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Advanced Finite Element Analysis and Simulation in Superplastic Forming Process of Stepped Semispherical Die

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Abstract: Superplastic forming has become a viable process in manufacturing aircraft and automobile parts such as turbine disc, fan, compressor blades, window frames and seat structures etc., which require relatively high tooling and assembly cost. Superplasticity is a property of certain metallic materials which enable them to achieve very high elongations (500% and more) without necking under certain conditions. This is attributed to the viscous behavior exhibited by those metals and alloys with very fine and stable grain structure at temperatures above half the melting point. The present work proposes to develop an experimental setup to find out the parametric influences and their effects on superplastic forming of aluminum alloy. This alloy is most suitable materials for producing complex shapes using superplastic forming methods. This work analyzes data on the friction coefficient, strain rate sensitivity, optimum pressure, bulge forming time and strain rate on the thickness distribution. Superplastic deformation is carried out close to isothermal conditions under controlled strain rate. The optimum strain rate varies with the material, which is usually in the order of 0.001-0.00001 sec^{-1}. Owing to the recent advancements in modeling and analysis, Finite Element Method (FEM) has evolved as a powerful tool in the simulation of superplastic forming processes (SPF) with accurate prediction of the deformation characteristics. The numerical simulation and FEA analysis result are reasonably agrees for the parametric relation of pressure and time.

Key words: Superplastic forming, rectangular die, aluminum alloy, FEA-Abaqus

INTRODUCTION

Superplastic forming is a net-shape manufacturing process permitting the fabrication of complex shapes and curved surface using thin metal sheets. Superplastic forming is a low investment process that takes advantages of certain materials ability to undergo large strains to failure when deformed under the right conditions, which usually involve elevated temperature and slow strain rates. Product development and manufacturing benefits associated with SPF include low capital investment, part consolidation and increased design freedom with materials that have limited room temperature ductility.

Superplasticity appearing in some metallic materials, such as aluminum, titanium, iron, magnesium, nickel based alloys, etc. when some materials with a fine grain size (usually less than 10 μm) are deformed within a controlled strain rate (range 10^{-5} to 10^{-1} sec^{-1}) at temperatures greater than 0.5 T_m (where T_m is the melting point in Kelvin), they can give a tenfold more increase in elongation compared to that for conventional room temperature processes. Superplastic deformation is characterized by low flow stress and this combined with the high uniformity of plastic flow has led to considerable commercial interest in the superplastic forming of components.

A few works concerning SPF (Fields and Stewart, 1971; Al-Naib and Duncan, 1970; Cornfield and Johnon, 1970) processes have focused on metallurgical experimental research (Fields and Stewart, 1971; Al-Naib and Duncan, 1970). However, studies using experimental approaches are often time-consuming and of low efficiency. Among the analytical investigation (Ghosh and Hamilton, 1980; Chandra and Chandy, 1991; Ragab, 1983; Jovane, 1968; Holt, 1970) on SPF processes, Ghosh and Hamilton (1980) used the plane strain analysis to explore the effects of the thickness of the sheets and

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the shape of the die on the optimized pressurization profile during blow-forming in a long semispherical die. Ragab (1983) investigated the thickness distribution in a cylindrical or conical die, but the plane strain analysis and the sticking mode for the contact between the sheet and die were adopted in the analysis. Holt (1970) examined the effects of the forming pressure, geometrical shape and mechanical properties (K, m-values) of the sheet on the thickness distribution and shape of the products during blow-forming of a circular sheet. Chandra and Chandy (1991) developed a computational process model using the membrane element method for superplastic forming in a box with complex cross-sectional shape. Bonet *et al.* (1994a) have proposed a finite element model using incremental flow formulation to simulate superplastic forming of thin sheet Bonet *et al.* (1990) and thick sheet components. Bonet *et al.* (1994b) also proposed a pressure control algorithm incorporated into their finite element program during the simulation of SPF, in order to obtain the optimum strain rate. In this study, the finite element method is used to simulate the plastic deformation of 7475 Al alloy sheets in stepped semi spherical die, in which the deformation of the sheet belongs to the category of three-dimensional analysis.

The effects of various forming conditions (Senthilkumar *et al*., 2006; Balasubramanian *et al*., 2004; Balasubramanian *et al*., 2009) such as the friction co efficient, the aspect ratio of the die, bulge height, constant strain rate, forming time, variation of thickness at contact edge of bulge profile etc, on the optimized pressurization and thickness distribution of the product will be discussed. Furthermore, analytical and Abaqus are also carried out to verify the validity of this model.

THEORETICAL MODELING

Superplastic forming process: The superplastic material is formed into the desired component by exploiting this phenomenon in metal forming process such as pressure forming, vacuum forming, thermo forming, deep drawing, etc. The most widely used method for forming of superplastic metals into desired component is the pressure forming technique. Superplastic forming process is a material is heated to the superplastic forming temperature within a closed sealed die. Inert gas pressure is applied, sheet to take the shape of the pattern with controlled strain rate. The flow stress of the material during deformation increases rapidly with increase in pressure. Superplastic alloy can be stretched at higher temperature by several times of their initial length without breaking.

In order to simulate mathematically the optimum pressure profile for superplastic forming, numerous constitute equations have been proposed to characterize the material flow stress response. The flow stress for the superplastic material can be expressed as:

$$\sigma = k\acute{\varepsilon}^m$$

Basic assumptions: The following basic assumptions have been made during the theoretical modeling of the superplastic forming process:

- The material is isotropic and incompressible
- The elastic strain is negligible compared with the extensive plastic deformation of the material
- The diaphragm is rigidly clamped at the periphery of the die
- Process is assumed to be plane strain condition for long length direction
- Die entry radius assumed to be zero

Geometric model: The bulge profile of the sheet at different stages during superplastic forming process is a geometric relationship established to predict the thickness variation, radius of curvature, arc length, time required to form the curvature and forming pressure during different stage of bulge forming. In the theoretical analysis (Ghosh and Hamilton, 1980) it is assumed that the depth of the die is equal to half of the width of the die.

Radius of the curvature of the various stage:

$$R = B/\sin\dot{\alpha} \tag{1}$$

Arc length of bulge is:

$$S = 2\,R\,\sin^{-1}(W/R) \tag{2}$$

The time required for the formation of radius of curvature:

$$T = \ln(S_0/S)/2.8\times10^{-3} \tag{3}$$

According to plane strain condition, the thickness variation in formed sheet:

$$S = S_0(\sin\dot{\alpha}/\dot{\alpha})^2 \tag{4}$$

The sheet is treated as a membrane during forming, the forming pressure is:

$$p = (4\times\sigma\times S_0\times h/h^2+R_0^{\;2})\times(\sin\dot{\alpha}/\dot{\alpha})^2 \tag{5}$$

According to the plain strain condition, Angle of sheet for various of stage:

$$\dot{\alpha} = \text{arc sin}\,(2\times h\times R_0/h^2+R_0^2) \tag{6}$$

Using the above equations, the various parameters are analyzed at every stage of forming until the profile reaches the bottom of the die.

Subsequently, the forming takes in the edge direction, ΔX and ΔY is the lengths contacted on the bottom and sidewall respectively during each step of processing. Using $Y_{i+1} = Y_i-\Delta Y$ and $X_{i+1} = X_i-\Delta X$, for each process assign a small positive value of ΔX and ΔY:

$$t_{i+1}= t_i+(2/\sqrt{3}\ \dot{\varepsilon})\ \ln\,[(R_{i+1}\ \varnothing_{i+1}+\ \Delta Y/2+\Delta X/2)/(R_i\ \varnothing_i-\Delta Y/2-\Delta X/2)] \tag{7}$$

The time, thickness and pressure computation are carried out in this manner until profile reaches the edge of the die.

FINITE ELEMENT METHOD

FEM model: Superplastic blow forming is a complicated process involving large strain, large deformation and material nonlinearity. Usually deformation is dependent on boundary conditions. Consequently, the numerical analysis of such a highly nonlinear system presents formidable computational problems. Fortunately, the superplastic behaviors of materials are characterized by the dependency of the flow stress upon the strain rate, which allows the material to be described as rigid viscoplastic. Therefore, the simulation of superplastic blow forming can be performed using the creep strain rate control scheme within Abaqus.

The FEM model of our work are shown. In Finite Element simulation a sheet metal with stepped semispherical geometry 160×160×80 mm with 3 mm flange all around it. A quarter of the blank is modeled using shell elements. The initial dimension of the blank is 180×180 mm and 3.0 mm thickness. The blank is rigidly clamped on all its edges. A finite element mesh was generated using 4-node, 3D- shell element for a quarter of a cylindrical pan. The nodes of element have three degree of freedom, i.e., in the X, Y and Z direction.

The FEM and Boundary condition nodes on the blank outer edge had all their degree of freedom constrained. All nodes of the die surface were totally restricted for any movement in any directions. Pressure has applied to the blank surface in the Y direction as a distributed load. Now several load steps corresponding to each operational procedure are carefully modeled to obtain an accurate simulation of a superplastic blow forming process in Abaqus.

Materials model: The behavior of superplastic alloy is generally characterized by a relationship between the von-misses equivalent stress and the equivalent strain-rate. The material model developed in FEM is described as:

$$\sigma_e = k\dot{\varepsilon}^{\,m}\,\varepsilon^n \tag{8}$$

'm' the strain-rate sensitivity that could be obtained as follows:

$$m = (\ln \sigma_e)/(\ln \dot{\varepsilon}) \tag{9}$$

For simplicity, the equivalent flow stress may be regarded as a function of the strain-rate as given in the equation:

$$\sigma_e = k\ \dot{\varepsilon}^m \tag{10}$$

The superplastic behavior of the sheet is considered as nonlinear viscoplastic material with the above constitutive Eq. 10.

Material selection: Aluminum alloys can be used in the fabrication of airframe control surface and small scale structural elements where low weight and high stiffness are required. 7475 Al-alloy used for the theoretical modeling and finite element simulation of the superplastic forming process. Table 1 and 2 show the composition and mechanical properties of 7475 Al- alloy.

Blow forming components at various stages: After Applying boundary conditions and initial conditions the

Table 1: Composition of 7475 Al alloy

Alloy	Composition (%)
Aluminium	88.5-91.5
Chromium	0.18-0.25
Copper	1.2-1.9
Ferrous	Max. 0.12
Magnesium	1.9 -2.6
Manganese	Max. 0.06
Silicon	Max. 0.1
Titanium	Max. 0.1
Zinc	5.2-6.2

Table 2: Mechanical properties of 7475 Al alloy

Mechanical properties	Value
Yield strength	462 MPa
Ultimate strength	531 MPa
Shear strength	310 MPa
Melting point	477-635°C
Modulus of elasticity	71.7 GPa
Poisson's ratio	0.3
Material constant (k)	610MPa S^m
Strain-rat sensitivity index (m)	0.67

bulge forming takes in FEM as shown. The different stages of blow forming of the sheet in to the semispherical die.

RESULTS AND DISCUSSION

A simple mathematical modeling of superplastic forming of circular box has been developed and the finite element package is used to predict the superplastic forming parameters such as the thickness distribution, forming time and optimization pressure profile.

Pressure distribution of a bulge profile as a function of forming time: Superplastic forming depends upon the pressure of the gas and the time. The pressure distribution with respect to time as shown:

- In this profile the rate of change in pressure initially increases and decreases and further increases rapidly as evidenced
- The reason for this shape is due to simultaneously change in radius and thickness
- This might be the rate of change of the radius is much greater than the rate of change of the thickness and hence increase in pressure is required
- As the forming of the profile continues, the rate of change of thickness increases while the radius decreases, and the pressure may be reduced to sustain the constant flow stress
- Once the bulge envelope contacts the base of the die cavity, the rate of change of the radius again dominates, and hence the pressure is rapidly increases is also noticed

Effect of pressure profile with forming time at different width condition: Based on aspect ratio concept, here to analyses the forming pressure with respect to forming time at different with conditions (says 20, 40 and 120 mm).

From the graph it is inferred that as the width of the die increase the pressure required is decreased:

- The changing thickness and radius of curvature is strongly depended on the diameter/depth or aspect ratio
- The changing width on the pressure profile is illustrated In this significant portion D = 80 mm the profile involves decreasing pressure. This reflects the significant deformation, which occurs after the half section is formed and before the diaphragm contacts the die bottom
- During this part of the forming sequence, the radius of curvature is constant but the thickness is decreasing. Once the die bottom is contacted, the pressure raises rapidly, a common characteristic of each of these profiles are shown
- When D =120 mm, the pressure rises throughout the forming process continuously. This occurs because of the forming diaphragm contacts the die bottom before the thinning dominates the process and there is no decrease in pressure

Effect of forming pressure as a function of forming time: Here, to analysis the time and optimum pressure required is decreased to form the bulge profile if small variation in input pressure as shown.

Effect of thickness distribution as a function of forming time: Here, the forming time is decreased to obtain the required thickness when increases in input pressure:

- It show that the pressure profile and thickness distribution are obtained with respect to forming time at different initial pressure condition
- The optimum pressure and forming time decreases with increasing initial pressure condition
- And also obtain the thickness distribution rapidly with increase in initial pressure

CONCLUSION

The Mathematical model and FEM simulation has been made for superplastic forming of 7475 Al alloy sheet in to a stepped cylindrical die. The following conclusions have been made:

- Pressure is increased rapidly when the rate of change of radius is greater than rate of change of thickness
- Optimum pressure value decreases with increase in diameter of the die
- The changing thickness, optimum forming pressure and radius of curvature is strongly depending on the aspect ratio
- Forming time rapidly decrease with increase in pressure
- The optimum pressure and forming time decrease with increase in initial pressure

NOTATION

σ = Stress (N mm^{-2})
k = Material parameter
$\acute{\varepsilon}$ = Strain Rate (sec^{-1})
m = Strain rate sensitivity
R = Radius of curvature (mm)
T = Time (s)

w = Half the die width (mm)
D = Depth of the die (mm)
S = Instant thickness (mm)
S_0 = Original sheet thickness (mm)
p = Pressure (N mm^{-2})
$\acute{\varepsilon}_w$ = Strain-rate in width direction (sec^{-1})
σ_w = Stress in width direction(N mm^{-2})
$\dot{\alpha}$ = Half angle subtended b a dome surface at its centre of curvature (degree)

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