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Analytical Modeling and FEM Simulation of Superplastic Forming

S. Saravanan, Prem Narayan P

Abstract— Absence of a well-defined predictive model for superplastic forming (SPF) process makes manufacturers to think twice for implementing it. This also stands as the reason why the manufacturing process has still not entered the world of bulk manufacturing. This document reviews few works done during past decade to find the importance and need for an analytical model for the process. An attempt is also made to generate a predictive mathematical model to define pressure time path for the process. The validating process is taken down by comparing with the results of simulation using Finite element modeling method.

Index Terms— Analytical model, forming technology. Pressure Path, Square cup, Superplastic forming.

1. Introduction

"The ability of polycrystalline material to exhibit in a generally isotropic manner, very high elongation prior to failure" [1]. Forming complicated shapes from polycrystalline materials using the above defined property of superplastic flow is termed as super plastic forming. SPF of sheet metal has been used to produce very complex shapes and integrated structures that are often lighter and stronger than the assemblies they replace. Complex structure incorporated by the SPF process reduces the part assemblies thus reducing the overall cost of production.

The phenomenon of superplasticity does not refer to any class of martial instead defines the deformation characteristics of given material at a specific range of temperature and rate of deformation. Though it is estimated that Superplasticity has been successfully found well over 10,000 different materials, commercial applications is restricted to aluminum, titanium, iron and zinc based metals and alloys.

The term superplasticity has been known for a long time, the first commercial application is found dated back to 2500BC in bronze and 350BC Damascus steel. Later in 1934 SnBi- alloy was deformed to more than 2000%. However its potential as an economic manufacturing tool was discovered in 1970's and 1980's by forming complex parts using titanium alloy sheet. The current world record for elongation in metals stands at 8000% elongation in commercial bronze and 1038% in yttrium stabilized zirconia.

Some of the advantages considered while taking SPF into account are as follows:

- It is a one step process.
- The process can be used to form complex components in shapes that are very near the final dimension.
- Higher material elongations.
- Elimination of unnecessary joints and rivets.
- Necking and spring back is absent.
- Reduction of subsequent machining.
- Minimizes the amount of scrap produced.

The far limit elongation percentage and formability of complex shapes along with above mentioned advantages makes the process a necessary implementation in fields of manufacturing. In spite of having so many advantages the process is still a figure of question for design engineers. Few reasons for this condition are stated below,

- Limited predictive capability due to lack of accurate constitutive model for Superplastic deformation.
- High processing temperature reduces tool life and is subjected to frequent toll change.
- High production cost.

This paper work concentrates on studying and generating a predictive mathematical model for the process. The work done by J.L. Duncan [2] was studied and result where extended to thin Square cup geometry of predefined dimension. M.J.Nategh & B.Jafari's [3] work was studied to generate the time equation for the above geometry. The pressure time graph generated analytically is compared with simulation output of FEM analysis done using PAM STAMP 2G, standard analysis software designed for forming processes. Inorder to extend the importance of developed model, the maximum pressure and time for forming a rectangular pan was also calculated using the developed equation, and the result was compared with the experimental output from Y.M. Hwang's report [4].

2. Analytical Modelling

SPF forming as a production process is influenced by several design and technical factors which are listed in table1. Considering the listed factors applied pressure and process time are chosen as parameters for generating the pre predictive analytical model.

TABLE 1
FACTORS INFLUENCING SPF

DESIGN	TECHNICAL
Weight Limit	Maximum reachable pressure
Maximum allowed stress	Maximum press power
Material selection	Production time
Product life cycle	Cost

Reference [2,6] states that the behavior exhibited by superplastic materials resembles to that of amorphous solids and viscous liquids, taking this into account many

TABLE 2
MATHEMATICAL MODELS FOR DIFFERENT GEOMETRIES

Geometry	Mathematical model	Reference
Cylindrical shell	$p = \frac{4\sigma_\theta t_0 bh^2}{(b^2+h^2)^2 \sin^{-1}\{\frac{2bh}{b^2+h^2}\}}$	[2]
Cylindrical shell	$p = \frac{2}{a\sqrt{3}} AS_0 \dot{\varepsilon}^m e^{-\dot{\varepsilon}t\sqrt{3}} \left\{6\left(1-e^{-\frac{\dot{\varepsilon}t\sqrt{3}}{2}}\right)\right\}^{\frac{1}{2}}$	[11]
Hemispherical Dome	$p = \left\{4\sigma\left(\frac{S_0}{R_0}\right)(e^t - 1)^{\frac{1}{2}}\right\}/e^{t(1-m)}$	[3]
Hemispherical Dome	$p = \frac{2KS_0\dot{\varepsilon}^m}{a}\sin\alpha\left(\frac{S_p}{S_0}\right)$	[10]

modeling works are laid down considering theory of viscosity and creep theory. Ridha Hambli and R.A.Vasin [7,8] uses this method to tabulate mathematical equations for uniaxial deformation. The mathematical model developed by deferent authors for different geometries in the literature reviewed is listed in table 2.

Considering the geometries selected for the propose of mathematical modelling from the last decade hemispherical dome is found to be most common one [3,10], then comes the cylindrical model [2,11]. Some numerical formulations is also done for rectangular box and conical flask models for carrying out FEM analysis.

While taking into account the complex models of motor vehicle parts and aeronautical parts most of them incorporate rectangular shapes in one or other form. Generating a mathematical model for rectangular box form will make the process of designing the SPF process a work of ease.

Considering the mathematical modelling done in various references, an idea of extending the equation for cylinder to a rectangular box shape is taken into account. For this certain geometrical constrains are considered

TABLE 3
THE MATHEMATICAL EXPRESSION FOR PRESSURE IN EACH PART OF FORMING

PART 1

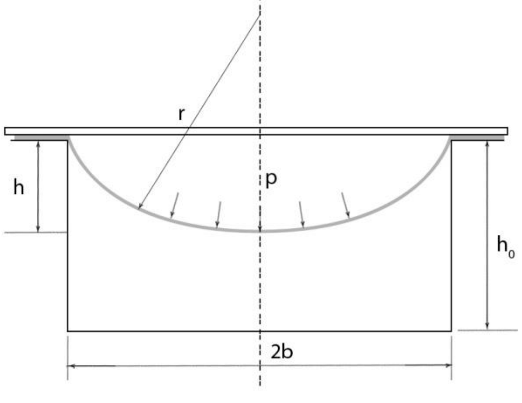

Fig. 1. Diagram showing geometries of bulging process

As per [2].
From the geometry,

$$r = \frac{b^2+h^2}{2h} \quad (2)$$

$$\frac{t}{t_0} = \frac{b}{r\theta} = \frac{2bh}{(b^2+h^2)\sin^{-1}\{\frac{2bh}{b^2+h^2}\}} \quad (3)$$

$$p = \sigma_\theta \frac{t}{r} = \frac{4\sigma_\theta t_0 bh^2}{(b^2+h^2)^2\sin^{-1}\{\frac{2bh}{b^2+h^2}\}} \quad (4)$$

PART 2

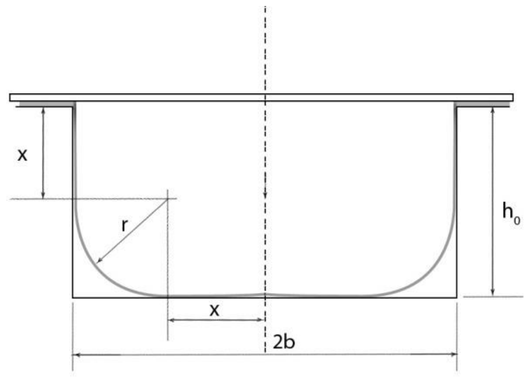

Fig. 2 Diagram showing geometries of stretching process

As per [2]
From the geometry

$$r = (b - x) \quad (5)$$

$$\frac{t}{t_0} = \frac{b(\frac{b-x}{b})^{4/\pi}}{r\theta} = \frac{2}{\pi}(\frac{b-x}{b})^{(\frac{4}{\pi}-1)} \quad (6)$$

$$p = \sigma_\theta \frac{t}{r} = \sigma_\theta \frac{2t_0}{\pi b}(\frac{b-x}{b})^{(\frac{4}{\pi}-2)} \quad (7)$$

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- Depth of the box equal to half the width of the box.
- The 2D geometry is taken into account for deriving the equation

Formulation of the equation is done by dividing the process into two parts

- Bulging process
- Stretching process

The constitutive equation of superplastic forming was developed by Backofen who laid down the modern foundation for the research works in the field,

$$\sigma = K\dot{\varepsilon}m$$

In the above equation K is material constant, m is strain rate sensitivity index, $\dot{\varepsilon}$ is strain rate and σ is stress acting on the formed sheet. The formulas derived are shown in the Table 3. The time relation for the process is derived as per the relations explained in the work of M.G.Zelin [11].

In the above equations r, b and h are dimensions given in the figure. t is the thickness of the blank at any time interval T and t0 is the initial thickness of the blank. p is the applied pressure and σθ is the hoop stress considered while taking plain stress condition. Equation (8) shows the expression for σθ derived from constitutive equation of SPF (1) [2].

$$\sigma_\theta = \left(\frac{2}{\sqrt{3}}\right)^{(m+1)} K\dot{\varepsilon}^m \qquad (8)$$

In order to find out the expression for process time, T the Von messes equivalent strain rate condition is taken into account. Resulting equation (9) is shown below [3,11].

$$T = \frac{2}{\dot{\varepsilon}\sqrt{3}} \ln\left(\frac{t}{t_0}\right) \qquad (9)$$

3. Finite Element Modelling And Simulation

From the literature survey its clear that majority of the work relay on Finite element modeling and simulation for validation, prediction and optimization of superplastic forming process. Here also we consider finite element modeling as tool for validating the analytical model and predicting variation they show while considering the experimental data. PAM STAMP 2G inbuilt codes where used for simulating the Superplastic forming process for square cup and rectangular pan. The square and rectangular dies where designed using surface 3d modeling software CATIA as per the dimensions shown in figure 3. The designed die where imported and the sheet metal blank was defined with the material properties of AA2054 aluminium alloy. The simulation was carried out at 8 x 10-4 s-1 strain rate using fluid gas pressure.

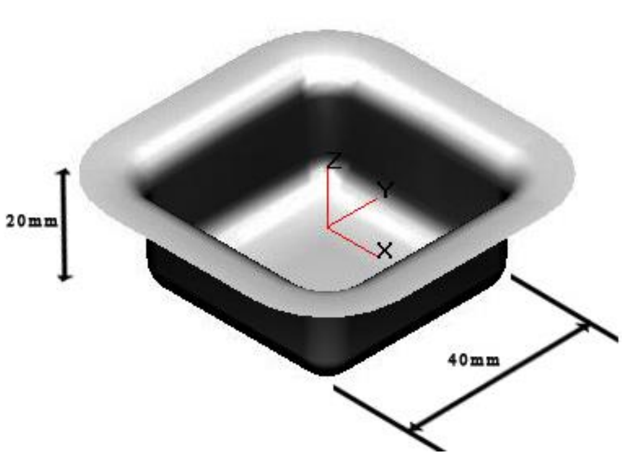

Fig. 3 model of square cup and rectangular pan

4. Validation and Conclusion

Using the analytical model developed the pressure path for forming square cup was tabulated and graph was drawn with pressure on ordinate and time on abscissa. Using the equation the thinning ratio and final thickness of the square cup was also calculated and compared with the FEM result. The maximum pressure that can be applied for forming rectangular box was calculated by considering the longest side of the geometry.

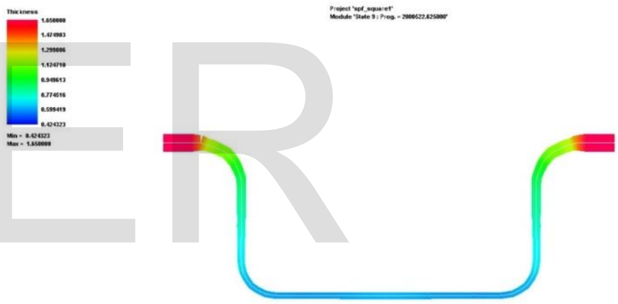

Fig. 4. Thickness variation across the blank

The comparisons show that the thickness ratio at the end of superplastic forming process using FEM method as shown in figure 4. is about 0.2545 which is more close to the tabulated value of 0.2808 from analytical model. The minimum thickness is of the order of 0.4243mm (FEM result) which is also matching with that of analytical model (0.4633mm).

From figure 5. It can be seen that the simulation result of FEM doesn't show much variation with the mathematical result except at towards the end of the process. By studying the graph it can be seen that the maximum pressure value of both analytical and finite element analysis are around 5Mpa, while time varies. The Finite element analysis shows a 15% higher time value than that of mathematical.

Using the analytical model developed the maximum pressure for square as well as rectangular boxes can be found out. As majority of the aerospace and aeronautical components incorporate rectangular geometry, the process can be used to find out the maximum gas pressure that can be applied for the forming process. The tabulation of exact pressure path for rectangular cup and other complex model incorporating rectangular geometry was not considered due to time limitation. This limitation will be overcome in the future work.

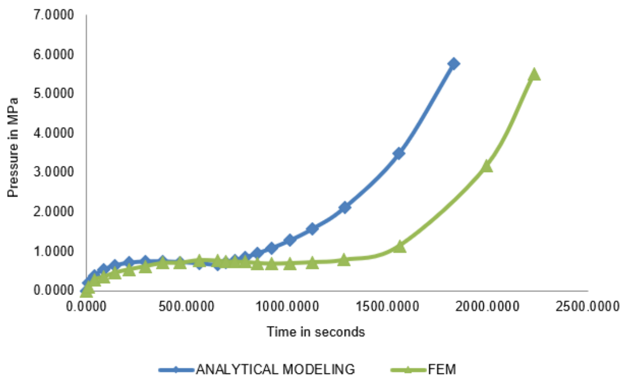

Fig. 5. Comparison of analytical and FEM result

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