

# Research on the Forming Process of Large-Diameter and Thin-Walled Shells Made of Titanium Alloy

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## Abstract

For the local defects such as thinning and thickening in the process of hot stamping of titanium alloy shells, the evolution process, mechanism and causing thinning of the equivalent stress strain at different casting temperatures are analyzed, and the results show that the equivalent stress after forming decreases with the increase of temperature and the minimum thinning is at 800°C. It is necessary to formulate a reasonable stamping and turning process for the hot stamping forming of large diameter thin-walled titanium alloy, and the hot treatment after stamping forming is very necessary; a reasonable turning process can improve the qualified rate of finished products.

## Keywords

Spherical Head, Titanium Alloy, Hot Stamping, Finite Element Analysis

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## 1. Introduction

The manufacturing of thin-walled shells is a multi-process cooperative endeavor that involves both stamping deformation and heat transfer processes. It encompasses not only the stamping forming process but also the heat exchange between the sheet material and the air, as well as between the sheet material and the mold. These processes all impact the forming quality of the shell, and there are currently not many studies focused on this aspect. This paper analyzes the variation laws of equivalent stress and equivalent strain of titanium alloy shells over time at different temperatures, the variation laws of the thinning amount, and the influences of the die-out temperature and friction coefficient on them. The findings provide

valuable guidance for the high-quality hot stamping manufacturing of titanium alloy shells.

## 2. Geometric Modeling and Mesh Generation

The stamping forming process of the shell component represents an extremely complex plastic deformation phenomenon, incorporating both geometric nonlinearity and physical nonlinearity characteristics. In this study, the elastoplastic finite element method was employed, which comprehensively considers both elastic effects and plastic behavior during metal deformation. The theoretical foundation is based on the Prandtl-Mises constitutive equation, with simulations conducted using DEFORM-3D—a specialized finite element analysis platform specifically developed for metal plastic processing applications.

The inner diameter of the shell is  $\phi 2000$  mm, with a thickness of 16 mm. Due to the high strength of the titanium alloy, the upper die of the stamping mold uses a spherical punch with a diameter of  $\phi 2000$  mm, while the lower die adopts a drop-through design with an inner diameter of  $\phi 2040$  mm. To reduce stress concentration at sharp corners of the mold, the inner edges are rounded with a radius of R80 mm. The blank size is  $\phi 2400$  mm  $\times$  16 mm, and the material of the blank is TC4 titanium alloy.

The geometric models of the die and blank were created using 3D design software UG and then imported into DEFORM-3D for meshing. A relative meshing approach was employed, where by inputting the required mesh quantity and selecting tetrahedral elements, the automatic mesh generation was completed.

Mesh independence verification was conducted, with the primary focus on the sheet metal deformation behavior. The results demonstrate that when the number of mesh elements for the blank exceeds 41,000, the simulation outcomes stabilize and show negligible variation with further mesh refinement.

## 3. Finite Element Simulation of Shell Forming

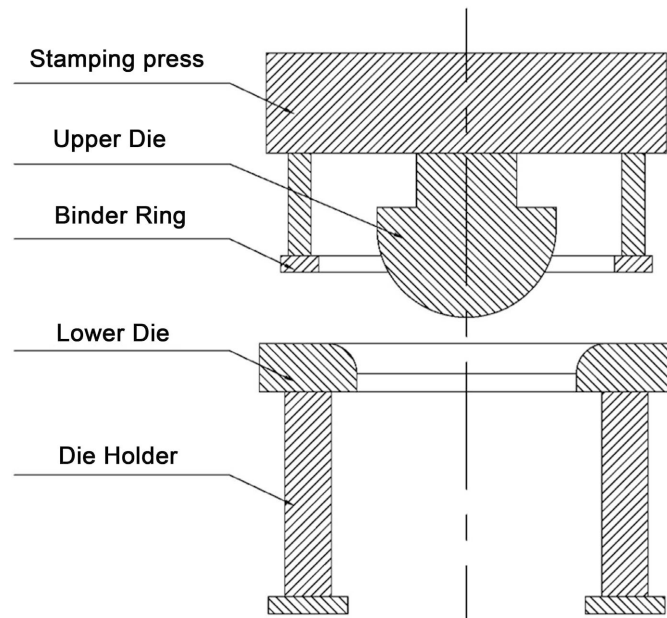
The theoretical basis for the stamping forming of the shell is the Prandtl-Mises constitutive equation, and the simulation is performed using DEFORM-3D, a specialized finite element analysis platform for metal plastic processing.

The titanium alloy sheet and steel plate are modeled as elastoplastic materials, while the dies are treated as rigid bodies. The initial heating temperature is determined based on process requirements, with an ambient temperature of 20°C. The thermal conductivity ( $\lambda$ ) of the blank is 7.62 W/(m·K), and that of the die is 45 W/(m·K). The shear friction factor is set to 0.1, and the simulation is run in 98 steps. The heat transfer coefficient is automatically assigned as 1, with the object relationship defined as Slave-Master (where the workpiece is the Slave and the die is the Master).

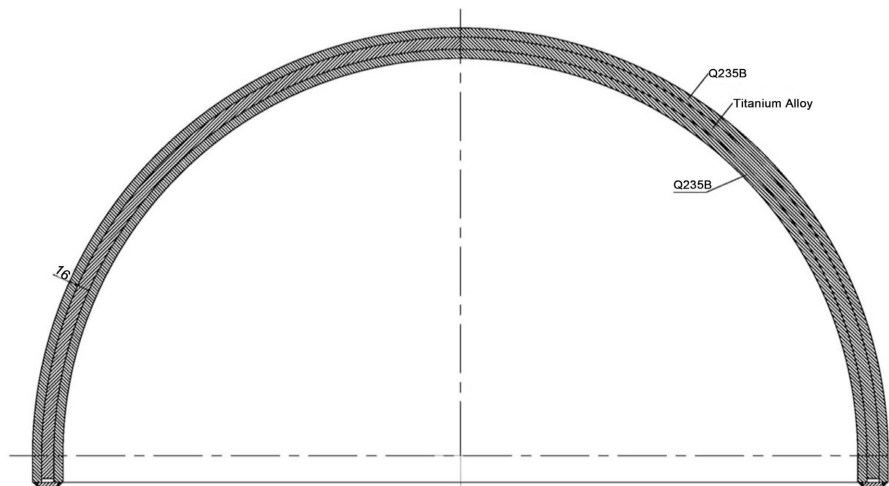
During natural cooling, the upper die moves upward at a speed of 0.03 mm/s. The total cooling time is 2800 s, continuing until the workpiece reaches room temperature.

#### 4. Analysis of Simulation Results

TC4 is a ductile material subjected to triaxial stress. The following **Figure 1** and **Figure 2** illustrate the stamping process.



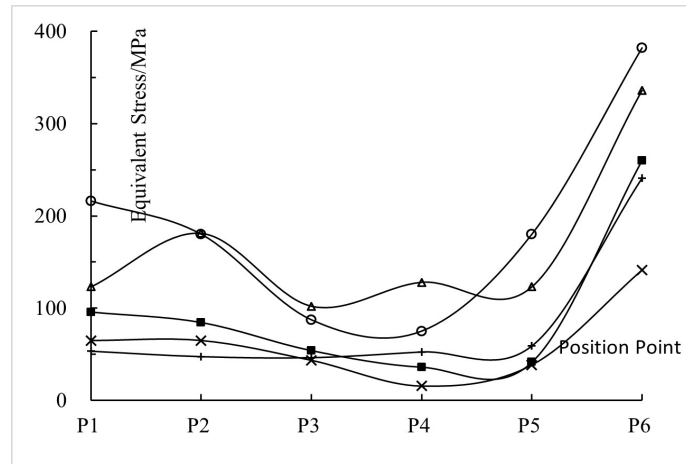
**Figure 1.** Stamping schematic diagram.



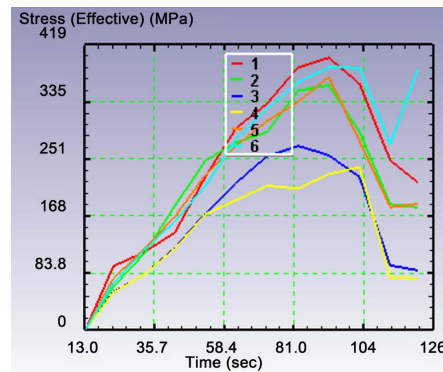
**Figure 2.** Stamping forming diagram.

To analyze the influence of heating temperature on stress and strain, the stamping forming process of the shell was simulated at three different temperatures: 500°C, 600°C, and 800°C. To examine the stress variation during the shell deformation process, **Figure 3** illustrates the evolution of equivalent stress over time at different positions on the shell under varying temperatures. The figure marks six equidistant points along the same generatrix of the shell, spanning from the center to the edge.

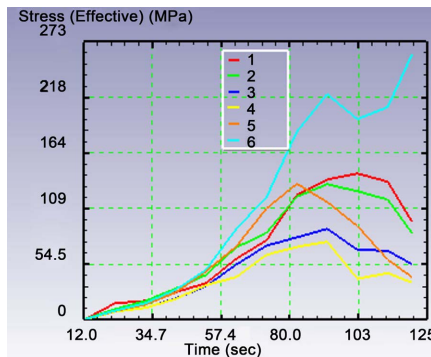
What we can see in **Figure 4**:



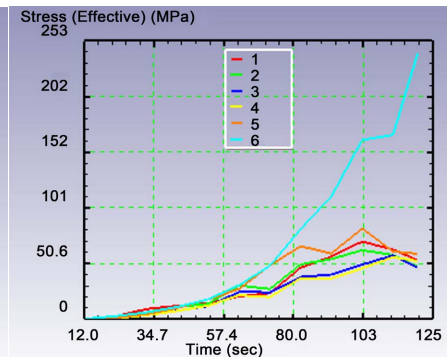
**Figure 3.** Equivalent stress distribution at various points after forming.



(a) 500°C Equivalent stress



(b) 600°C Equivalent stress



(c) 800°C Equivalent stress

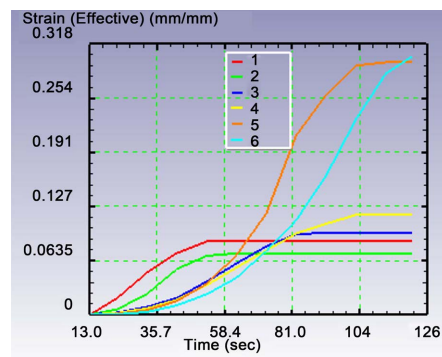
**Figure 4.** Variation of equivalent stress with time at different temperatures.

1) At the beginning of stamping, since the upper die first contacts the central region, the equivalent stress at the central point increases first, while the other points follow sequentially due to induced deformation. As the upper die moves downward, the bending area of the sheet expands, and the applied force increases continuously, leading to a steady rise in equivalent stress. At 500°C - 800°C, the

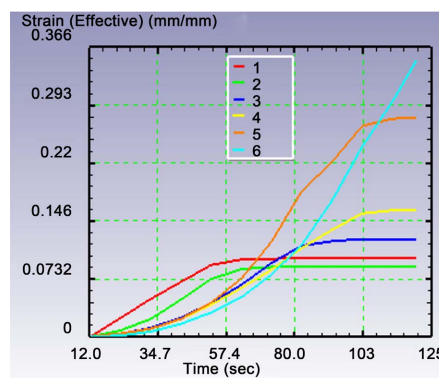
equivalent stress increases at an almost constant rate. Above 800°C, the initial growth rate is slower, but as the process approaches the mid-stage, the curve steepens, and the equivalent stress increases at an accelerating rate. In the late mid-stage, due to increased deformation, the equivalent stress rises sharply.

2) To better characterize the equivalent stress distribution after forming, **Figure 3** and **Figure 4** demonstrate that the edge point P6 exhibits significantly higher equivalent stress compared to other points, while intermediate points P3 and P4 (located between the center and edge regions) show the lowest equivalent stress levels. **Figure 5** presents the temporal evolution of equivalent strain at various positions along the same generatrix under different temperatures. The figure reveals distinct sequential forming characteristics during deformation:

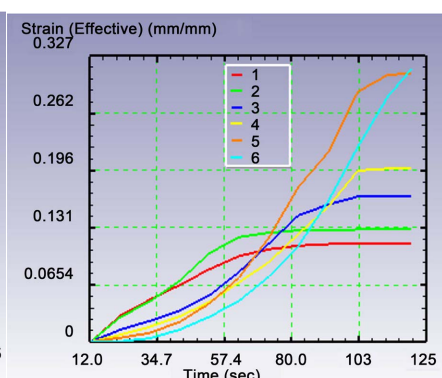
During the stamping process, as the upper die descends and initially contacts the central points P1 and P2, these two points undergo deformation first. Their equivalent strain curves display an upward trend with accelerating strain accumulation. The remaining four points experience induced deformation and follow the downward movement, but primarily undergo rigid-body motion with significantly less bending deformation than P1 and P2, resulting in gentler slopes in their equivalent strain curves.



(a) 500°C Equivalent Strain



(b) 600°C Equivalent Strain



(c) 800°C Equivalent Strain

**Figure 5.** Time evolution of equivalent strain at different temperatures.

After a certain period, P1 and P2 become fully conformed to the upper die surface, essentially completing their deformation. Their equivalent strain curves tran-

sition from an increasing trend to a plateau, indicating stabilized deformation and constant equivalent strain.

Points P3 through P6 sequentially undergo identical deformation stages: contact—accelerated deformation—rapid strain increase—deformation completion—strain curve plateau—constant equivalent strain. However, points farther from the center experience this sequence later, exhibit longer periods of accelerated strain increase, and ultimately reach higher strain plateaus.

This phenomenon occurs because: Before direct contact with the die, peripheral points already experience preliminary deformation induced by preceding points' deformation, albeit with smaller magnitudes. When these points eventually undergo accelerated deformation, the preceding points have already completed their deformation and contribute only rigid-body motion. Consequently, points farther from the center experience longer durations of accelerated deformation. The total deformation of subsequent points combines both the induced deformation from preceding points and their own direct deformation upon die contact. This cumulative effect results in greater total deformation and higher final strain plateaus for points farther from the center. Notably, the edge point P6 fails to fully establish a stable strain plateau before process termination, particularly at elevated temperatures, making its plateau less distinct [1]-[5].

## 5. Experimental Verification

**Figure 6** shows the titanium alloy shell produced in the experiment, as illustrated below. The thickness of the stamped shell is 15 - 16 mm after forming, meeting the requirements.



**Figure 6.** Experimentally produced titanium alloy shell.

## 6. Machining of Titanium Alloy Thin-Walled Shells

The large-diameter thin-walled titanium alloy shell requires final machining to achieve a gradually varying wall thickness ranging from 0.5 to 5 mm, presenting significant machining challenges (**Figure 7**).



**Figure 7.** The product of large-diameter thin-walled titanium alloy shell.

## 7. Conclusions

1) During the forming process, at heating temperatures of 600°C - 800°C, the equivalent stress increases at a constant rate. Above 800°C, the equivalent stress initially rises slowly, then rapidly increases to its peak before gradually decreasing. However, at the edge regions, the stress declines and then rises again. Higher temperatures result in smaller stress reduction amplitudes.

2) The equivalent strain of the shell undergoes a process of rapid increase to a constant value in sequence from the middle to the edge. The further back the point is, the longer the duration of this process and the higher the constant value reached.

3) For the stamping forming of TC4 titanium alloy thin-walled shells, increasing the thickness and minimizing temperature drop can effectively reduce wrinkling and cracking issues.

4) After forming, the end cap undergoes CNC machining, and a fixture is made to facilitate clamping. Selecting the appropriate cutting tools is beneficial for meeting surface quality and dimensional requirements.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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