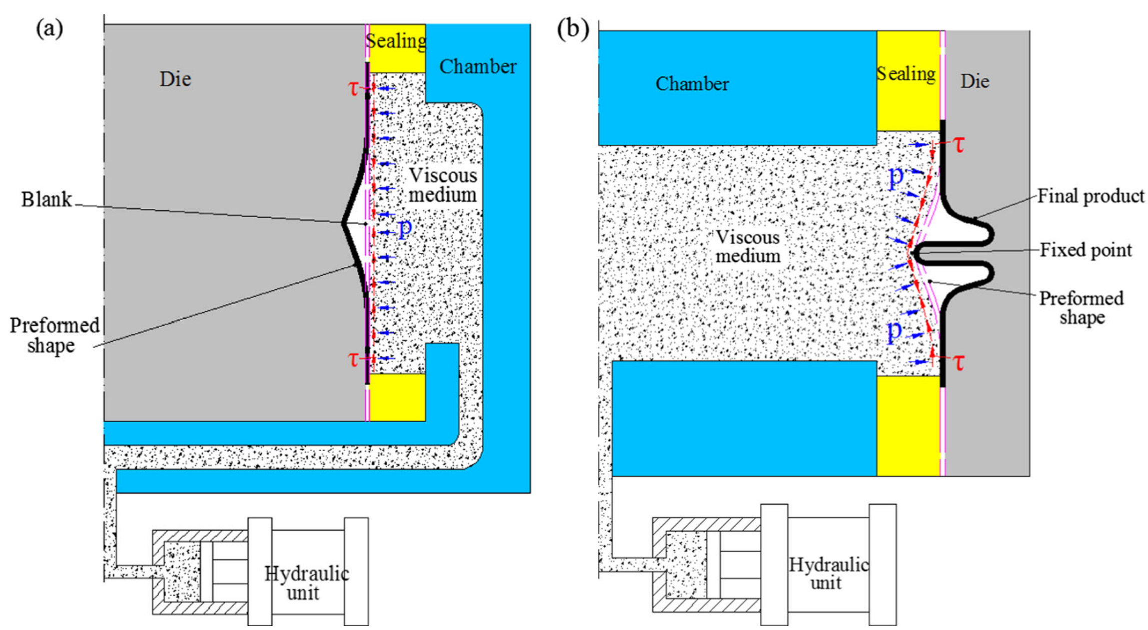


Fig. 9 Illustration of improved process design: **a** compression preforming and **b** expansion forming

constitutive relationship of blank was calculated as $\bar{\sigma} = 1130\bar{\varepsilon}^{0.3}$. Viscous medium is a strain rate sensitive material [20]. The flow stress-strain rate relationship of viscous medium is defined as Eq. (2).

$$\bar{\sigma} = c\dot{\bar{\varepsilon}}^{m} \tag{2}$$

where c is the material constancy, which equals to 0.24; $\dot{\bar{\varepsilon}}$ is the strain rate; and m is the strain rate sensitive exponent. The change of strain rate sensitive exponents (m) reflects the variation of mechanical properties of the viscous medium. The value of m was determined in the following method. First of all, the combination of extrusion test and finite element analysis was used to get the flow stress versus strain rate curves of viscous medium [11]. Then, the strain rate sensitive exponents of viscous medium were determined by nonlinear fitting of these curves.

3.2 Forming limit of thin-walled metal circular rings

For the forming of thin-walled metal circular rings employing viscous medium as pressure-carrying medium, the main characteristic is the viscous adhesive attraction between ring-shaped metal blank and viscous medium. Since viscous medium is of various types, different viscous medium has different mechanical properties such as molecular weight, density, and viscosity, which are reflected by the variation of strain rate sensitive exponent (m). Thus, the adhesive attraction varies with the mechanical properties of viscous medium, which probably influences the deformation of thin-walled metal circular rings and the forming limit.

Figure 6 shows the simulated contour and the FLD of thin-walled metal circular rings corresponding to different strain rate sensitive exponents (m) in expansion forming. Elements on the meridian of bulge region were selected to examine the strain. The major and minor strain all stay in the right hand of FLD, which indicates the biaxial stretch of material of ring-shaped metal blank along circumferential and meridian direction. ΔD refers to the diameter variation of circular rings before and after deformation. The rectangular and circular points respectively represent the strain near the boundary of bursting and beneath the boundary of excessive thinning. When viscous medium with strain rate sensitive exponent of 0.5 is employed, the maximum diameter variation without necking or fracture is only 3.2 mm. It slightly rises to 4.1 when viscous medium with m of 0.4 is used. If m reduces to 0.25, the limit of diameter variation sharply increases to 8.0 mm, while with the further decrease of m, the limit of diameter variation increases smaller. It is inferred that the molecular weight, density, and viscosity of viscous medium all increase with the value of m. Thus, viscous medium behaves like solid material when m is large enough. Then, pressure of viscous medium increases with m, which results in the increase of frictional force at blank/die interface in the forming processes, the tensile force subjected by ring-shaped metal blank along the meridian direction increases with m as a result and the necking or fracture is prone to occur when m is large enough. Therefore, the limit of diameter variation of thin-walled metal circular rings reduces. On the contrary, the limit of diameter variation increases with the decrease of m.

Table 3 Mechanical properties of viscous medium in experiments

Molecular weight (g/mol)	Density (kg/m^3)	Viscosity (kPa s)	Strain rate sensitive exponent, m	Poisson ratio
500,000	978	17	0.25	0.47

Figure 7 gives the simulated contour and the FLD of thin-walled metal circular rings corresponding to different strain rate sensitive exponents (m) in compressive forming. The major and minor strain of selected elements all stay in the left hand of FLD, which indicates the tensile deformation along meridian direction and compressive deformation along circumferential direction of circular rings. The maximum diameter variation of circular rings without necking or fracture is only 3.4 mm when m of viscous medium is 0.5. It increases dramatically to 7.2 mm when m of viscous medium reduces to 0.25. However, it is noted that evident tendency of wrinkling appears when m reduces to 0.2 and 0.1. As the reason behind this, smaller m means the viscous medium is “softer,” thus pressure of viscous medium in the forming processes is smaller, which cannot resist the wrinkling caused by compressive deformation of ring-shaped metal blank along circumferential direction.

The limit of diameter variation and the maximum thinning corresponding to different value of m is illustrated in Fig. 8. Obviously, m of 0.25 is a critical value in both expansion and compression forming for thin-walled metal circular rings. When the value of m is larger than 0.25, the limit of diameter variation decreases evidently and the maximum thinning of wall thickness increases rapidly. For compression forming, though the limit of diameter variation is larger and the

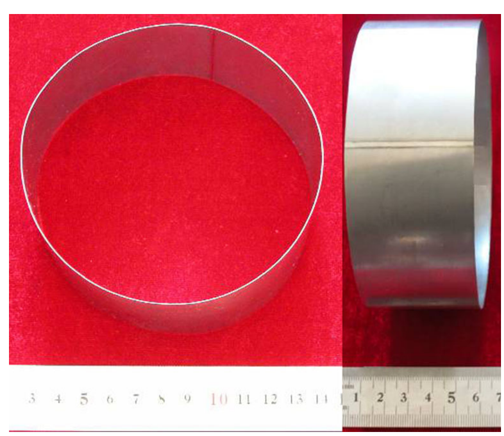


Fig. 10 Welded ring-shaped blank used in experiment

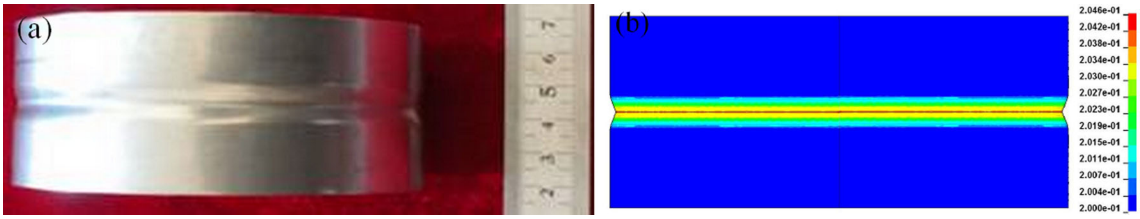


Fig. 11 Preformed specimens obtained from compression forming step: **a** preformed specimen in experiment and **b** wall thickness distribution in FEA

maximum thinning is smaller when the value of m is 0.2 or 0.1, viscous medium of these types cannot be used to form thin-walled metal circular rings due to the inevitable tendency of wrinkling.

4 Experiments and discussion

4.1 Process design

Since the initial wall thickness of circular rings is small, additional thinning of wall thickness is not allowed in the manufacture of circular rings. The maximum diameter variation of thin-walled metal circular rings without excessive thinning should be found out to provide a reference for the process design. Table 2 lists the maximum diameter variation without excessive thinning and the corresponding thinning ratio predicted by FEA. It is obvious that neither expansion forming nor compression forming can achieve the required diameter variation (6.6 mm) of the investigated circular rings shown in Fig. 3.

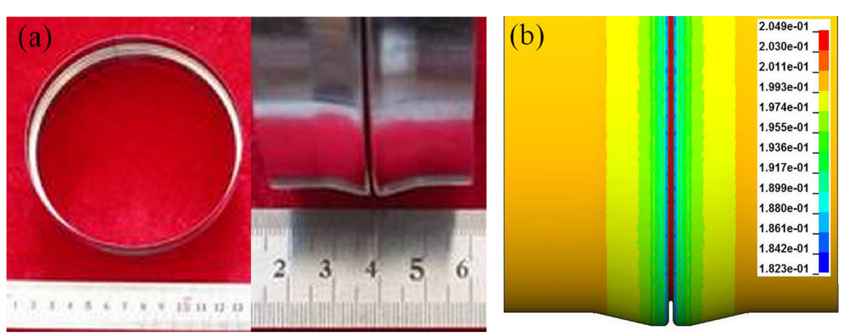
If expansion and compression forming process for thin-walled metal circular rings is combined as illustrated in Fig. 9, the achievable amount of diameter variation will be extended. Specifically, ring-shaped blank is firstly pushed into the die cavity in compression forming to achieve several millimeters' decrease of diameter, then the preformed metal blank is drew into the die cavity in expansion forming to get the desired shape. Thereafter, the required diameter variation is probably obtained. Moreover, for the combined forming process involving the expansion and compression forming for circular rings, the axial distance of deformation region is much larger than 1 mm for either expansion forming step or compression forming step. The large axial distance of bulging region can avoid the unstable metal flow and improve the filling of material of ring-shaped blank into the die cavity, thus the combined forming process will further increase the achievable amount of diameter variation and decrease the thinning of wall thickness compared with simple compression or expansion forming process.

4.2 Verified experiments

The combined forming method with compression and expansion forming steps was used to form "type 1" thin-walled circular rings. Viscous medium with m of 0.25 was employed in experiments. The mechanical properties of viscous medium are shown in Table 3. Conventional hydraulic press provides clamp force for the setup. Viscous medium is injected through specialized injection system and the maximum injection pressure is 250 MPa. The injection pressure and displacement of piston was collected in real time through computer date collecting system. The process was designed as follows. Diameters of ring-shaped blank were reduced by 3.6 mm in compression forming step at first, then increased by 3.0 mm in expansion forming step. The axial distance of bulge region is 12 mm for compression forming step and 20 mm for expansion forming step, respectively.

GH4169 sheet metal in the state as delivered is rolled and welded to make the ring-shaped blank as shown in Fig. 10. The ring-shaped blank was preformed by compression forming step at first. The comparison of preformed part in experiment and FEA is shown in Fig. 11. The wall thickness reduction is neglectable in the preforming step. The shape of final product and relevant finite element results are shown in Fig. 12. Figure 13 gives the wall thickness distribution of formed type 1 circular ring. In general, wall thickness reduction in FEA is smaller than that in experiments, which is

Fig. 12 Final product obtained from expansion forming step: **a** final product and **b** wall thickness distribution in FEA



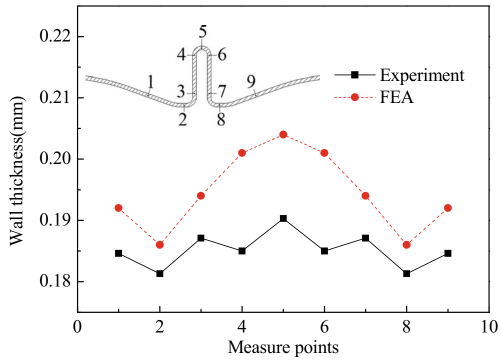


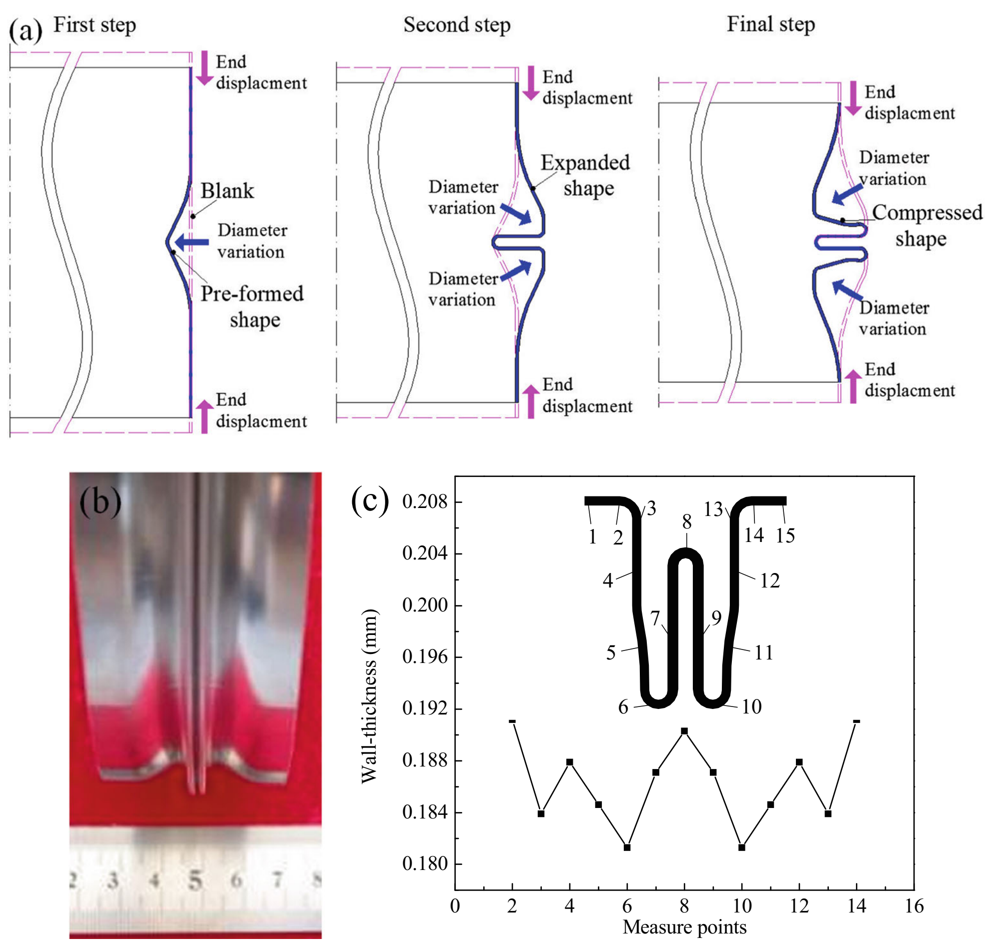
Fig. 13 Wall thickness distribution of specimen

probably attributed to the fact that the selected frictional coefficients is smaller than that in the practical condition. The wall thickness of measurement point 5 in FEA is distinctly larger than that in experiment. It is probably interpreted that sealing pressure on blank ends in experiment is larger than that used in FEA; thus, tensile stress suffered by circular blank along meridian direction in experiment is larger than that in FEA, which results in the larger wall thickness reduction in experiment. However, FEA basically predicts the deformation of the circular rings and the wall thickness distribution. The maximum wall thickness thinning is 9 %. The end displacement of ring-shaped blank along axial direction is measured as 1.47 mm, which is smaller than the theoretical value by 0.19 mm. It can be used to explain the slight wall thickness reduction. However, it is testified that viscous medium promotes the metal flow of ring-shaped blank.

4.3 Forming thin-walled circular rings with two convolutions

Based on the forming of type 1 thin-walled circular rings (i.e., only one convolution), thin-walled circular rings with two convolutions (i.e., “type 2”) were produced. Type 2 parts were manufactured by three steps: compression preforming, expansion forming, and final compression forming (see Fig. 14a). Figure 14b shows the thin-walled circular ring with two convolutions obtained from experiment and the wall thickness distribution. The maximum wall thickness thinning is 9.3 %, which is slightly larger than that of type 1 parts. Since the forming steps increase when forming thin-walled circular rings with two convolutions, parts suffers repeated pressure; thus, the wall thickness reduction increases. But, the difference is small and neglectable. The end displacement of ring-shaped blank during the whole forming process is 4.15 mm. In

Fig. 14 Illustration of the forming of thin-walled circular rings with two convolutions: **a** forming procedures, **b** final product, and **c** wall thickness distribution



general, thin-walled circular rings with two convolutions can be stably formed in the condition that no axial compressive load is applied.

5 Conclusion

Thin-walled metal circular rings with corrugated meridians were formed in a process without use of axial compressive load in this work. Based on the numerical and experimental investigation, the following conclusions were obtained:

1. A forming method employing viscous medium as pressure-carrying medium without use of axial compression on blank ends was utilized to form ring-shaped parts with extremely thin wall. Ring-shaped blank deforms under the combined action of normal pressure and tangential viscous adhesive stress, which compensate the insufficient axial feeding. The process failures such as wrinkling and fractures are avoided and the forming process and equipments are simplified.
2. The limit of diameter variation of thin-walled metal circular rings is influenced by mechanical properties of viscous medium, especially the strain rate sensitive exponent (*m*). Employing viscous medium with appropriate value of *m* may increase the maximum achievable diameter variation. It is attributed to the variation of medium pressure and resulting frictional resistance, which is related to the change of *m*.
3. GH4169 parts with one and two convolutions were produced successfully in the forming experiments based on the combination of expansion and compression forming steps. Considerable end displacement of ring-shaped blank was observed in each forming experiment; thus, it is clearly that viscous medium indeed promote the metal flow of ring-shaped blank. The proposed process was verified to be able to form thin-walled circular rings with complex shapes without use of axial compression.

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