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Process of back pressure deep drawing with solid granule medium on sheet metal

DONG Guo-jiang(董国疆)[1, 2], ZHAO Chang-cai(赵长财)[2], CAO Miao-yan(曹秒艳)[3]

1. College of Vehicles and Energy, Yanshan University, Qinhuangdao 066004, China;
2. Key Laboratory of Advanced Forging & Stamping Technology and Science of Ministry of Education of China (Yanshan University), Qinhuangdao 066004, China;
3. National Engineering Research Center for Equipment and Technology of Cold Strip Rolling (Yanshan University), Qinhuangdao 066004, China

Abstract: The experimental die apparatus of the solid granules medium forming on sheet metal was designed and manufactured. Typical parts, such as conical, parabolic, cylindrical and square-box-shaped components, were successfully trial-produced as well. According to the analysis of the changing trends of the cross-section shape and the wall thickness during the process, it can be found that the shape of the free deformation zone of the sheet metal, which is the most critical thinning area, can be described as an approximately spherical cap. According to this forming feature, back pressure deep drawing technology with solid granules medium on sheet metal was proposed to restrain drastic thinning at the bottom of the part through the joint friction effect of solid granules medium, the back pressure tringle and the sheet metal. Therefore, the deep drawing limit of the sheet metal is significantly improved. In order to fabricate thin-walled rotary parts with great drawing ratio and complex cross-sections, a finite element model based on the material property test of the solid granules medium was established to optimize the scheme of the back pressure deep drawing. The effects on the forming performance of sheet metal from back pressure load and the approach of blank holding control were analyzed through this model.

Key words: solid granules medium forming; drawing; sheet metal; finite element simulation

1 Introduction

With the growing requirements of lightweight, integration and precision in the manufacturing fields such as aviation, aerospace and automotive industry, soft mold forming technology on sheet metal, which is known as an advanced and flexible forming method, has gained rapid development and wide application. It has gradually become one of the mainstream manufacturing technologies for thin-walled parts. Soft mold forming on sheet metal employs a rigid female die (or punch) and a soft punch (or female die) as the specific pressure-transfer medium, which can be solid medium such as rubber or polyurethane, liquid medium such as water or oil, gaseous compressive air and viscous medium. The sheet metal is shaped under the effect of the pressure-transfer medium. Solid elastomer, such as rubber or polyurethane, has been applied relatively earlier in the soft mold forming on sheet metal. However, the flowability and deformation ability of the solid elastomer are so limited that the pressure control and reasonable envelopment of the parts are difficult to achieve. Therefore, it is hard to shape complex parts with deeper drop or local curved surface with small radius. Recently, as the representatives of the soft mode forming technology, hydroforming deep drawing (HDD) [1−2] and viscous pressure forming (VPF) [3−4] have been developed rapidly.

CHOIA et al [5] used differential temperature hydroforming technology to soften the flange of the sheet and reduce its flow stress. The punch could rapidly lower the temperature of the area that has been formed by touching with it, thereby the strength of the force transfer area and the drawing ratio limit were improved. LANG et al [6] simulated and tested the hydroforming process of aluminum and stainless steel with complex curved surface through the multistage hydraulic drawing method, in which the measures of controlling forming quality were presented. PALUMBO et al [7] proposed the technology of movable die sheet hydroforming, by which the drawing and bulge forming were realized,

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Corresponding author: ZHAO Chang-cai, Professor, PhD; Tel: +86−335−8047087; Fax: +86−335−8047087; E-mail: zhao1964@ysu.edu.cn

the hydroforming of low-carbon steel cup was studied, and the influence of the anisotropy and the pre-expansion pressure on the results was analyzed. XU et al [8] and LIU et al [9] conducted in-depth study on initial anti-inflation pressure control and hydroforming technology of controlled radial pressure, and their achievements were significant. They led liquid into the cavity of flange edge so that the radial pressure can significantly improve the ability of resisting the drawing rupture of the sheet. Aluminum alloy 5A06 cylindrical cup with deep ball end with a drawing ratio of 2.8 was obtained. WANG et al [10] proposed hydrodynamic deep drawing with radially inward flowing liquid. To establish the limit drawing ratio and pressure ratio of the forming region, an aluminum alloy 2A120 cup with a drawing ratio of 2.85 was obtained [10].

AHMETOGLU et al [11] applied VPF process to form non-symmetric part from steel, aluminum and nickel alloy, and studied how process parameters, such as clamping load, forming speed, medium pressure and part geometry, influenced the formability through finite element simulations and experimental analysis. WANG and LI [12−13] got the forming limit curve of 6k21-T4 sheet through viscoelastic-plastic flexible-die bugling experiments. The car outer door with scale-down dimensions was chosen as experimental simulating subject, and the viscoelastic-plastic flexible-die forming experiments were carried out to analyze the influence of the medium pressure and blanker holding force (BHF) on the formability of aluminum panels. LIU and WANG [14] formed aluminum ladder parts with VPF process, and the fracturing and flange wrinkling failures were predicted via the sectional finite element simulation. Their study shows that the increase of interface friction force is helpful to restrain the flange wrinkling and local fracturing in VPF process.

Scholars from various countries have conducted relevant researches on aspects of forming equipments, theoretical analysis, experimental and numerical simulation according to the features of soft mold forming process. The main focuses are on parts with complex shape, extraordinary deep drawing limit and materials with low plasticity and difficult formability. Some of the technologies have been successfully applied to aerospace, automotive manufacturing and other fields.

Through in-depth studies of the current soft mold forming technologies on sheet metal, the research group proposed a new flexible forming technology, with solid granules medium as the pressure-transfer medium—solid granules medium forming (SGMF). An outstanding advantage of this technology is the use of solid granules as the pressure-transfer medium, which can be metallic or nonmetallic spherical-like particles with diameters from 0.05 mm to 2 mm. These particles have a wide selection range and therefore can be picked up according to different process requirements. A large number of material property tests and technology tests [15−16] conducted by the group prove that:

1) The solid granules medium has favorable filling ability and flowability, therefore it is easy to seal the medium and form the pressure.

2) The pressure transmission of solid granules medium presents an uneven distribution. Based on this, the deformation sequence and deformation degree can be regulated by reasonable load control, thereby improving the deep drawing limit of the sheet metal.

3) Heat-resistant granules medium is employed, which can overcome the sealing and loading problems of general media at high temperatures. Additionally, it has favorable chemical stability and brings no corrosion to the part.

4) The technology implementation process is simple, while the shaped part enjoys many advantages, such as satisfactory surface quality, favorable die fitness and high precision.

5) The solid granules medium has a long service cycle and is free from industrial pollution, which makes it suitable for the pressure forming of high-strength alloy materials with complex shape and low deformability.

The SGMF technology was first proposed by the research group with independent intellectual property, with which extremely broad application prospect has provided new ways and methods for material processing and preparation.

In recent years, the research group has carried out numerous experimental and theoretical studies with respect to the SGMF technology on sheet metal. The primary research includes the selection of appropriate solid granules media and exploration of mechanical properties such as pressure-transfer and friction characteristics. Study of the SGMF process route on sheet metal and verification of the feasibility through tests. Based on the results above, the deformation laws of the sheet metal during the SGMF process were studied and analyzed in this work, and the back pressure deep drawing method with solid granules medium on sheet metal was put forward. Based on the material property test for the solid granules medium, the finite element numerical model was established and the process parameters were optimized. This work laid a theoretical foundation for the in-depth research and brought increasing application of this technology.

2 Research on sheet metal forming test

2.1 Test of SGMF on sheet metal

In the SGMF process on sheet metal, no rigid punch would match the female die, instead, the pressure head contacted with the medium, which transferred the pressure to the sheet surface, caused the sheet surface to deform along the shape of the female die. The schematic diagram of the SGMF on sheet metal is shown in Fig. 1.

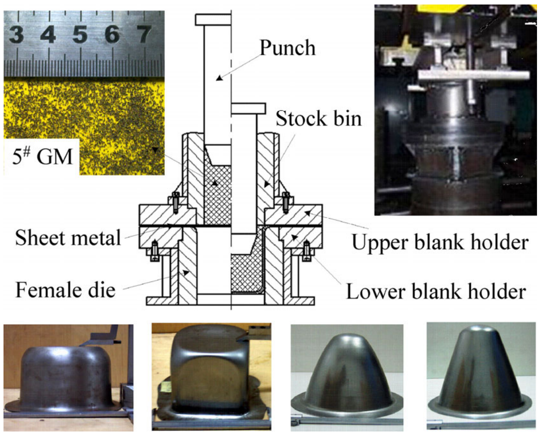

Fig. 1 Schematic diagram of SGMF on sheet metal

ST12, ST14 and 0Cr18Ni9Ti sheet metals with thicknesses from 0.8 mm to 1.2 mm and the medium $5^{\#}$ granules medium (GM) (diameters ranging from 0.117 mm to 0.14 mm) at ambient temperature were selected and four typical parts were successfully trial-produced. These typical parts can achieve their anticipated shapes in only one process by SGMF technology, while 2−4 processes were required in traditional stamping deep drawing technology. It was shown through the tests that the drawing workpieces had reliable die fitability and smooth surface. Due to the change of the forming mechanism, there is smaller residual stress in the parts and little rebound performance on the generatrix profile. Besides, the shaped parts have higher size precision and over 95% yield, which has verified the feasibility of this technology.

2.2 Test analysis

Through the tests, workpieces of different forming stages were obtained and their contour shapes were measured, as shown in Fig. 2. Analysis shows that in the forming process, the shape of the free deformation zone can be precisely fitted by a spherical cap surface, whose radius R gradually decreases with the deformation proceeded and finally fits the bottom of the female die. This deformation law is similar to that of general soft mold forming processes of sheet metal. The solid granules medium possesses flowability, and the forming process is a coupling deformation process of the solid granules medium and the sheet metal, which is suitable for parts with complex shape.

During the forming process, the solid granules medium always covers the sheet surface. The friction effect between them not only significantly raises the trend of the sheet in the flange zone flowing into the

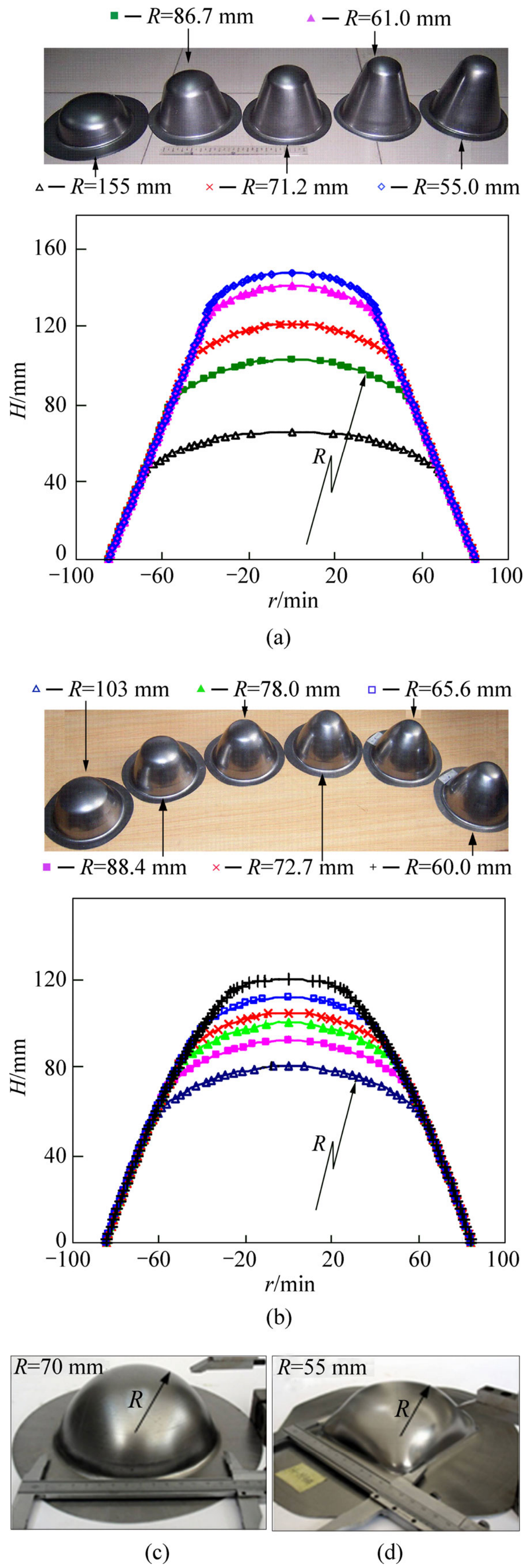

Fig. 2 Shaping processes of parts: (a) Conical parts; (b) Parabolic parts; (c) Cylindrical parts; (d) Square-box-shaped parts

female die, but also relieves the thinning of wall thickness, local instability and even rupture. The drawing limit and formed parts, which cannot be achieved by traditional drawing method with rigid mold are greatly improved. This feature is similar to the role of the tangential adhesion force in the viscous pressure forming, but its performance is more superior. When the pressure varies from 10 MPa to 140 MPa, the measured friction coefficient between the granules medium and the sheet metal ranges from 0.08 to 0.3 [15−16].

During the forming process, the stress−strain state of the fillet transition zone on the bottom is the most complicated issue (see Fig. 3). In this region, there is a clear transition between the tensile and compressive stress state in the die fitting zone and the double tensile stress state in the free deformation zone. Consequently, there must exist a turning point Q with σ_2=0, which can be considered as the unidirectional tensile stress state. Therefore, during the deformation process, the thinning at point Q was more severe and became the weak section of the part. Besides, the thinning in the free deformation zone which bore double tensile stress was severe as well. It can be seen from the thickness distribution of the parabolic part that the thinning effect of the fillet transition zone on the bottom and the free deformation zone are the most severe, and the strain in thickness direction ε_t=−0.25.

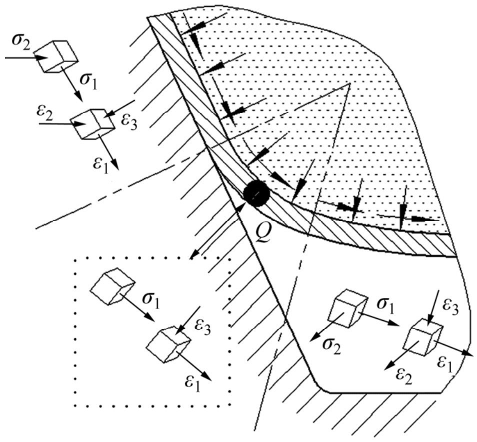

Fig. 3 Stress and strain of fillet transition zone on bottom

The solid granules medium was employed as pressure transfer medium during the sheet metal forming process for its favorable characteristics such as flowability, simple seal, and heat resistance. As a consequence, the hanging segment and hazardous zones existing in the conventional sheet metal forming processes were eliminated. The friction effect between the granules medium and the sheet metal is proved to be beneficial to the deformation flow of the sheet, which can improve the deep drawing limit and broaden the application range of this technology.

3 Back pressure deep drawing process with solid granules medium on sheet metal

3.1 Technology principle

Engineer testing of the SGMF on sheet metal has demonstrated its significant advantages. Meanwhile, the free deformation zone on the bottom, which is under double tensile stress state, has been proven to be the most dangerous thinning region. Based on this, this work proposed back pressure deep drawing technology with solid granules medium on sheet metal (see Fig. 4).

1) The initial state. Place the sheet, the blank holding gap (BHG), close the moulds and impose the blank holder force N_1, then fill the solid granules medium.

2) Back pressure deep drawing. Set the overflow pressure of the hydraulic system to control the pressure force F of the back pressure tringle; apply force to the solid granules medium by pressure head; the back pressure tringle will simultaneously move with the sheet metal deformation when its reaction force reaches the intended back pressure F, i.e. the back pressure deep drawing is achieved.

3) Deep drawing to shape. The floating tringle moves with the sheet metal through rigid position control. It will not be fixed until it reaches the forming height H_1, and the deep drawing is completed.

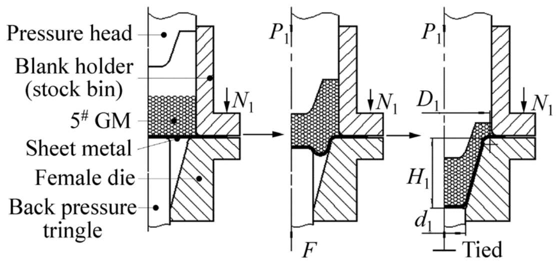

Fig. 4 Flow diagram of back pressure deep drawing process

During the back pressure deep drawing process with solid granules medium, deformation of the sheet central area was produced by the co-pressing effect of the medium and the floating tringle. The thinning on the part bottom was effectively inhibited due to the rubbing action, so that the drawing limit was further improved. The application of solid granules as pressure transfer medium effectively resolved the difficulties in loading, sealing, blank holding and other technical aspects, which were produced by general soft-mode media. Therefore, simple die structure and portable process realization could be achieved, which serves as a significant prerequisite of smooth conduction of the process.

3.2 Technology scheme design

A certain part has thin-walled rotary structure with complex cross section, which consists of the top spherical cap, parabolic and cylindrical sidewall, fillet and flange. The shape with primary dimensions is shown in Fig. 5. With the neglect of the sheet thinning, the calculated required blank diameter is 432 mm, the drawing ratio reaches up to 2.16, and the relative height h/d=1.2, belonging to the so-called larger deformation scope. This part is made of 0Cr18Ni9Ti, 1.2 mm in thickness, wherein the thicknesses of the spherical cap and the sidewall shall be kept no less than 0.8 mm, and the local convex-concave value, where the surface separation remains within 20 mm, shall be kept less than 0.1 mm. If traditional rigid die deep drawing technology is employed to shape this part, 5 to 6 working steps should be required to complete the drawing and shape-righting processes, which is so complex that the forming quality is difficult to guarantee.

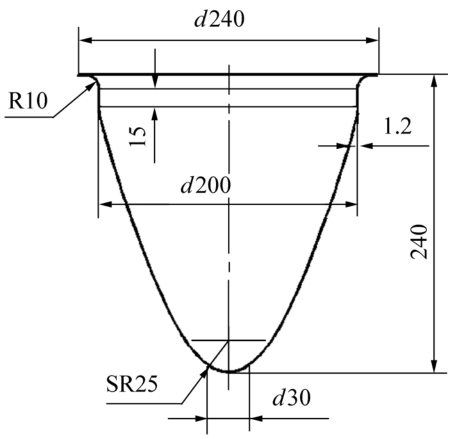

Fig. 5 Cross-sectional shape of part (Unit: mm)

Based on the molding surface and structural characteristics of the part, the back pressure deep drawing with solid granules medium on sheet metal was applied, including two sub-processes, the performing (see Fig. 4) and the final forming (see Fig. 6) processes, and the latter is mainly for the completion of the redrawing and shaping processes.

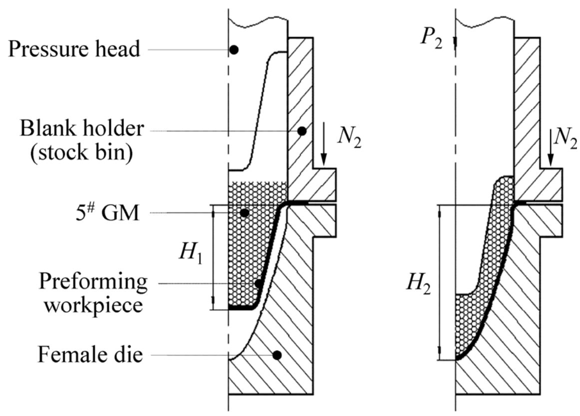

Fig. 6 Final forming process

4 Finite element numerical simulation and analysis

4.1 Finite element model establishment

The key technique of the numerical simulation of this drawing technology lies in true reflection of the interactions between the granules medium and the sheet metal, mainly reflected in the material model establishment of the granules medium and disposal of the contact boundary conditions.

The solid granules are granular bodies which exhibit hydrostatic stress state during the forming process and produce certain volume compression during their coupling deformation phase with the sheet metal. Internal friction exists between the granules with manifestations of the non-equivalent pressure transferring in all directions. Therefore, the material shearing dilatancy should be taken into consideration. Based on the characteristics, the material model of solid granules medium could be constructed by the extended Drucker-Prager linear model. The $5^{\#}$ GM granules adopted in this work belong to the non-cohesive granular material, with compliance with the Mohr-Coulomb strength yield criterion:

$$\tau = c - \sigma \tan \alpha \tag{1}$$

where τ is the shear strength, σ is the normal stress, α is the Mohr-Coulomb friction angle, c is the material cohesion force, and for $5^{\#}$ GM granules, c=0. Through the material shearing performance test [14], the shear strength of $5^{\#}$ GM granules under different pressures was gained, which was then substituted into Eq. (1), and α=17.7° was obtained.

For materials with smaller friction angle, there exist the following conversion relationships between parameters of the Mohr-Coulomb model and the Drucker-Prager linear model:

$$\tan \beta = \frac{6 \sin \alpha}{3 - \sin \alpha} \tag{2}$$

$$X = \frac{3 - \sin \alpha}{3 + \sin \alpha} \tag{3}$$

where β is the Drucker-Prager friction angle, and X is the ratio of the triaxial tensile yield stress to the triaxial compressive yield stress (i.e. the flow stress ratio).

Through the shearing performance test [15−16] of the non-viscous $5^{\#}$ GM granules, the derived dilation angle ψ=17.5° is close to $\beta/2$, which is basically the same with that in Refs. [17−18]. The parameters of Drucker-Prager linear model are shown in Table 1.

The Drucker-Prager hardening curve can be determined through the triaxial compression test and fitted by the following power function:

Table 1 Simulation parameters of 5# GM granules

Friction angle, β	Flow stress ratio, X	Dilation angle, ψ
34.1°	0.82	17.5°

$$\overline{\sigma}=2.82\times10^{5}\,\overline{\varepsilon}^{2.61} \tag{4}$$

With the application of the adaptive grid technology, the 8-node linear hexahedral elements with reduced integration C3D8R were applied in the solid granules medium.

The contact friction between the solid granules medium and the sheet metal exhibited considerable influence on the sheet deformation. Therefore, without precise frictional contact establishment in the simulation, accurate reflection of the forming characteristics could not be obtained. Through experiments, the friction coefficient f_w curves between the sheet metal and GM particles with different diameters are obtained (see Fig. 7), and nonlinear variations in f_w with the increase of contact pressure could be observed. The penalty function method was adopted in the numerical model to achieve relatively smooth sliding between the contact surfaces, with the surface-surface contact as contact type. The friction coefficients between the granules medium and the sheet metal can be set according to the curves in Fig. 7. The contact friction coefficient between the sheet metal and the die was set to be 0.08.

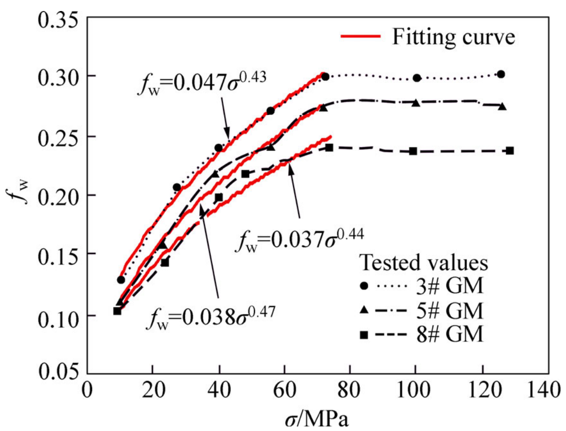

Fig. 7 Friction coefficients between granules medium and sheet metal

In order to describe the bending effect, the thickness direction stress and strain characterized more accurately during the sheet deformation process, seven integrated points were set along the thickness direction. The sheet material was 0Cr18Ni9Ti, which was 1.2 mm in thickness, and the power hardening model was employed in its constitutive expression, namely

$$\overline{\sigma}=1.426\times10^{3}\,\overline{\varepsilon}^{0.502} \tag{5}$$

A quarter of the analysis model was established on the condition that the punch, the female die, the pressure head and the floating tringle, etc were all treated as rigid bodies, and the BHG, back pressure and other parameters were set in accordance with the actual working condition, as shown in Fig. 8. The thickness and shape of the work-piece in the final forming process inherited from that of the preformed one, and the conditions above were adopted for model establishment.

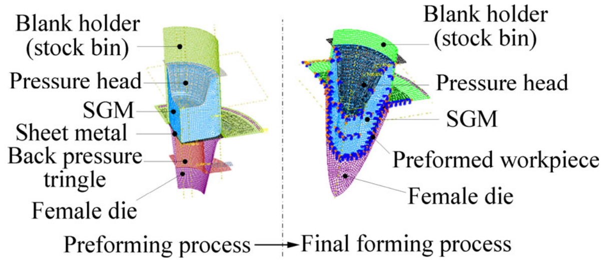

Fig. 8 Numerical simulation model

4.2 Numerical analysis of preforming process

In the preforming process, the tringle shape, the back pressure and the blank holding parameters were mainly designed so as to obtain reasonable preforming shape and effectively inhibit the sheet thinning or wrinkling. To analyze the effects of various process parameters, the preforming shape of the workpiece was preliminarily designed according to the target shape, as shown in Fig. 5, wherein H_1=140 mm, D_1=210 mm and d_1=115 mm.

4.1.1 Pressure setting analysis of back pressure tringle

With the operability in actual production process taken into account, in order to study the influence of pressure variations of the back pressure tringle on the drawing process, the tringle pressure during the drawing process was set constant, and that of nine analyzing samples was set from 0 to 15.6 MPa, with 1.95 MPa as a gradient. Except for the back pressure, the material properties, boundary conditions and elements partition of the samples were all set the same. In addition, the BHG was controlled to be constant, 1.17 times the sheet thickness. When the flange radial shrinkage reached 42.5 mm in the simulation, relation curves between the back pressure F, the drawing height H and the strain ε_t of the distinctive elements in the thickness direction were output, as shown in Fig. 9.

In Fig. 9(a), deformation state with the same amount of flange shrink was selected, and it can be found through analysis that the sheet deep drawing height decreases with increasing the given back pressure, and it tends to be constant when the pressure reaches a certain value. The sheet deformation state shows that without back pressure exerted, the bottom shape of the workpiece appears an approximate spherical cap; while with back pressure exerted, the bottom of the workpiece fits with the tringle. Additionally, with the increase of the given back pressure, the fitting area increases and the transition

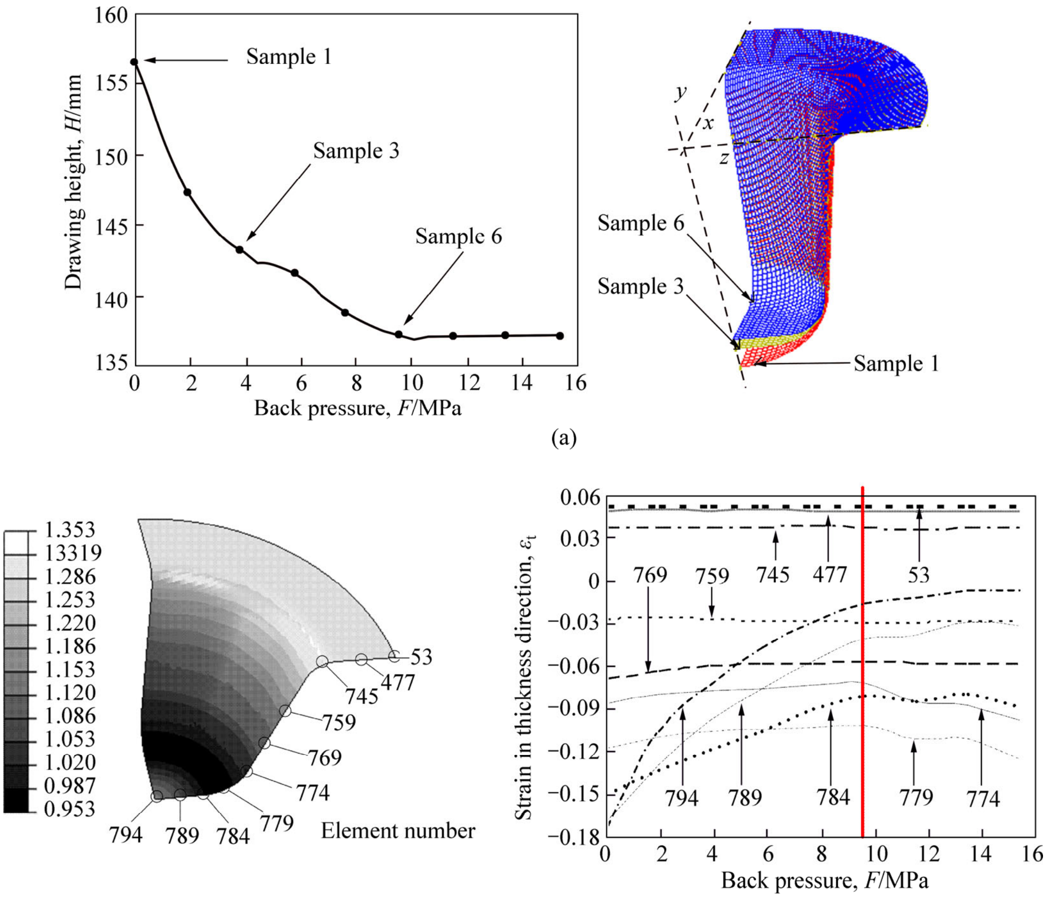

Fig. 9 Numerical simulation results: (a) Relation curves between back pressure and drawing height; (b) Relation curves between back pressure F and strain ε_t of distinctive elements in thickness direction

fillet between the fitting surface and the sidewall decreases. Through comparisons of the thickness variations of distinctive elements in the nine samples of the deformed workpieces, it is shown that (see Fig. 9(b)) when the back pressure F<9.75 MPa, as the back pressure increases, the thickness thinning of the die fitting zone on the workpiece bottom has been significantly improved; while the back pressure F>9.75 MPa, as the back pressure increases, thinning emerged in the transition fillet zone between the fitting surface on the workpiece bottom and the sidewall. The wall thickness distributions in other zones were immune to back pressure variations, which is also evident in Fig. 10, which shows the thickness comparisons of preformed workpieces under different back pressures.

The friction between the solid granules medium, the back pressure tringle and the sheet metal effectively inhibits the dramatic thinning on the bottom of the preformed workpiece. However, the increase of back pressure raises the deep drawing pressure to some extent, which increases the pressure of the inside medium. Without back pressure friction to prohibit its thinning effect, the sheet suspends in the transition fillet zone,

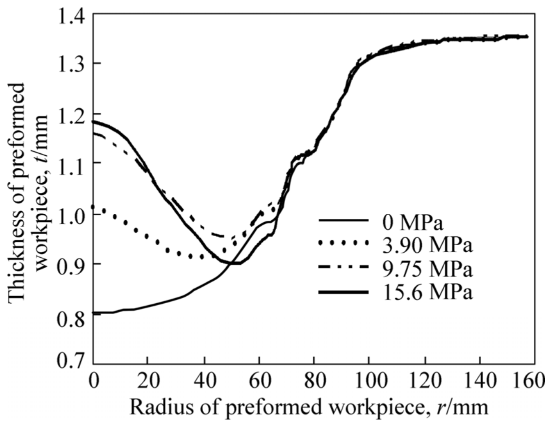

Fig. 10 Thickness comparisons of preformed workpiece under different back pressures

where the bottom of the thickness curve of the preformed workpiece comes into being. It can be seen in Fig. 10 that as the back pressure increases, there is a maximum value at the bottom of the thickness curve, where the least thinning and a more uniform thickness distribution take place. Consequently, for the preformed workpiece in this work, there is an optimal value of the back pressure load, F=9.75 MPa, i.e. the back pressure is set to be 100 kN.

4.1.2 Blank holding scheme analysis

During the deep drawing process, constraint force was exerted on the blank flange through the blank holder and the female die so as to prevent process failure caused by wrinkles. The controlling method of setting the BHG was adopted, i.e. the BHG was kept constant in the drawing process, and different radial pressures were achieved by adjusting the BHG to guarantee successful completion of the drawing process. The influence of the BHG on the sheet drawing process was analyzed through application of the numerical model above, wherein the initial sheet thickness t_0=1.2 mm, the back pressure was 100 kN, and seven BHG samples with range of (1.04−1.16)t_0 were selected. When the drawing height H is 140 mm, the workpiece thickness curves under different BHG and the axial displacement curves of nodes along the circumferential direction of the flange outer margin (see Fig. 11) are output.

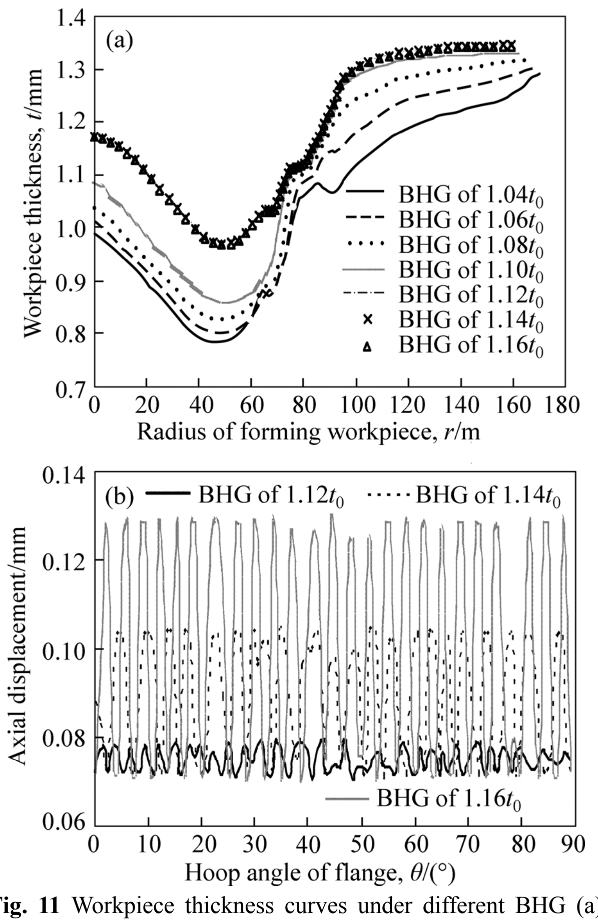

Fig. 11 Workpiece thickness curves under different BHG (a) and curves of nodes on outer margin of flange (b)

It can be seen from Fig. 11(a) that BHG variations have a greater impact on the thickness distribution of the workpiece. As the BHG increases, the differences in wall thickness of the whole workpiece gradually decrease, wherein the thickness variations of the flange zone and the bottom zone are the most significant. However, when the BHG increases to 1.12t_0, the thickness distribution curves of three samples are essentially coincident, which is caused by the increase of the sheet flow resistance due to flange wrinkles. It can be seen from Fig. 11(b) that ripples of different degrees take place on the flange of workpieces with BHG of 1.14t_0 and 1.16t_0, which become more significant as the gap increases, while the flange with BHG of 1.12t_0 appears relatively flat. Greater BHG will lead to wrinkles and warps on the flange zone, thereby impacting the deep drawing quality of the sheet metal.

Based on the analysis above, the following process parameters may be initially adopted: the back pressure tringle diameter d_1=115 mm, the forming height H_1= 140 mm, the back pressure of 100 kN and the constant BHG of 1.12t_0. The wall thickness contours of the preformed workpiece were obtained through simulation, as shown in Fig. 12.

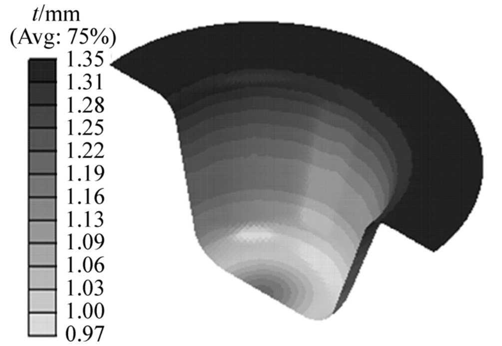

Fig.12 Thickness distribution contours of preformed workpiece

4.3 Numerical analysis of final forming process

The geometry and thickness distribution of the final formed parts have inherited from the preformed one, and the SGMF is applied to complete the drawing and shape-righting processes. After the preforming process, the maximum thickness of the flange zone achieves 1.35 mm. Therefore, three BHG schemes for numerical simulations of the final forming process are designed, i.e. the BHGs are set to 1.21t_0, 1.16t_0 and 1.14t_0, respectively. The obtained thickness distribution curves of the shaped parts are shown in Fig. 13.

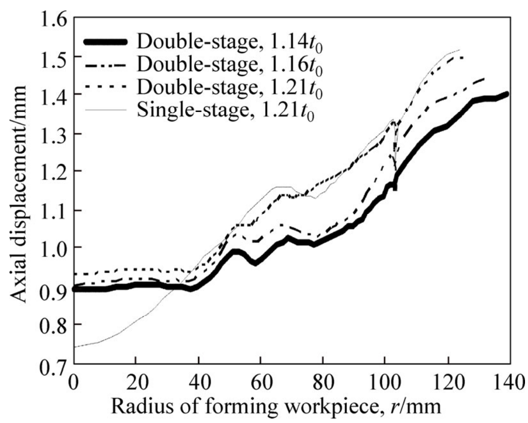

Fig. 13 Thickness curves of final formed parts

In order to compare the thickness variations of the part shaped through one drawing process by the SGMF, two schemes of the BHG, $1.16t_0$ and $1.14t_0$, were designed in the simulations, wherein fracture of thinning took place in the straight wall of the cylindrical zone at the entrance of the female die. While the BHG is set to be $1.21t_0$, the part can be shaped through one drawing process, with wall thickness curves shown in Fig. 13. When the part is shaped through one drawing process, its thickness is thinned to be 0.74 mm on the central bottom zone and the overall wall thickness difference exceeds 0.75 mm. Additionally, critical thinning takes place in the straight wall segment at the flange fillet entrance, which does not comply with the technical requirement that the local convex-concave value where the surface separation remains within 20 mm should be kept less than 0.1 mm. When the BHG is set to be $1.14t_0$, the wall thickness difference decreases to 0.51 mm, among which the thickness of the flange outer margin is 1.40 mm, and the thinnest thickness at the central bottom of the spherical cap is 0.89 mm, which adheres to the technical requirements. The thickness distribution contours of the final formed part are obtained through simulation, as shown in Fig. 14.

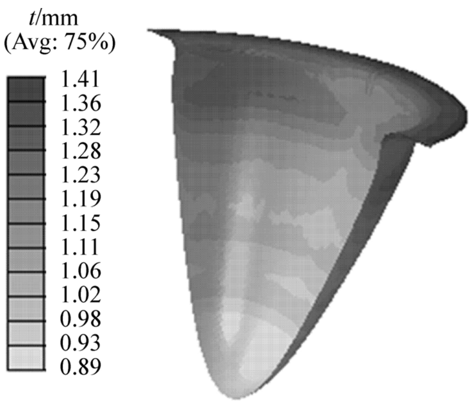

Fig. 14 Thickness distribution contours of final formed part

5 Conclusions

1) Typical parts are successfully trial-produced through the SGMF technology on sheet metal, and the thickness-direction strain curves as well as the variation laws in shape and the size of the part during the forming process are obtained. It proves through tests that the most serious thinning area is produced in the free deformation zone, with shape of spherical cap, which becomes the weakest region during the deep drawing process.

2) The back pressure deep drawing with solid granules medium on sheet metal is put forward, and it is shown through finite element numerical analysis that the comprehensive friction between the solid granules medium, the back pressure tringle and the sheet metal can effectively inhibit the thinning in the sheet bottom of the part, which provides a guideline for the application field expansion of this technology.

3) The forming of the thin-walled rotary parts with complex cross-sections is enormously influenced by the process parameters, and there are optimal values for the back pressure load and the BHG. Parts meeting with the technological requirements can be produced with the following parameters adopted: the back pressure, the forming height and the BHG during the preforming process are 100 kN, 140 mm and $1.12t_0$, respectively; and the BHG in the final forming process is $1.14t_0$.

4) In the future work, by fully using the special properties of solid granule medium such as easy to seal, heat and pressure resistant, the process should be applied to forming warm and hot high-strength aluminum alloy sheet components. In order to provide a new technical mean to solve the difficulty of forming light alloy sheet, the application fields of the process should be further expanded.

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