Viscous Backpressure Forming And Feasibility Study of Hemispherical Aluminum Alloy Parts

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Research Article

Keywords: Hemispherical parts, Viscous medium, Aluminum alloy, Backpressure, Finite element analysis

Posted Date: September 7th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-851191/v1>

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Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on January 14th, 2022. See the published version at <https://doi.org/10.1007/s00170-022-08656-9>.

Abstract

Hemispherical aluminum alloy parts are extensively used in modern aerospace and other manufacturing fields. However, wrinkling and cracking easily occur due to the large deformation of the parts, which leads to a complicated forming process. This research proposes a viscous backpressure forming method for hemispherical aluminum alloy parts. The forming limit diagram of LF2 sheet is established through the forming limit experiments. By the combination of finite element analysis and experimental verification, the forming process of the parts under different viscous backpressure and loading path conditions as well as the distribution law of stress-strain and wall thickness of the parts, are obtained. By comparing with the forming limit diagrams, technical feasibility of this forming process is discussed. The research results show that qualified parts can be formed using the viscous backpressure forming method under the conditions of viscous backpressure loading throughout the process with the backpressure at or above 12MPa. This provides a reference for the backpressure forming of hemispherical aluminum alloy parts.

Introduction

In the ever-changing modernization process, national comprehensive strength is based on its industrial foundation, and the manufacturing industry is a highlight in the industrial development of various countries. An increasing number of countries have proposed strategic plans to promote the development of manufacturing, represented by "Germany's Industry 4.0", "American's Advanced Manufacturing Partnership", "Made in China 2025", which puts forward higher requirements for the forming process of sheet forming[1]. In the past 100 years, sheet parts have become indispensable in modern manufacturing. Lightweight alloys featured by high strength and low plasticity are widely used in aerospace, automotive, electronics, and other fields [2]. As a typical lightweight alloy, aluminum alloy has low density, good elasticity, high specific strength, good electrical and thermal conductivity, fatigue resistance, and corrosion resistance compared with other metal materials and it is widely used in the field of aircraft and automobile manufacturing [3,4]. However, compared with traditional metal material, aluminum alloy has poor plasticity at room temperature and is prone to quality defects such as excessive thinning and cracking during the forming process. Therefore, it is difficult to form parts with complex shapes and large deformations using traditional forming processes.

In order to improve the formability of aluminum alloy sheet in room temperature, controlling or changing the stress state of the sheet is considered to be an effective way, such as overlapping the aluminum alloy sheet on one or two sides with other sheets of excellent plasticity, known as the overlapping sheet forming, which can change the force state and deformation law of the aluminum alloy sheet. Similarly, by controlling the inverse pressure in hydroforming method, the formability can also be improved. In addition, the viscous pressure forming(VPF) characterized by semisolid and viscosity during force transmission is also feasible. In the overlapping sheet forming, Gao et al. [7,8] analyzed the effect of the material properties of the overlapping sheet and the interface friction between the overlapping sheet and the aluminum alloy sheet on the formability and ultimate deformability, and found that the stronger the plasticity of the overlapping material and the greater the friction coefficient of the interface with the

forming sheet, the more significant the improvement effect on the forming performance of the aluminum alloy sheet. Aiming at the low formability of FVS0812 hemispherical parts, Tao [9] carried out overlapping sheet forming on both sides of the target sheet using sheet with high strength, large thickness, and good plasticity, and the obtained parts meet the requirements Yilamu et al. [10] studied the springback of aluminum sheet bending, and obtained aluminum sheet bending parts with smaller springback by overlapping the outside of the aluminum sheet with a stainless steel sheet. In the inverse pressure hydroforming, Lang et al. [11] qualitatively analyzed the relationship between wrinkling and critical strain in inverse hydrolic deep drawing of conical parts. By adjusting the loading path, the wrinkling in the suspended area of the side wall was effectively controlled, and the conical part with no wrinkling on the side wall was successfully obtained. Sun et al. [12] analyzed and optimized the inverse hydroforming process of aluminum alloy engine hoods, and optimum process parameters which can reduce the forming steps are determined. They found that the quality of the part can be improved when increasing the inverse pressure Liu et al. [13] studied the effect of inverse hydroforming on the stress, strain, and wall thickness of the hemispherical cylindrical part at the bottom of AA5052 aluminum alloy and found that the inverse pressure provided by the liquid can effectively reduce the thinning of the hemispherical bottom and improve the drawing limit of the aluminum alloy cylindrical cup. In viscous pressure forming, T.Altan [14] et al. studied the viscous deep drawing process through finite element simulation and used the limit damage value as a criterion to judge the formability and found that the parts obtained by deep drawing with viscous medium as a soft die have a more uniform wall thickness than those obtained by deep drawing with rigid hemispherical die. Wang [15] et al. studied the coupling effect of viscous medium and sheet metal during deformation of sheet parts with complex shapes, i.e., the influence of non-uniform pressure field induced by viscous adhesion force produced by viscous medium. They successfully formed thin-walled rings with large diameter variation by using viscous medium with different strain rate coefficients. Gao et al. [16] investigated the deformation law of PEI sheets with complex shapes during viscous warm bulging and the results showed that thin-walled PEI sheets with high quality can be formed under appropriate temperature conditions.

In this paper, based on the principle of viscous pressure forming and the characteristics of inverse hydroforming, viscous backpressure forming method is proposed aiming at the forming of hemispherical aluminum alloy parts with large deformation. It is expected that the good rheological properties and sealing properties of the viscous medium is available for further improving the formability and quality of the parts through backpressure controlling and process parameter optimization.

Forming Parts And Solutions

2.1 Part geometry and process analysis

The geometric shape and size of the hemispherical aluminum alloy part are shown in Fig. 1. The part is composed of a spherical crown area (A_1), a straight wall area (A_2), a rounded corner area (A_3), and a flange area (A_4). The spherical crown radius, straight wall length and fillet radius of the part are 50mm, 2mm, 8mm, respectively. The overall height, flange diameter and thickness of the part are 60mm, 120mm,

1mm, respectively. The material of the part is aluminum alloy LF2, and its mechanical properties are shown in Table 1.

Table 1 Mechanical properties of LF2 aluminum alloy sheet

Yield Strength/ MPa	Tensile strength/ MPa	Strength factor/ MPa	Work Hardening Index	Elongation/ %	Elastic module/ GPa
98	186	166	0.23	24	70

Assuming that the area of the blank remains constant before and after deformation, the blank diameter D can be obtained by Eq. (1):

$$D = \sqrt{\frac{4}{\pi} \sum A_i} = \sqrt{\frac{4}{\pi} (A_1 + A_2 + A_3 + A_4)} \quad (1)$$

Where $\sum A_i$ is total surface area of the part.

The blank diameter D calculated by Eq. (1) is 163.8mm, and the corresponding drawing coefficient is 0.62. Under normal circumstances, the drawing coefficient of hemispherical parts is 0.71. Therefore, the drawing coefficient of the blank in this work is so small that it cannot be formed in one step with a rigid die.

2.2 Experimental scheme and principle

The main quality problem in the forming of hemispherical parts is cracking and wrinkling as shown in Fig. 2. Cracking is generally caused by excessive thinning of the bottom of the hemispherical part due to the biaxial tensile stress state in the later stage of forming. Generally, low friction coefficient between blank and punch may lead to cracking at the bottom of parts, while high friction coefficient may retard local thinning and the cracking position moves from the top to 1/4~1/3 of the punch radius (Fig. 2(a)). Wrinkling often appears in the early or mid-stage of deformation caused by the compressive stress on the edge of the parts during deep drawing process, which exceeds the critical compressive stress. Wrinkling may appear in the flange area, i.e., outer wrinkling, and it may also appear in the suspended area in the gap between the punch and die, i.e., inner wrinkling (Fig. 2(b)). In the deep drawing process, cracking or wrinkling are generally related to blank holder force and material formability. Under the condition of not less than the drawing coefficient of the blank, the problem of cracking or wrinkling can be solved by adjusting the blank holder force, such as reducing the blank holder force to prevent the occurrence of cracking or increasing the blank holder force to restrain wrinkling in the flange area. However, if the part is so complex that beyond the material's limit formability. It is difficult to solve it by adjusting the blank holder force.

However, if the geometric shape of the blank is changed and the deformation law is adjusted appropriately during the forming process, so that a larger amount of deformation is dispersed to other areas, thereby improving the uniform deformation ability of the blank, accordingly one-step forming is still realizable. Therefore, according to the investigations [17], [18], considering the shape characteristics of the parts, the viscous backpressure forming method for hemispherical parts is proposed (as shown in Fig. 3). In the forming process, viscous medium is used as flexible die, combined with a rigid punch. Utilize the coupling effect between viscous backpressure and the punch, and the change of deformation induced by viscous backpressure, wrinkling and cracking can be avoided during the forming process. As a result, the uniformity of plastic deformation is improved and the high-quality part is able to be formed in one step.

Generally, the pressure required for the forward flexible die forming process is determined according to Eq. (2):

$$q = \frac{2\sigma_b t}{r} \quad (2)$$

Where, q is fluid pressure, σ_b is ultimate strength, t is thickness, r is curvature radius of forming surface.

The minimum clamping force of the equipment is determined according to Eq. (3):

$$F_T = qS \quad (3)$$

Where S is projected area of blank in contact with viscous medium.

Since the deformation process and deformation capacity of hemispherical aluminum alloy parts exceed the limit deformation capacity of LF2, it is of great significance to solve or to predict the cracking effectively for the analysis and determination of the deformation process. According to the theory of tensile instability and forming limit, the forming limit diagram of aluminum alloy LF2 sheet is determined by the bulging experiment with rigid hemispherical punch. In order to obtain the ultimate deformation capacity under different strain paths, nine sizes of parts were designed in the experiment as shown in Fig. 4. The length of the sample is 180mm, the middle width is 20mm~180mm with an interval of is 20mm. In order to study the strain evolution of the blank during deformation, electrochemical etching was used to print concentric circles with a diameter of 2.5/5 mm on the surface of the part before deformation. The parts deformed to the forming limitation are shown in Fig. 5.

Finite Element Analysis Of Forming Process

The viscous backpressure and loading path are the key factors affecting blank forming performance and forming quality. In order to that the high-quality hemispherical parts can be formed in one step, the effects of viscous backpressure and loading path on the forming process of hemispherical parts are analyzed by using the finite element software ANSYS / LS-DYNA. By the comparison of numerical

simulation and forming limit diagram of LF2, feasibility of the proposed method and its optimum process parameters can be determined. The finite element analysis model is shown in Fig. 6, composed of medium bin, viscous medium, blank, blank holder, punch. The plunger, blank, blank holder and punch are meshed with SHELL163 thin-shell elements, and viscous medium are meshed with SOLID164 solid elements; The friction coefficient between the blank and the blank holder and the media bin is 0.125; A pressure is set on the plunger, which can be transmitted to viscous medium as backpressure; A constant blank-holder gap, 0.01mm, is used.

3.1 Finite element analysis scheme

According to the mechanical properties of LF2 and Eq. (2), if the part is formed by a forward flexible die, the required pressure is 7.4MPa. Considering the characteristics of viscous backpressure forming method, the viscous backpressure is selected as 0, 6, 9, 12, 16 MPa respectively during finite element analysis. When the viscous backpressure is 0 MPa, it is equivalent to drawing with rigid punch. Meanwhile, three different loading path is used as shown in Fig. 7. Path I is to load the viscous backpressure after the rigid punch contacts the blank. Path II is to load the viscous backpressure after the punch stroke reaches 10mm. Path III is to load the viscous backpressure after the punch stroke reaches 20mm. Through the above method, appropriate viscous backpressure and loading path, which can improve the quality of the hemispherical part, is determined.

3.2 Finite element analysis results

3.2.1 Deformation process analysis

Fig 8 shows the central cross-sectional shape of the part under different CVP and loading path conditions when the punch stroke is 5, 15, and 25mm, respectively. It can be seen from Fig. 8 (a) that when the punch stroke is 5mm and the viscous backpressure is loaded under path I, because the suspended area between the punch and the blank holder is large and the viscous backpressure is directly loaded at the early stage of the deformation process, so a “inverse deep drawing” phenomenon appears due to viscous backpressure, namely a “pre-inverse forming”. And the greater the viscous backpressure, the more obvious the “pre-inverse forming” effect. However, for loading paths II and III (Fig. 8 (b), Fig. 8 (c)), the viscous backpressure is loaded during the deformation process. Due to the work hardening of the material and the suspended area decreases, the “pre-inverse forming” area is smaller. Also, the loading the viscous backpressure at a larger punch stroke (path III) could lead to the decrease of the “pre-inverse forming” area. It can also be seen from Fig. 8 that as the stroke of the punch increases, the space between the punch and the blank holder gradually decreases. As a result, the “pre-inverse forming” effect gradually disappears and gradually changes from “inverse deep drawing” to “forward drawing” until the blank fits the mold completely.

3.2.2 Stress-strain analysis

Fig. 9 shows the maximum equivalent stress distribution of the formed parts under different viscous backpressure and loading path conditions. It can be seen that the maximum equivalent stress of the part after the pressure of the viscous backpressure is reduced compared with that without the viscous backpressure, and the greater the pressure of the viscous backpressure, the greater the reduction of the equivalent stress. Under the three paths, compared with the case of path Ⅰ and path Ⅱ, the equivalent stress decreases more in the case of path Ⅲ. This shows that the earlier the viscous backpressure is loaded, the better the “inverse pre-forming” effect, and the more conducive to the forming of hemispherical parts. Fig. 10 shows the minimum wall thickness distribution of formed parts under different viscous backpressure and loading paths. The minimum wall thickness under the three paths with viscous backpressure is higher than that of 0.56 mm without viscous backpressure. And with the increase of the viscous backpressure, the minimum wall thickness of the part continues to increase. At the same time, due to the viscous backpressure, the position of the minimum wall thickness of the part has also changed. Compared with the position of the minimum wall thickness at the top of the part when there is no viscous backpressure, the position is transferred to the fillet area in the condition with backpressure, which is consistent with the equivalent stress distribution result (see Fig. 9).

The above analysis results show that, on the one hand, a “pre-inverse forming” effect appears under the combined effect of the viscous backpressure and the rigid punch, which changes the deformation law of the blank. At the same time, due to the change of the geometry of the blank in the deformation process, the stress and strain state has also changed greatly, including the maximum equivalent stress and its location, the maximum wall thickness reduction and its location, resulting in the improvement of the uniformity during deformation. On the other hand, the blank clings to the punch under a higher backpressure, which increases the contact area between the blank and the punch. At the same time, there will be a large viscous friction between the viscous medium and the blank. Under the influence of “double friction” between rigid die and viscous medium, it can not only effectively improve the bearing capacity of force transfer zone, but also prevent the occurrence of “inner wrinkling” in the forming process. Therefore, the earlier the viscous backpressure is loaded, and the higher the pressure, the more conducive to the forming of high-quality parts.

Fig. 11 shows the major and minor strain in forming limit diagram under different viscous backpressure and loading paths. It can be seen that the forming limit of the part is in the rupture zone during forming without the viscous backpressure, which means that the part cannot be formed in one step. Only in the condition of path I with a viscous backpressure $\geq 12\text{MPa}$, the forming limit of the part is in the safe zone, and the hemispherical part can be formed in one step.

Experimental Verification

As shown in Fig. 12, experiments were carried out on a 1,000kN four-column universal hydraulic press. In the experiment, the deep drawing force of the rigid hemispherical punch is provided by the movable beam of the hydraulic press. The viscous backpressure is provided by the hydraulic ejector cylinder. And the medium bin and blank holder are fixed on the workbench through six M20 bolts and pressing plates, so

as to realize constant gap blank holder. In the forming process, the viscous backpressure of different sizes can be obtained by adjusting the relief valve of the hydraulic circuit.

From the results of finite element analysis, it can be seen that the parts are cracked in the conditions of loading paths Ⅱ and Ⅲ. Therefore, only path I is verified in the experiment. Fig. 13 shows hemispherical aluminum alloy parts in initial stage under different viscous backpressure in loading path I. It can be seen that the “pre-inverse forming” effect appears due to the viscous backpressure in initial stage. With the increasing of viscous backpressure, the height and area of the “pre-inverse forming” area become larger

Fig. 14 shows the comparison of the of the part under different viscous backpressure for loading path I. With the increase of the viscous backpressure, the ultimate deep drawing height of the hemispherical aluminum alloy parts continues to increase. And when the viscous backpressure is 12.5 or 16MPa, hemispherical parts meeting the requirements are formed. Fig. 15 shows the wall thickness distribution of the formed parts under different viscous backpressure in loading path Ⅱ. When the viscous backpressure is 7.0MPa, the minimum wall thickness position appears in the middle of the part, which is 0.73mm. When the viscous backpressure is 12.5MPa, the minimum wall thickness position of the part moves from the top to the fillet area, which is 0.81mm. It can also be seen that the uniformity of the deformation is also different under different viscous backpressure. When the viscous backpressure is ≥ 12.5 MPa, the wall thicknesses at different positions of the part are similar, indicating that the material flow is more uniform. The above experimental results are consistent with the finite element analysis results.

Conclusions

1. By changing the loading path and the viscous backpressure, the distribution law of stress, strain and wall thickness of hemispherical parts is compared and analyzed. It is found that the viscous backpressure directly loaded in the early stage of forming is better than that loaded during the forming process. When the whole process is loaded with viscous backpressure ≥ 12 MPa, the hemispherical aluminum alloy parts that meet the requirements can be formed in one step.
2. In the viscous backpressure forming process of hemispherical parts, with the increase of viscous backpressure, the blank forms a “pre-inverse forming” effect. The earlier the load is applied and the larger the viscous backpressure is, the more obvious the “pre-inverse forming” effect is, and more conducive to the improvement of uniformity in deformation and wall thickness distribution.
3. By controlling the loading path and viscous backpressure, the geometry shape of the part is changed and furtherly contributing to the stress-strain states changing to an expected way. Therefore, the uniformity of the blank deformation is improved, and the ultimate deformation capacity of the blank is continuously increased.

Declarations

Acknowledgments The authors are grateful to the National Natural Science Foundation of China (No. 52075347, 51575364) and the Liaoning Innovation Talents in University (No. LR2017069) for supporting

the investigation.

- Funding: The National Natural Science Foundation of China (No. 52075347,51575364). The Liaoning Innovation Talents in University (No. LR2017069).
- Conflict of interest/Competing interests: There is no conflict of interest in this article.
- Availability of data and material: The data and materials of this article are obtained in the experiment and are real data.
- Code availability('Not applicable'):This article has no code.
- Ethics approval: This article has no problems with ethics approval and it has been approved by all parties.
- Consent to participate: All parties have agreed.
- Consent for publication: Agree to publish by your magazine.
- Authors' contributions: The three authors have made relevant contributions to the experiment, data processing or thesis writing.

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Figures

Figure 1

Geometric shape and size of hemispherical parts

Figure 2

Quality defects in the forming process of hemispherical parts. (a)Cracking. (b) Wrinkling

Figure 3

Principle and process of viscous backpressure forming. (a) Initial stage. (b) Mid stage. (c) Late stage

Figure 4

Shape and size of the forming limit parts

Figure 5

Parts after LF2 forming limit

Figure 6

Figure 7

Figure 8

The cross-sectional shape of the part under different strokes and paths(a) Punch stroke 5mm. (b) Punch stroke 15mm. (c) Punch stroke 25mm

Figure 9

The maximum equivalent stress of the part under different loading paths and backpressure

Figure 10

The minimum wall thickness of the part under different loading paths and backpressure

Figure 11

The major strain and minor strain under different loading paths and backpressure

Figure 12

Experimental device

Figure 13

The initial forming parts of loading path $\square$ under different backpressure

Figure 14

The comparison of the ultimate drawing height of the part under different backpressure for loading path I

Figure 15

The wall thickness distribution of the formed parts under different backpressure in the loading path

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