Investigation on granular medium forming formability of TA1 titanium alloy cylinder-shaped parts

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Abstract
In order to investigate the formability of the granular medium forming (GMF) based on the Mohr–Coulomb constitutive model with the tri-axial compression test of granular medium and the true stress–strain curves of TA1 titanium alloy from uniaxial tensile tests, the numerical simulation of TA1 titanium alloy sheet deep drawing with finite element method was performed, and the deep drawing tests were also carried out. Simulation analysis and test results show that the GMF process is suitable for titanium alloy sheets and can effectively improve the uniformity of the wall thickness of the formed parts, reduce the tendency of wrinkles, and improve the forming quality.

Keywords TA1 titanium alloy · Granular medium forming · Numerical simulation

1 Introduction
At present, with the wide application of lightweight components in aviation, aerospace, automobile, energy, and other fields, higher and higher requirements are put forward for the advanced forming technology of lightweight alloy thin-walled parts. There are many limitations in the existing processing methods, which cannot meet the increasingly demanding processing requirements. In order to solve this problem, research institutions of various countries have proposed a variety of processes to improve the forming quality of lightweight parts [1–4].

The GMF process, which uses granules as a pressure-transfer medium in order to form a workpiece, is a newly proposed flexible die-forming technique [5–8]. Because the application of this process can fully exploit recent advances in the formability of lightweight materials at elevated temperatures, as well as overcome the limitations that the heat-resistant oil used in warm hydroforming operations can withstand temperatures of no more than 350 °C [9–11] and that the inert gas used at higher temperatures in hot pneumatic bulging processes usually causes leakage problems [12, 13], the GMF process has recently attracted considerable attention by several researchers.

The principle of the GMF technology is shown in Fig. 1. A sheet is placed on the concave die; the charging barrel is pressed on the sheet, thus playing the role of edge pressing and sealing; then, the granular medium is loaded into the charging barrel, and pressure is applied to the convex die block, and the pressure is transferred to the sheet through the granular; the middle part of sheet firstly produces plastic deformation because it is subjected to the action of bidirectional tensile stress under the action of forming pressure, and then, the flange material gradually enters the die under the action of radial tensile stress,
and finally, the sheet is completely attached to the die and formed into the cavity shape of the die [14].

Cylinder-shaped part is the most classic and the most representative part, which can well show the uniformity of wall thickness and wrinkle phenomenon of the formed parts. Many researchers take cylinder-shaped parts as the research object to study the forming process formability. Zhao [15] et al. conducted an experimental study on the granular soft die deep drawing of cylinder-shaped parts and found that the thickness of each part of the forming parts decreased and the thinning amount increased with the increase of the depth of the drawing. Chen [16] et al. took cylinder-shaped parts as the research object and studied the influence of liquid chamber pressure loading path, forming liquid chamber pressure, blank holder force, and blank holder clearance on the sheet hydroforming effect. It is found that the reasonable pressure loading path and blank holder gap of the liquid chamber can effectively control the wrinkle in the flange area of the part and prevent the punch from cracking. At present, the researchers mainly used the cylinder-shaped parts to study the hydroforming process and the granular soft die forming process formability; however, very few investigation concentrates on the GMF process formability, which is a main target of this research.

Therefore, the purpose of this study is to investigate the GMF formability of TA1 titanium alloy cylinder-shaped parts. In this work, the simulation calculation and experimental verification of the GMF process are conducted. In order to improve the accuracy of simulation calculation, the dynamic flow characteristics of granular materials were obtained by the tri-axial compression test and the mechanical property data of TA1 titanium alloy sheet were obtained by uniaxial tensile test. As this study presents a new and precise approach of investigating the GMF formability, it is important to carry out further studies of the GMF formability and provide a new method of forming manufacturing titanium alloy cylinder-shaped parts.

### 2 Material formability test

#### 2.1 Tri-axial compression test of granular medium

In this study, the yttria-stabilized tetragonal zirconia polycrystals (TZP) ceramic beads provided by Zibo Yubang company is used as the force transfer medium (Fig. 2), and its basic performance parameters are shown in Table 1. Zirconia ceramic is a new type of ceramic, which has the advantages of high temperature resistance and good thermal stability. Its melting point can reach 2650 °C; it is monoclinic system at low temperature, and the transition temperature between monoclinic phase and tetragonal phase is 1150 °C, which can maintain good mechanical properties between 0 and 1150 °C [17, 18]; and the material does not react with titanium alloy at high temperature, which fully meets the needs of high-temperature GMF process.

In order to explore the flow and deformation characteristics of granular medium in the forming process, domestic and foreign scholars have used a variety of measurement methods, including axial static pressure transmission formability test and direct shear test [14, 19]; however, these methods are unable to reflect the dynamic flow properties of the granular material during the compression deformation process; therefore, it is not suitable for studying the dynamic flow characteristics of granular materials in the GMF process. The tri-axial compression test, which is a relatively mature geotechnical test method, is suitable for measuring the dynamic compression deformation characteristics of granular materials under the condition of triaxial compressive stress. Therefore, in order to determine the parameters of the Mohr–Coulomb model of

![Fig. 1 Schematic of granular medium forming process [14]](image1)

![Fig. 2 Yttria-stabilized Tetragonal Zirconia Polycrystals (TZP) ceramic beads](image2)

| Parameters                  | Value |
|-----------------------------|-------|
| Density (g/cm³)             | 6.0   |
| Elastic modulus (Gpa)       | 220   |
| Fracture toughness (Mpm¹/₂) | 8     |
| Melting point (°C)          | 2650  |
| Surface hardness (HRA)      | 88–90 |
granular materials, the tri-axial compression test is selected to determine the deformation characteristics and pressure transmission laws of granular materials.

When the Mohr–Coulomb strength theory index is obtained by the tri-axial compression test, the Mohr circle of stress when the material fails (or yields) under different confining pressure levels should be drawn, and then, the outer circle of different Mohr circle of stress is the shear strength line of the geotechnical material. In three-dimensional stress space, the yield surface of Mohr–Coulomb strength theory is a hexagonal pyramid with hydrostatic stress line as symmetry axis (Fig. 3), and its intersection line with the π plane is not a regular hexagon inscribed to the Mises circle. In addition, it should be noted that the positive direction of each coordinate axis is the direction of compressive stress, which is opposite to the symbol in the calculation of metal plastic deformation. In the three-dimensional stress space, the Mohr–Coulomb yield surface function is expressed as follows [20]:

\[ F = R_{mc} q - p \tan \varphi - c = 0, \]  \hspace{1cm} (1)

\[ R_{mc}(\Theta, \varphi) = \frac{1}{\sqrt{3 \cos \varphi}} \sin \left( \Theta + \frac{\pi}{3} \right) + \frac{1}{3} \cos \left( \Theta + \frac{\pi}{3} \right) \tan \varphi, \]  \hspace{1cm} (2)

where \( \varphi, c \) are the internal friction angle and cohesion of the material, respectively, \( \Theta \) is the polar deflection angles of the stress state point of the material in the \( \pi \) plane, and \( p, q, r \) are the invariants of the first, second, and third stress states, respectively:

\[ p = \text{trace}(\sigma), \]  \hspace{1cm} (3)

\[ q = \sqrt{3/2S : S}, \]  \hspace{1cm} (4)

\[ r = \sqrt{9/2S : S}, \]  \hspace{1cm} (5)

\[ S = \sigma + pl, \]  \hspace{1cm} (6)

The parameters of Mohr–Coulomb model obtained by tri-axial compression test are shown in Fig. 4. It can be seen from the figure that the Mohr–Coulomb friction model of non-metallic granular material selected in this study has good fluidity and can effectively transfer the forming deep drawing force with the cohesion \( C = 1.6255 \text{kPa} \) and the internal friction angle \( \varphi = 14.9352^\circ \).

2.2 High-temperature uniaxial tensile test of TA1 titanium alloy

In order to obtain the tensile property of titanium alloy TA1 material at high temperatures, the high-temperature uniaxial tensile test was carried out on the sheet of titanium alloy TA1 with the thickness of 1.0 mm. The test was conducted on ZWICK unidirectional tensile testing machine of Shougang Research Institute. The effective heating length of the furnace was 300 mm, and the clamping scheme of superalloy pin was adopted. High-temperature uniaxial tensile tests were carried out at same temperatures (500 °C) and at different strain rates (0.1 s\(^{-1}\), 0.02 s\(^{-1}\), 0.005 s\(^{-1}\)).

The uniaxial tensile specimen used in the test generally has a rectangular section and a certain length of parallel section. The strain value of sheet specimen in the deformation process can be measured by an extensometer clamped in the width and length direction of uniaxial tensile specimen, and then, the stress can be calculated by obtaining the real-time tension at both ends of the tensile testing machine [21, 22]. However, the accuracy of the stress and strain measurement method is based on the deformation uniformity of the specimen. When the uniaxial tensile
specimen exhibits dispersive instability (necking), the measured stress–strain curve will have errors. Therefore, the extensometer measurement method can only obtain the material flow stress variation before necking. For sheet metal plastic deformation process, especially the forming process of bulging and deep drawing with the characteristics of two-way drawing deformation, the ultimate strain of the material in the uniform deformation stage is often much larger than the strain value in uniaxial tensile test. In the simulation analysis of forming process, if the material mechanical behavior before necking obtained by uniaxial tensile test is used as the basis to predict the plastic deformation process of sheet metal, a large error will be generated. In order to obtain the accurate stress–strain curve of titanium alloy TA1 material after necking, a reverse modeling algorithm which is based on FEA method proposed by Lang [23] et al. was adopted in this study. The reverse modeling process flow chart is shown in Fig. 5. Figure 6 shows the stress–strain curves optimized by iterative steps in reverse modeling at different strain rates (0.005 s\(^{-1}\), 0.02 s\(^{-1}\), 0.1 s\(^{-1}\)). It can be seen that, under the condition of 500 °C, the lower the strain rate, then the higher the maximum elongation; however, different strain rates have no significant effect on the hardening curve.

3 Numerical simulation of GMF process for cylinder-shaped parts

3.1 Numerical simulation of GMF process

The thickness uniformity of the parts formed by the traditional hot stamping process is poor, and wrinkles are prone to occur; so, it is difficult to meet the processing needs of the cylinder-shaped parts. The optimum forming temperature of titanium alloy is generally higher than 500 °C, while the highest heat-resistant temperature of heat transfer oil does not exceed 350 °C. Therefore, the hydraulic oil widely used in the conventional liquid-filled forming process no longer meets the requirements of titanium alloy thermal medium forming, and low melting point alloy, viscous medium or non-metallic ceramic particles must be used as the forming medium. In consideration of safety and sealing, the TZP ceramic beads (Fig. 2) are selected as the force transmission medium.

Figure 7 shows a schematic diagram of the GMF process, where a fluid granular medium to replace the rigid punch. During the forming process, the flexible punch continuously changes the contour of the bottom along with the deformation of the material, thereby ensuring that the plate maintains proper normal stress support in the thickness direction, reducing the tendency of wrinkling and improving the formability.

In this study, the simulation is based on ABAQUS/explicit dynamic algorithm and uses the Lagrangian element calculation model and elastoplastic model. The material parameters of titanium alloy obtained from high-temperature uniaxial tensile test and the pressure-transfer parameters of granular medium obtained from tri-axial compression test, which were used to establish the calculation model of the GMF process as shown in Fig. 8. The thickness of TA1 sheet
is 1 mm, the test temperature is selected as 500 °C, and the fixed gap between blank holder and die is 1.2 mm. The cavity in the central part of the blank holder is filled with liquid granular material with particle size of 0.117–0.14 mm [24].

### 3.2 Analysis of simulation results

The calculation and analysis results are shown in Fig. 9. It can be seen that under the conditions of different billet diameters (160 mm, 180 mm) and different forming heights (42.5 mm, 44 mm, 58.3 mm, 81.5 mm), the forming parts all show good forming formability.

It can also be seen that during the GMF process, the minimum wall thickness appears in the central area of the pass bottom, and the wall thickness value increases uniformly from this area to the edge of the part. The formed part has good uniformity of wall thickness, and its maximum thinning rate is only 18%.

### 4 High-temperature granular medium test of TA1 titanium alloy cylinder-shaped part

#### 4.1 Experimental equipment and material

In order to evaluate the accuracy of simulation calculation of the GMF process, the high-temperature GMF experiment was carried out on YRJ-50 sheet metal experimental machine independently developed by Beijing University of Aeronautics and Astronautics. The inner diameter of the charging barrel is 80 mm, the inner diameter of the die is 85 mm, the thickness of TA1 titanium alloy sheet is 1 mm, and the blank holder clearance is 1.2 mm. The diagram of the high-temperature GMF test die is shown in Fig. 10. Under the condition of 500 °C, TA1 titanium alloy sheet with blank diameter of 160 mm and 180 mm was formed with different depth of drawing.

Under the condition of high temperature, colloid graphite water agent is selected as lubricant, which smears on the surface of the blank and waits for drying. Graphite water agent not only plays the role of lubrication but also can effectively prevent oxidation on the surface of titanium alloy plate under high-temperature conditions. The forming process is controlled by constant drawing rate, and the drawing rate is 5 mm/min.

#### 4.2 Part forming process analysis

The parts formed under the condition of master cylinder pressure of 40 tons of equipment are shown in Fig. 11. It can be seen that the surface of the formed parts is smooth without wrinkling. The three dimension coordinate measurement and the measurement of the wall thickness distribution of the parts with forming height $H = 58.3$ mm and $H = 81.5$ mm were carried out, and the results were compared with the simulation results. The comparison results under corresponding forming conditions are shown in Fig. 12. It can be seen from the figure that the test data points are in good agreement with the simulation curve, reflecting that the material parameters obtained from the tri-axial compression test and high-temperature uniaxial tensile test can accurately characterize the flow deformation law of granular medium and TA1 titanium alloy sheet under high-temperature conditions, as well as the accuracy of the simulation results.

It can be seen from Fig. 11 that the formed part presents a good geometric symmetry. Not only that, the part always shows a good geometric symmetry in the process of the whole forming. This is due to the symmetrical forming pressure provided by the granular medium. Moreover, it is obviously observed from Fig. 12a that the bottom contour of the part is an arc surface under high-temperature conditions.
and the curvature of the bottom contour of the part keeps increasing and finally fits with the concave die surface with the increasing of the depth of drawing. According to the distribution curve of the bottom wall thickness of the part shown in Fig. 12b, the minimum bottom central wall thickness of the part forming height of 58.3 mm and 81.5 mm is 0.92 mm and 0.80 mm, respectively. Combined Fig. 12a with Fig. 12b, it can be seen that the deformation characteristics of the blank in the granular medium forming process are different from those in the active liquid-filling/air-expanding forming process. The blank deformation of the GMF process is not achieved by thinning and deep drawing. The forming process is accompanied by the flow of the blank, so that the plate has a more uniform wall thickness distribution.

Fig. 9 Results of numerical simulation

Fig. 10 Diagram of experimental equipment for hot granular medium forming
Conclusion

Using a combination of numerical simulation and experimental verification, a GMF experiment was conducted on titanium alloy sheets in order to investigate and verify the formability of granular medium forming. The main conclusions were summarized as follows.

1. In order to improve the accuracy of simulation calculation, the dynamic flow characteristics of granular materials were obtained by the tri-axial compression test and the mechanical property data of TA1 titanium alloy sheet were obtained by uniaxial tensile test. The simulation results have been compared with the experimental data and good agreement has been achieved.

2. The results of simulation and experiment show that the cylinder-shaped parts of titanium alloy formed by the GMF process have a good uniformity of wall thickness and geometric symmetry.

3. Under the action of compressive stress in the thickness direction, the wrinkling tendency of titanium alloy parts is effectively suppressed and the forming quality is improved.

Author contributions Conceptualization: GC, BH, and KL; methodology: GC, KL, BH, and LL; software: JF, YX, and KL; experiments: BH and KL; validation: GC, BH, and KL; formal analysis: GC, BH, and LL; investigation: JF; resources: GC; data curation: YX; writing—original draft preparation: BH and GC; writing—review and editing: GC, BH, and JF; visualization: LL; supervision, YX; project administration: JF; funding acquisition: GC.

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Data availability All the data presented and/or analyzed in this study are available upon request to the corresponding author.

Conflict of interest The authors declare no conflict of interest.

Informed consent The author agrees to publication in the International Journal of Advanced Manufacturing Technology and confirms that the work described has not been published before, and its publication has been approved by all co-authors.
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