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Determination of Material Parameters during Superplastic Forming of AA 5086 Alloy

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Abstract

Superplastic forming (SPF) process is an important advanced manufacturing method that has the benefit of certain materials capability to undergo large strains to failure when deformed atprominent temperature and at lesser strain rates. The major problem encountered during the Superplastic Forming of sheet metals, is the vagueness in determining the specific time necessary for attaining the steady state temperature, forming time by the sheet material to arrive the required geometry for a given input parameters such as pressure and temperature, thickness distribution along the profile. Hence in this work, a steady state equation is derived to determine the approximate time for the sheet metal to attain the set temperature and also the most favorable temperature and pressure necessary for achieving the deformation of the workpiece based on equal thickness distribution is determined. Graphs are plotted to show the varying parameters at different temperature and pressure values.

*Keywords:*Strain-rate, Strain rate sensitivity, Superplastic forming, Cavitation.

Nomenclature

m_a	mass of air
m_s	mass of solid
C_{Pa}	Specific heat capacity of air
C_{Ps}	Specific heat capacity of solid
T_{req}	Required temperature at the workpiece
T_i	Set temperature

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1. Introduction

Superplastic forming (SPF) process is an important advanced manufacturing method that has the benefit of some materials ability to undergo large strains to failure when deformed at prominent temperature and at lesser strain rates. Superplastic forming process takes place with the material heated to the super plastic forming temperature within a sealed die. The superplastic materials show elongation more than 200%. These elongations help in producing complex, high strength components which are of use in various aircraft and automobile industries. Many of the complex shapes can now be formed superplastically with a much lower manufacturing cost by reducing the dies, part counts and accordingly the number of subsequent operations. The forming time in superplastic forming process ranges from 20 minutes to several hours due to very less strain rates in the range of 10^{-5} - 10^{-2} s^{-1} [1]. This time-consuming rate of forming of components has limited the marketable use of superplastic forming job order production, especially those used in ship building and aerospace industries. The essentials of superplastic forming include controlling the strain rate, temperature and increased elongation without necking. The predominant parameter of superplastic materials is its high strain rate sensitivity of flow stress [2].

The workpiece considered for the analysis is AA5086 aluminium alloy. The motive of considering this is being its excellent ductility and formability at elevated temperatures and its wide commercial use. The optimum strain rate sensitivity at 400^{o} C with strain rate ranging from 10^{-5} to 10^{-3} s^{-1} for any superplastic material should be from 0.4 to 0.8. The Al5086 alloy supports the above condition. AA 5086 is the favorite hull material for small aluminiumboats or larger yachts. The material has high strength and good corrosion resistance thus making it as an excellent match for yachting. AA 5086 is commonly used in the manufacture of unfired, welded pressure vessels, marine, auto aircraft cryogenics, drilling rigs, tanks, TV towers, transportation equipment, and in missile components. The easy availability and economic aspects also contribute to the selection of this alloy.Barnes [3] stated the important advances that have been taking place in superplastic forming including various alloy developments, improved formed techniques and ever increasing number of commercial applications in aerospace and automotive markets. Jung-Ho Cheng [4] emphasized on the relative easy procedure and the lower cost of the test equipment required for conducting the superplastic forming test. Cheng performed superplastic forming on a circular Ti-6Al-4V sheet of 1mm thickness and 70 mm diameter. Giualiano (2012) determined a speedy procedure for determining the materials constants of superplastic AA5083 alloy at 723 K. To assess the thickness at the dome and also the displacement of the metal sheet, bulge forming experiments were carried at constant pressure by Giualiano [5]. The author stated that pole of the sheet alone is subjected to equi-biaxial stress and the other portions of the sheet i.e along the profile,were subjected to non-equibiaxial stress. Senthil Kumar et al [6] developed a numerical modeling for predicting the instantaneous radius of curvature, instantaneous pole thickness of the sheet into a hemispherical dome during superplastic formingby assuming that, the geometry of the formed component is always a part of a sphere at any instant of deformation, the material is isometric and incompressible, neglecting the effect of cavitations and balanced biaxial state of stress at the pole. Ragab [7] analyzed the thickness distribution in a cylindrical or conical die but the analysis of steady state of the work piece was not adopted. Holt [8] proposed a numerical study based on the variation of sheet thickness, corresponding to the pressure and mechanical properties (K, m – values) of the circular sheet. Ghosh and Hamilton [9] improvised the ideas of Holt[3] by using plane strain analysis on a long hemispherical sheet. Several researchers found the presence of superplastic behaviour in many aluminium alloys using uniaxial tension tests. These experimental data’s are not totally dependable because in actual superplastic forming on sheet metals, the workpieces are subjected to two state of stresses. Hence, in this work, the superplastic forming behaviour of AA5086 alloy has been analyzed at prominent temperatures by means of blow forming technique. And also a theoretical model was developed to approximately determine the time taken by the forming die to reach the steady state temperature value and also the material parameters such as strain rate and the strain rate sensitivity index were found for AA5086 alloy.

2. Experimental Procedure

The experiment is carried out with two different temperatures i.e. 400ºc & 450ºc. For each temperature, three pressure values (0.4 MPa, 0.5MPa, 0.6MPa) were applied. The temperature range were selected in such a way that the superplasticity temperature range should be in between (0.6 - 0.7) times the melting point temperature of the Al5086 [9]. The melting point of the metal alloy is 670ºc. The optimum temperature is based on the formation of the uniform thickness formed on the workpiece. The dies are placed inside the press, and the furnace is subjected to electric heating. Each die is in the form of a hemisphere with small grooves which facilitates holding each other. The thermocouples are inserted at four different positions which are dimensionally equal from the geometric centre of the die. When the die reaches the particular temperature set initially, the dies are unclamped and the work piece is placed between them and clamped. This is done to prevent the oxidation of the work piece. The die is maintained at the set temperature for the work piece to attain the operating thermal range. After the choking time, the pressure is applied constantly by passing argon gas for the material to bulge. The thickness begins to decrease and the work piece starts assuming the form of the die. The shape of the die is verified with the Linear Variable Differential Transformer positioned at the centre of the die. The schematic arrangement showing the position of die, heating elements is shown in Fig. 1. The bulging of the work piece is noted for every five seconds till maximum dome height is reached. The parameters such as true stress, true strain, strain rate and strain rate sensitivity index were determined using the equations described by bycheng [4] and Senthil Kumar et al. [6]. The superplastically formed component is shown in Fig. 2.

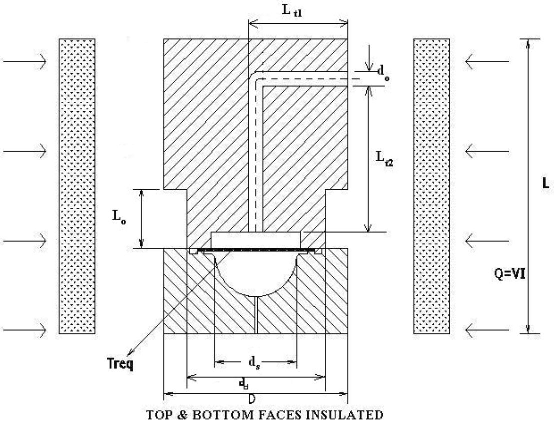


Fig. 1 Schematic arrangement of the setup

Fig. 2. Superplastically formed component

2. Approximate Analysis on the Heat Transfer in the SPF Die:

An approximate analysis to determine the time taken for the SPF die to reach the steady state temperature is achieved by Lumped Heat Analysis Method. The assumptions made are as follows

1. Solids of large thermal conductivity with surface areas that are large in proportion in volume to their volume like thin metallic wires or plates, the internal resistance can be assumed negligible. This approach is called "Newtonian Heating Or Cooling Process".

2. The System is assumed to be closed one, with no Mass transfer between the system and the surroundings.

3. By Lumped Heat Analysis approach the temperature throughout the closed given system is assumed to be constant at a given point of time.

Time taken by the air to reach the required temperature is

$$t_a = \frac{m_{aC_{Pa}}\left(T_{req} - T_i\right)}{V.I} \qquad \textbf{(1)}$$

Time for the solid to reach the required temperature is

$$t_s = \frac{m_s C_{Psolid}\left(T_{req} - T_i\right)}{VI} \qquad \textbf{(2)}$$

Time for the work piece to attain the required temperature is

$$t_w = \frac{m_w C_{pworkpiece}\left(T_{req} - T_i\right)}{VI} \qquad \textbf{(3)}$$

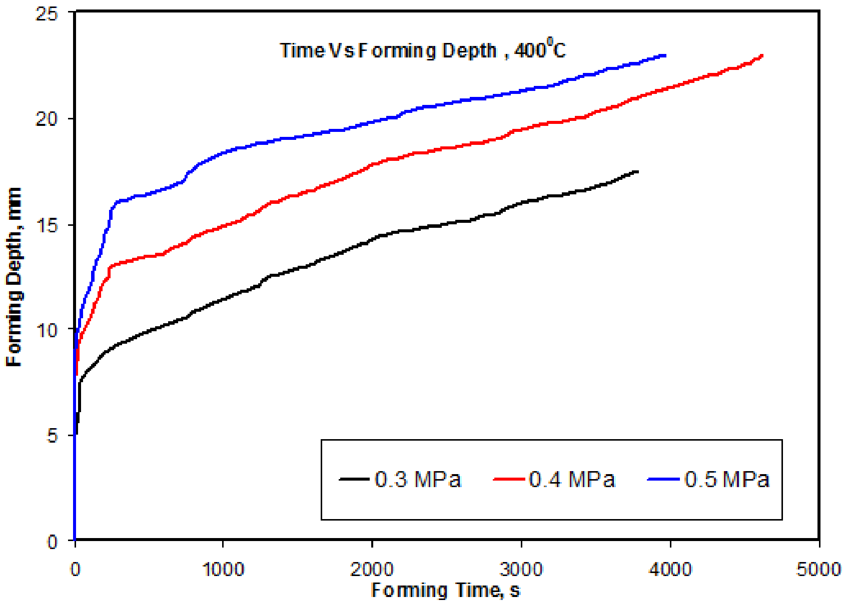
Total time taken by the system to attain the steady state is given by

$$t = t_a + t_s + t_w \qquad (4)$$

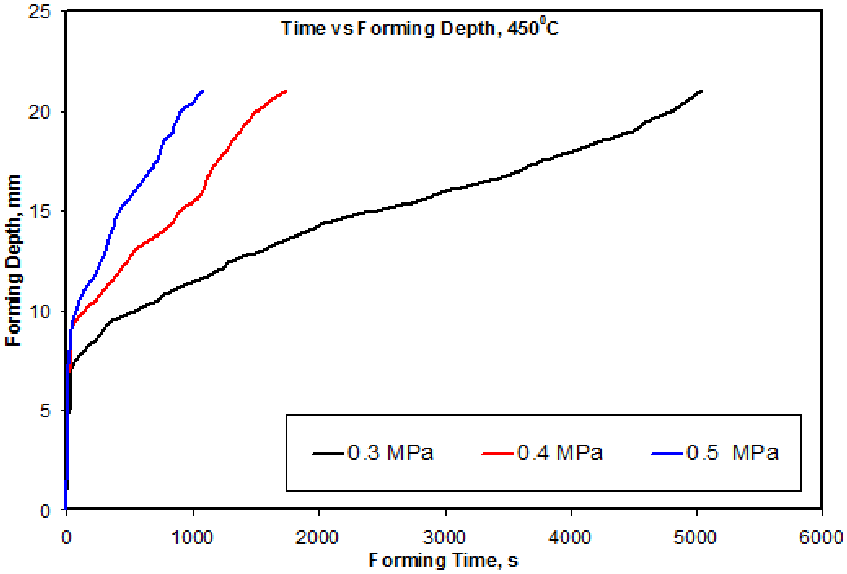
4. RESULTS AND DISCUSSIONS

4.1. Dome height vs forming time

The progress of the dome height with respect to the forming time at various pressure levels is shown in Fig. 3 (a, b) . It is inferred that the early part of the curve is described by abrupt growth of the dome height and in this part the slope of the curve is more. Further this increase in the slope corresponds to the elevated strain rate values. In the second part of the plot, the progress of the dome height with respect to time is gradual, due to which the slope of the curve in this region is almost stable and in the third part, the progress of the dome height is steep, due to which the strain rate also increases As the pressure increases, more deformation is obtained within the material and hence the forming time decreases. The similar observation was obtained as the forming temperature is decreased. This reduction in the forming time with an increasein the forming temperature is due to decrease in flow stress of the material at elevated temperatures. At higher temperature, the yield strength of the material decreases thereby reducing the forming load and also the forming time.



(a)



(b)

Fig.3 Dome Height versus Forming Time (a) At Temperature 400°C and (b) 450°C

4.2 True Stress-Strain Curves

The true stress–strain curve for various pressure ranges is shown in Fig. 4. It is inferred that for a given temperature, as the pressure increases the load/stress induced in the workpiece also increases. For any given pressure, the maximum stress is inducedat the initial part of the curve; then it gradually decreases and later increases during the final stage. At the initial part of the curve, the pressure acts on the entire surface area of the blank and for a given thickness. Due to the increase in the surface area of the formed depth because of plastic deformation at any instant, the forming area increases. Since the applied pressure is constant, the stress decreases at the later stage. Beyond a certain point, because of the continuous deformation the thinning of the workpiece occurs at the dome and hence the the strain or work hardening occurs in the formed material, due to which more pressure is required to form further depth.

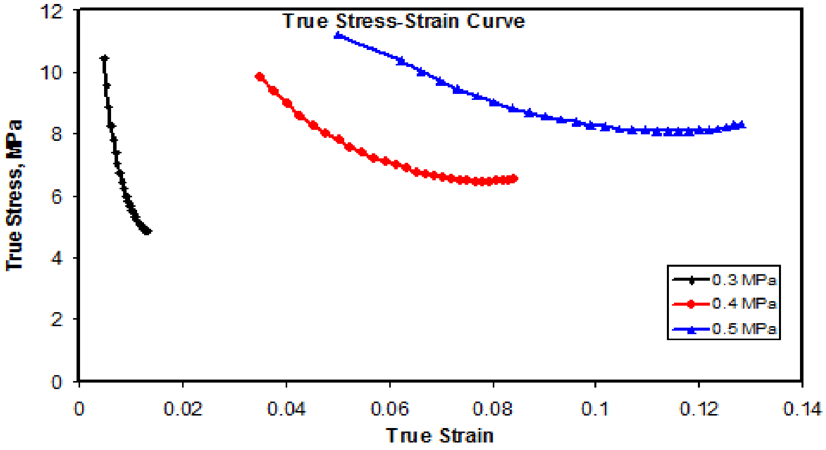


Fig. 4 True Stress curve

4.3 Strain Rate Sensitivity Vs Strain Rate

Strain rate sensitivity is an important index in the superplastic forming process that resists the formation of necking within the material. The strain rate sensitivity curve for various pressures is shown in Fig.5. It is observed that as the pressure increases, the strain rate sensitivity curve shifts towards the higher strain rate and also shows a decreasing trend. Hence for the material to have maximum deformation, the strain rate sensitivity value should be high i.e in the range 0.3 – 0.7. The strain rate sensitivity value at different temperatures and pressure is tabulated in Table 1.

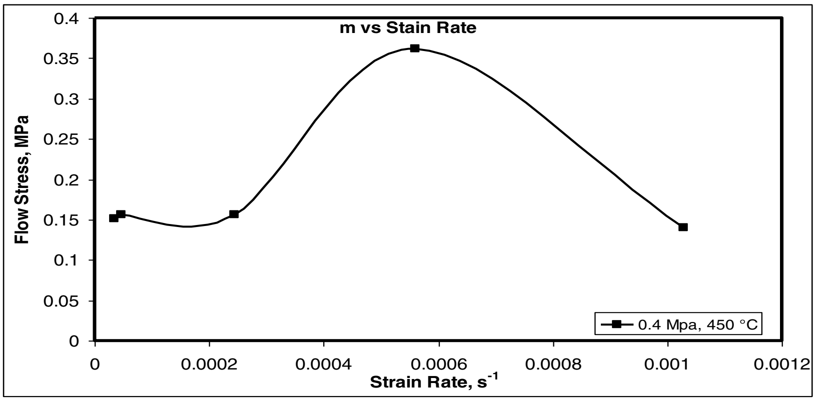


Figure 5. Strain Rate Sensitivity vs Strain Rate

Table 1 Strain Rate Sensitivity Index Values

Forming Temperature °C	Forming Pressure MPa	Strain Rate Sensitivity m	Strain Rate s-1
400	0.3	0.345	2.2 x10-4
	0.4	0.286	3.2 x 10-3
	0.4	0.289	9x10-3
450	0.3	0.362	5x10-4
	0.4	0.29	7 x10-3
	0.5	0.27	9.6 x 10-3

From Table 1, it is inferred that the strain rate sensitivity value is more when the forming temperature is 450°C and the forming pressure is 0.3 MPa. The decrease in strain rate sensitivity with an increase in pressure is well depicted by Ramesh Babu et al [2].

4.4 Cavitation Effect during superplastic forming

Cavitation is the opening of pores during superplastic forming, typically at grain boundaries. Superplastic forming is usually limited by the development of voids, a process commonly known as cavitation [10]. In recent years, wideconsideration has been paid to the cavitation behaviour of superplastic alloys since cavitation leads to degradation of all the properties of the post-SPF materials. It has been demonstrated that the post-SPF mechanical properties of the materials are significantly reduced when the cavity volume fraction exceeds approximately 1% [11]. The effect of strain rate, and temperature on the cavitation of superplastically deformed aluminium alloy was systematically examined and shown in Fig. 6 (a, b, c) for different strain rates. It is inferred that as the strain rate increases, the percentage density of cavity also increases. Hence for maximum deformation at elevated temperatures, the strain rate should be less.

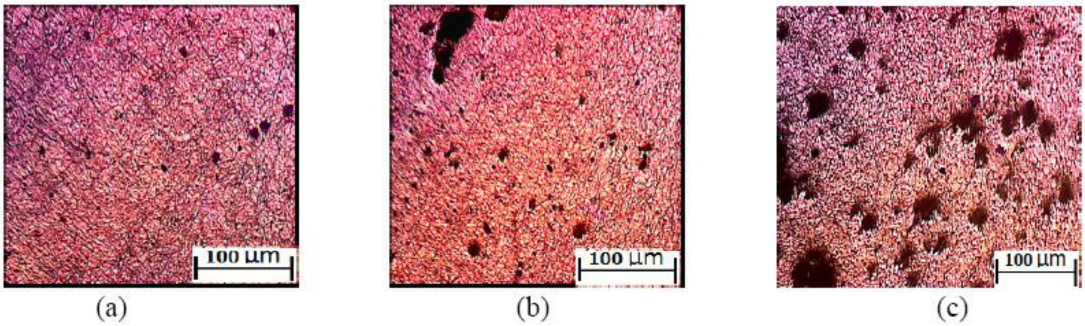


Fig. 6. Optical micrographs showing cavitation at the pole of the superplastically deformed component (a) 5x10-4 (b) 7 x10-3 (c) 9.6 x 10-3

3. CONCLUSION

The superplastic forming on as received AA 5086 Aluminium alloy was done and the following conclusion was arrived.

1. As temperature increases, the time taken for reaching the dome height decreases. This is because, the flow stress of the material decreases at higher temperature. The result validates with the experiment results of temperature (400 & 450ºc).
2. At a given temperature, as the pressure increases, the time taken to reach a given dome height decreases.

This is because the strain rate increases, which in turn decreases the forming time.

3. The cavitation density increased with an increase in the strain rate.
4. The forming temperature for the material to exhibit superplastic behaviour is identified as 450^0C

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