Optimization of Thickness Variation of Cone Formed by Superplastic Forming of Ti-6Al-4V Alloy

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ABSTRACT: Superplastic forming is a valuable tool for the fabrication of complex parts used in aircraft and automobile industries. A number of techniques are applied to form components in these industries. In common method called blow forming, a sheet of super plastic material is clamped in rigid die and formed into the desired shape through pressure applied by an inert gas. This process usually leads to rather non-uniform thickness distribution with greatest thinning occurring in regions where stresses are higher such as centre of the sheet. In order to obtain uniform thickness distribution, the suggested method is to pre-form the sheet in such a way that the thickness of the initial sheet before the blow forming at the center is high so that after the blow forming the component will have uniform thickness throughout. For this in a 3mm thick Ti-6Al-4V sheet superplasticity was induced by "quench- roll-recrystallise" method was used to form a cone by blowing argon gas over the sheet in a die. A second blank was pre-formed so that the thickness at the centre of the blank was 3 mm and that at the ends (periphery) was 1.5 mm. After blowing the cone, the variation in the thickness from the apex to base of the cone was reduced to 0.3mm. In order to obtain further uniformity in the cone formed, another blank was pre-formed, to make that central thickness as 2.5mm, which tapers down over periphery to 1.5mm. This time variation of thickness from the apex to base of the cone is 0.2 mm, which is nearly 10%, which is acceptable in most of the cases.

Keywords: Super Plastic Forming, Quench-roll-recrystallise, Thickness Variation

1. INTRODUCTION

The superplastic forming is an emerging technology involving the elevated temperature forming of sheet materials capable of achieving forming higher strains of 200-1000%. The exceptional formability afforded by the process permits the manufacture of complex-shaped parts in fewer stages with minimum waste. In this process the deformation is carried out under low pressure and large elongation is reached without failure. Materials such as titanium, aluminum alloys, when subjected to the proper conditions of pressure, temperature and strain rate can exhibit the phenomena of superplasticity [1, 2]. These conditions are summarized as, for a grain size less than 10 μm, low strain rate of less than 10^{-3} sec^{-1} and temperatures of $\geq 0.5\ T_m$ where T_m is the melting point of the material [3]. The main application fields of this process are aircraft and automobile industries. In fact, its application for aircraft structures have been expanding recently because of its superior characteristics, such as low-cost, light weight and short fabrication time[4-8].

The Ti -6Al-4V alloy (α + β) is widely used as a structural material in the aerospace industry due to its low density high specific strength, good corrosion resistance, excellent high temperature properties, high formability associated with super plasticity[9]. A number of techniques are applied to form components industrially. In a common method called blow/vacuum forming, a sheet of superplastic material is clamped in a rigid die and formed into the desired shape by a pressure differential applied by an inert gas. This process usually leads to rather non-uniform thickness distribution with the greatest thinning occurring in regions where strain rates are higher such as the center of the sheet. While the thinning characteristics can be strongly influenced by the forming method employed and associated die interactions. The material properties, such as m, can also have a pronounced effect on the thinning profiles. The influence of these parameters on thickness variation in spherical domes has been illustrated both experimentally [10, 11] and analytically [12-14] by a number of investigators. Thomsen, Holt and Backofen [15] evaluated such thinning characteristics as a function of m, with the finding that the lower the m the greater is the thinning. The aspects of optimization of thickness variation are seldom available in literature. Especially in the case of cone forming the thickness optimization is not readily available in literature.

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The common methods used to obtain uniform thickness distribution are female drape forming, reverse bulging plug assisted forming etc. [4]. But these methods require additional process / tooling. Hence the proposed method is to pre-form the sheet in such a way that the thickness of the initial sheet at the center is higher so that after the blow forming the component will have uniform thickness throughout.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Mill processed 15 mm thick Ti-6Al - 4V plate with ($\alpha + \beta$) microstructure was water quenched after soaking at a temperature of 1000^0 C for 30 min. This quenched plate was rolled at 700^0 C up to a thickness of 3 mm in one heat. The finish rolling temperate was recorded as 400^0C. Sample from the rolled plate were annealed at 850^0 C to obtain fine grains in turn induce super plasticity, which is one of the pre-requisite for super plastic forming. Three blanks of 80mm diameter were cut from the sheet processed by "quench-roll-recrystallise" method. From the first blank cone was formed by blowing the inert gas at a peak pressure of 500 psi(3.47MPa) and at a temperature of 850^0 and a strain rate of $10^{-4}s^{-1}$ in hydraulic press of 40 T capacity as shown in figure.1, in a conical die of diameter 40mm and apex angle 58^0. Thickness at various positions from the centre of the formed cone were measured by inter testing machine as shown in figure.2, and was observed non-uniform thickness distribution with greatest thinning at the centre (apex). The thickness of the cone formed at the apex was1.1mm and at the base as 3mm.Hence in order to obtain same thickness at the apex and the base, second blank was pre-formed so that the thickness at the centre of the blank was 3 mm and at the ends(periphery) was 1.5 mm. This was done by machining the blank on lathe by taper turning attachment. Now the blank was blown to form a cone in the same die at the same pressure and was observed almost uniform thickness at the apex and at the base. In order, to obtain further uniformity in the thickness of cone formed the third blank was pre-formed, so that the thickness at the end (periphery) was 1.5 and at the centre were 2.5. Now the blank was blown to form a cone in the same die at the same pressure and was observed uniformity in thickness from apex to the base of formed cone.

3. RESULTS AND DISCUSSIONS

3.1. Superplastic Cone Forming from "Quench-roll-recrystallise" Sheets

It is widely known that superplastic blow forming of a cone with apex angle 58°, under constant strain rate can be achieved by applying a constant gas pressure [16]. In other words constant gas pressure (P) induces a constant stress (σ) in the forming membrane which in turn produces constant strain rate.

3.1.1. Superplastic Cone Forming, with Uniform Thickness Blank

In the first experiment the Ti-6Al-4V blank of 80mm diameter and 3mm thickness was blow formed to a cone of 40mm base diameter (approximately) at a temperature of 850^0C, under a strain rate of 10^{-4} sec^{-1}.The corresponding flow stress (σ) at 850°C, under a strain rate of 10^{-4} sec^{-1} was obtained as σ =17.9 MPa. The required constant pressure for forming of the first stage i.e.,up to the stage where the membrane makes the first die-contact was calculated as 500 psi(3.74. MPa) from the following equations which was developed by Dutta[18]

$$P = \frac{4S_i}{a_i}\left(1 - e^{-\dot{\varepsilon}_e t}\right)^{1/2} e^{-3/2\ \dot{\varepsilon}_e\ t}\ \sigma_0 \tag{4.1}$$

The equation of Dutta & Mukerjee was further modified by Mihai Vulcan et.al,[18] for second stage of forming, for first stage the Dutta & Mukerjee equation is adequate as commented by Mihai Vulcan

$$\begin{aligned} P = \frac{2S_i}{\rho_i}&\left[a_i^2 e^{-\dot{\varepsilon}_e dt} - 2\rho_i^2 + 2\rho_i(\rho_i^2 - a_i^2)^{1/2}\right]^{1/2} \\ &\left[2\rho_i^2 - a_i^2 - 2\rho_i(\rho_i^2 - a_i^2)^{1/2}\right]\ e^{1/2\ \dot{\varepsilon}_e dt}\sigma_0 \end{aligned} \tag{4.2}$$

Where,

a_i is the die radius ρ_i is the radius of curvature at any instant;

ε_e is the equivalent strain rate which is equal to thickness strain rate;

dt is the infinitesimal small change in time;

S_i is the thickness of the membrane at any instant;

σ_0 is the initial flow stress.

After forming, the cone thicknesses at various regions were measured by inter testing machine. Thicknesses were measured from the centre of the cone (apex) at the intervals of 4mm and were tabulated as shown in table 1. It was found that that there is more thinning at the centre (apex) than at the ends (base of the cone) as shown in figure 3. The measured values of thicknesses at the apex and at the base were 1.1mm and 3mm respectively, which is obviously un-acceptable for any application. The absolute variation in the thickness from apex to the base was1.9mm.This is due to the prevailing stresses at the apex and base. The stresses at the apex are balanced bi-axial stresses $\sigma_1 = \sigma_2$ due to the symmetry. At the base plain strain conditions prevails ($\varepsilon_3 = 0$) due to the die resistance and hence effective strain rate ε is slower at the equator. As a result, the equator was thicker than at the pole. The cone formed was shown in figure 4.

3.1.2. Control of Thickness Variation of Cone by Pre-forming the Initial Blank

As mention earlier section 3.1.1 that while forming the cone from a uniformity thick blank, a wide thickness variation between the apex and base of the formed cone developed, therefore another blank was pre-formed to create a thickness profile i.e., 3mm at the centre was tapering down to 1.5 at the periphery. This was done by taper turning on a lathe machine. By observing the difference in thickness of the cone formed from uniform thick blank, the later blank was given this particular profile. After forming the second cone thickness at various regions was measured by, inter testing machine as mentioned earlier. The thicknesses at various points were tabulated in table 2, which shows nearly uniform thickness throughout the entire cone. Figure 5.shows the thickness profile of the cone. The measured values of thicknesses at the apex and at the base were 1.6mm and 1.9mm respectively, therefore the absolute variation in the thickness from the apex to base was 0.3m. In order to obtain further uniformity in the thickness of the cone formed, third blank was pre-formed to make that central thickness as 2.5mm, which tapers down to the periphery to 1.5mm. Taper turning on lathe machine as mentioned earlier was employed to make this variation on the blank. After forming, the cone shows less variation in thickness between apex to the base as shown in figure 6. The measured values of thicknesses at the apex and at the base were 1.5mm and 1.7mm respectively as shown in table 3 the absolute variation in the thickness was 0.2mm.The variation of thickness is nearly 10%, which could be acceptable for most of the applications. Numerical methods can be attempted in future to obtain a further refined thickness profile of initial blank, so that the final thickness of the component becomes still more uniform.

Figure 1: 40T Hydraulic Press

Figure 2: Inter Testing Machine for Measuring Thickness

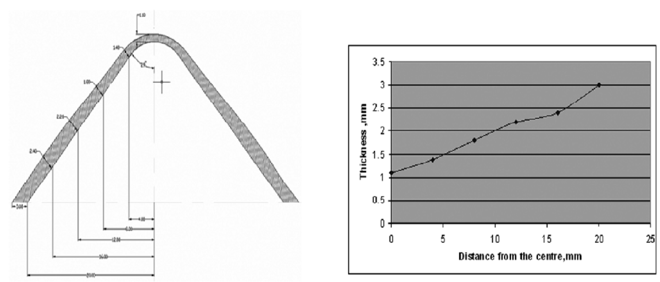

Figure 3: Thickness Variation of the Cone Formed from Centre (Apex) to the Base for Blank 1

Figure 4: Cone Formed by Superplastic Forming

4. CONCLUSIONS

Pre-forming the initial blank in such a way that the thickness at the center is higher gradually decreasing at the periphery, will lead to the development of a cone with nearly uniform thickness. Numerical Methods can be used to obtain the thickness profile of the pre-forming blank sheet, so that the final thickness of the component formed will have more uniformity

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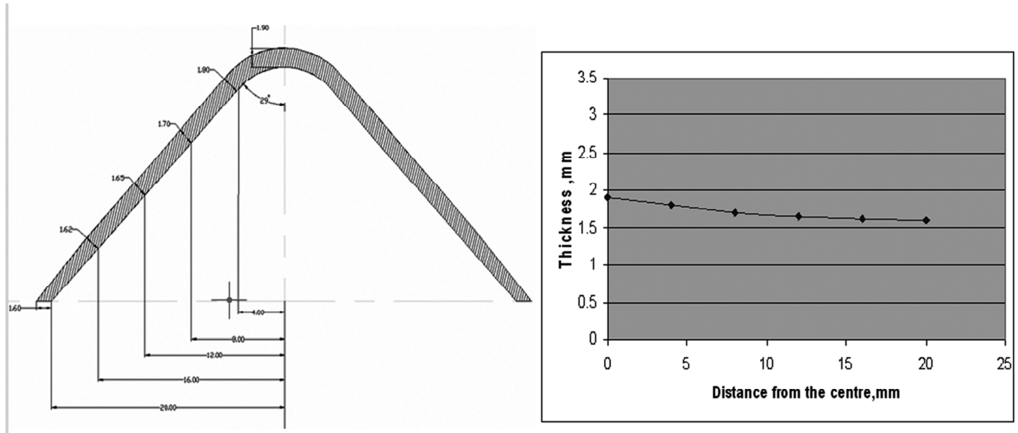

Figure 5: Thickness Variation of the Cone Formed from Centre (Apex) to the Base, for Blank 2

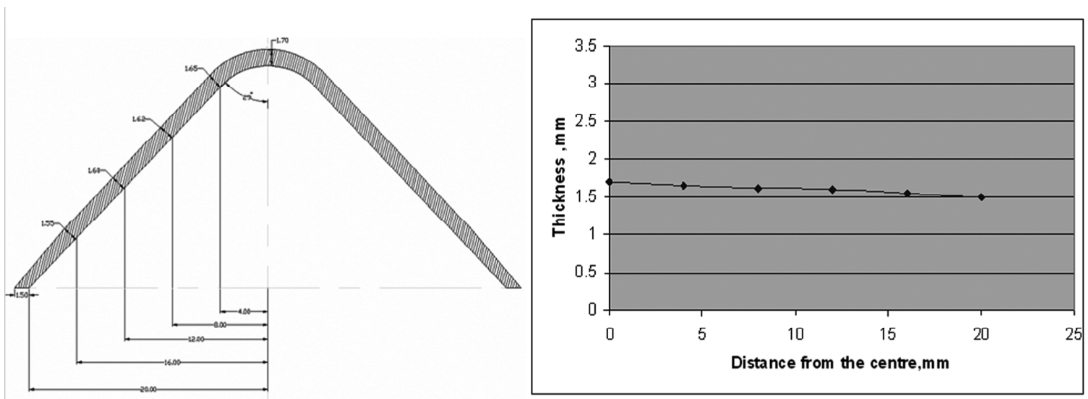

Figure 6: Thickness Variation of the Cone Formed from Centre (Apex) to the Base for Blank 3

Table1
Thickness of the Cone at Various Points as Measured from the Centre (Apex) of the Cone Formed from the Blank 1

Sl.No	*Distance from the centre in mm*	*Thickness in mm*
1	0	1.1
2	4	1.4
3	8	1.8
4	12	2.2
5	16	2.4
6	20	3.0

Table 2
Thickness of the Cone at Various Points as Measured from the Centre (Apex) of the Cone Formed from the Blank 2

Sl.No	***Distance from the centre in mm***	***Thickness in mm***
1	0	1.9
2	4	1.8
3	8	1.7
4	12	1.65
5	16	1.62
6	20	1.6

Table 3
Thickness of the Cone at Various Points as Measured from the Centre (Apex) of the Cone Formed from the Blank 3

Sl.No	*Distance from the centre in mm*	*Thickness in mm*
1	0	1.7
2	4	1.65
3	8	1.62
4	12	1.6
5	16	1.55
6	20	1.5

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