Viscous backpressure forming and feasibility study of hemispherical aluminum alloy parts

Tiejun Gao · Jiabin Zhang · Kaixuan Wang

Received: 27 August 2021 / Accepted: 30 December 2021 / Published online: 14 January 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

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 12.5 MPa. This provides a reference for the backpressure forming of hemispherical aluminum alloy parts.

Keywords Hemispherical parts · Viscous medium · Aluminum alloy · Backpressure · Finite element analysis

1 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[5, 6].

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 obtain parts meet the requirements. Yilmaz 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 hydraulic 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, Liu et al. [14] 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 et al. [15] 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. However, there are relatively few studies on the viscous backpressure forming. Only a few people such as

---

Fig. 1: Geometric shape and size of hemispherical parts

---

Table 1: Mechanical properties of LF2 aluminum alloy sheet

| Yield Strength/MPa | Tensile strength/MPa | Strength factor/MPa | Work Hardening Index | Elongation/% | Elastic modulus/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):

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

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

The blank diameter $D$ calculated by Eq. (1) is 163.8 mm, and the corresponding drawing coefficient is 0.62. Compared with other shape parts, the deep drawing process of hemispherical parts is more complicated, and there are many influencing factors (as shown in Fig. 2). Under normal circumstances, the drawing coefficient of hemispherical parts is 0.71 [19]. Therefore, the drawing coefficient of the LF2 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 $1/4 \sim 1/3$ 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 [20, 21], 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) [19]:

$$q = \frac{2\sigma_b t}{r}$$

where, $q$ is fluid pressure, $\sigma_b$ is ultimate strength, $t$ is thickness, $r$ is the radius of the circular projection area of the punch.

The minimum clamping force of the equipment is determined according to Eq. (3) [19]

$$F_T = qS$$

where, $F_T$ is the minimum clamping force of the equipment, $S$ 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 180 mm, the middle width is 20 mm ~ 180 mm with an interval of 20 mm. 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.

3 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 contact type between the blank and the blank holder and the punch is coulomb friction, and the friction coefficient is 0.10; the contact type between the blank and the viscous medium is Contact, and the friction coefficient is 0.125; a pressure is set on the plunger, which can be transmitted to viscous medium as backpressure; a constant blank-holder gap, 0.01 mm, 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 7.4 MPa. 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 10 mm. Path III is to load the viscous backpressure after the punch stroke reaches 20 mm. 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

Figure 8 shows the central cross-sectional shape of the part under different viscous backpressure and loading path conditions when the punch stroke is 5, 15, and 25 mm, respectively. It can be seen from Fig. 8(a) that when the punch stroke is 5 mm 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 decrease of suspended area, 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 punch completely.

3.2.2 Stress–strain analysis

Figure 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 II and path III, the equivalent stress decreases more in the case of path I. 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. Figure 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.

Figure 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 $\geq 12$ MPa, the forming limit of the part is in the safe zone, and the hemispherical part can be formed in one step.

4 Experimental verification

As shown in Fig. 12, experiments were carried out on a 1,000 kN four-column universal hydraulic press. And the viscous medium material is methyl vinyl silicone rubber with the molecular weight of 600 kg/mol [16]. 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 holder blank gap holder. In the forming process, the viscous backpressure of different values 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. Considering the error of the finite element results, the viscous backpressure during the experiment is slightly higher than that of the finite element. Therefore, the viscous backpressure used in the experiment was 0, 7.0, 9.7, 12.5, 15.3 MPa, respectively.

Figure 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.

Figure 14 shows the comparison of the limit deep drawing height of the part under different viscous backpressure in loading path I. When the viscous backpressure is 0, 7.0, 9.7, 12.5 MPa, the limit deep drawing height of the part is 43.6, 47.7, 56.1, 60 mm, respectively. With the increase of the viscous backpressure, the limit deep drawing height of the hemispherical aluminum alloy parts continues to increase. And when the viscous backpressure is $\geq 12.5$ MPa, the required hemispherical parts are successfully obtained. Figure 15 shows the wall thickness distribution of the formed parts under different viscous backpressure in loading path I. When the viscous backpressure is 0 MPa, the minimum wall thickness position appears in 20 mm away from the center of the part, which is 0.73 mm. When the viscous backpressure is 7.0 MPa, the minimum wall thickness position appears in the middle of the part, which is 0.74 mm. When the viscous backpressure is 12.5 MPa, the minimum wall thickness position of the part moves from the top to the fillet area, which is 0.81 mm. It can also be seen that the uniformity of the deformation is also different under different viscous backpressure. When the viscous backpressure is $\geq 12.5$ 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.
This paper proposed a viscous backpressure forming method for hemispherical aluminum alloy parts. Based on the principle of viscous pressure forming and material forming limit diagram theory, the deep drawing and finite element analysis of aluminum alloy were carried out. By changing the loading path and the viscous backpressure, the distribution law of stress, strain and wall thickness and of hemispherical parts is compared and analyzed. The research results found that by controlling the loading path and viscous backpressure, the geometric shape of the part will change, forming a certain “pre-inverse forming” effect. In the viscous backpressure forming process of hemispherical parts, the earlier the load was applied, the larger the viscous backpressure was.

Fig. 13 The initial forming parts of loading path I under different backpressure

(a) 7.0MPa

(b) 9.7MPa

(c) 12.5MPa

(d) 15.3MPa

Fig. 14 The comparison of the limit deep drawing height of the part under different backpressure for loading path I

Fig. 15 The wall thickness distribution of the formed parts under different backpressure in the loading path I

5 Conclusions

This paper proposed a viscous backpressure forming method for hemispherical aluminum alloy parts. Based on the principle of viscous pressure forming and material forming limit diagram theory, the deep drawing and finite element analysis of aluminum alloy were carried out. By changing the loading path and the viscous backpressure, the distribution law of stress, strain and wall thickness and of hemispherical parts is compared and analyzed. The research results found that by controlling the loading path and viscous backpressure, the geometric shape of the part will change, forming a certain “pre-inverse forming” effect. In the viscous backpressure forming process of hemispherical parts, the earlier the load was applied, the larger the viscous backpressure was,
the more obvious the “pre-inverse forming” effect was, and more conducive to the improvement of uniformity in deformation and wall thickness distribution. And when the viscous backpressure was loaded during the whole process and the value was $\geq 12.5$ MPa, the parts that meet the requirements can be formed.

Acknowledgements The authors are grateful to the National Natural Science Foundation of China (No. 52075347, 51575364) and the Liaoning Basic Scientific Research Projects in University (No. LJKZ0192) for supporting the investigation.

Author contributions The three authors have made relevant contributions to the experiment, data processing or thesis writing.

Funding The National Natural Science Foundation of China (No. 52075347, 51575364). The Liaoning Basic Scientific Research Projects in University (No. LJKZ0192).

Availability of data and material The data and materials of this article are obtained in the experiment and are real data.

Code availability This article has no code.

Declarations

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.

Conflict of interest/Competing interests There is no conflict of interest in this article.

References

1. Hu WQ, Jin T, Liu Y (2019) Effects of environmental regulation on the upgrading of Chinese manufacturing industry. Environ Sci Polit Res 26(26):27087–27099
2. Dong-Hwan P, Hyuk-Hong K (2015) Development of warm forming parts for automotive body dash panel using AZ31B magnesium alloy sheets. Int J Precis Eng Manuf 16(10):2159–2165
3. Nazih T, Mohamed A, Saîd A, Amine R (2020) Transition between severe and mild wear of 2024A–T4 anodized aluminum alloy under severe wear conditions. J Korean Phys Soc 76(10):899–903
4. Farhad Y, Saeed KM, Mohsen K (2020) Sound velocity in severely deformed aluminum alloys: AA1100 and AA2024. Appl Phys A Mater Sci Process 126(4):222–483
5. Bai Q, Mohamed M, Shi Z, Lin J, Dean T (2017) Application of a continuum damage mechanics (CDM)-based model for predicting formability of warm formed aluminium alloy. Int J Adv Manuf Technol 88(9–12):3437–3446
6. Selvamani ST, Umanath K, Palanikumar K, Vinothkumar P, Madhu G (2015) Developing the empirical relationship to predict the minimum microhardness of AISI 1020 grade low carbon steel joints. Appl Mech Mater pp 765–769
7. Gao TJ, Liu Y, Chen P, Wang ZJ (2015) Analysis of bulging process of aluminum alloy by overlapping sheet metal and its formability. Trans Nonferrous Met Soc China 25(4):1050–1055
8. Gao TJ, Yao YJ, Wang XK, Shao RW (2019) Effect of interface friction on overlapping sheets bulging formability and microstructure of 5A02 aluminum alloy. J Wuhan Univ Technol (Mater Sci) 34(04):919–924
9. Tao YR (2009) Experimental study and numerical simulation of the drawing of hemisphere-shaped FVS0812 part. Mech Sci Technol Aerosp Eng 28(6):814–818
10. Yilamu K, Hino R, Hamasaki H, Yoshida F (2010) Air bending and springback of stainless steel clad aluminum sheet. J Mater Process Technol 210(2):272–278
11. Sun ZY, Lang LH, Li K, Wang Y, Zhang QD (2017) Study on the mechanism and the suppression method of wrinkling in side wall using hydroforming of the fairing. Int J Adv Manuf Tech 90(9–12):2527–2535
12. Sun ZY, Lang LH (2017) Study on hydroforming process and springback control of large sheet with weak rigidity. Int J Precis Eng Manuf 18(6):903–912
13. Liu XJ, Xu YC, Yuan SJ (2009) Formation of aluminum-magnesium alloy cup by hydrodynamic deep drawing with twin-loading paths. J Wuhan Univ Technol-Mater Sci Edition 24(2):193–197
14. Liu J, Ahmetoglu M, Alfant T (2000) Evaluation of sheet metal formability, viscous pressure forming (VPF) dome test. J Mater Process Technol 98(1):1–6
15. Wang ZJ, Xiang N, Yi J, Song H (2016) Forming thin-walled circular rings with corrugated meridians via quasi-bulk deformation of metal blank and viscous medium. J Mater Process Technol 236:35–47
16. Gao TJ, Liu Q, Lv Y (2017) Investigation on feasibility and process of PEI sheet by viscous warm pressure forming. Int J Adv Manuf Technol 91(5–8):2143–2149
17. Wang XY, Xia J, Hu GA, Wang ZJ, Wang ZR, Yang HF (2002) Experimental investigations on aluminum and titanium alloy sheet viscous medium bulging with backpressure. Met Form Technol 20(06):12–15
18. Wang Z (2009) Study on the effects of normal pressure loading mode on sheet metal plastic deformation behavior. Dissertation, Harbin Inst Technol
19. Chinese Society for Technology of Plasticity, CMES (2008) Forging manual. China Machine Press, Bei Jing
20. Lang LH, Wang Y, Li K, Sun ZY, Zhang QD (2016) Factors influencing inverse bulging effect in sheet hydroforming. J Jilin Univ (Eng Tech Edition) 46(05):1567–1576
21. Liu XJ, Xu YC, Yuan SJ (2008) The influence of inverse bulging pressure on the hydrodynamic deep drawing process of aluminium alloy cylindrical cups with a hemispherical bottom. J Plast Eng 03:42–46

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.