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Evaluation of Strain and Strain rates at different stages of Superplastic Cone Forming

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Abstract

Superplastic forming (SPF) is a powerful tool to manufacture complex parts for industries like automobile and aerospace where strength to weight ratio of the part is the main criterion. Superplastic forming (SPF) of a sheet metal has been used to produce very complex shapes and integrated structures at much lighter and stronger than the assemblies they replace. Superplastic formed shapes like conical, hemispherical poses a problem of large thickness variation, minimum thickness results at the portion where die contact is made last. Proper understanding of strain and strain rates during forming and using the pressures accordingly can minimize this problem. The present investigation focused on the study of strain and strain rates during the forming, Experiments were carried on a model material Sn-Pb, which can be applicable for any other Superplastic materials. Results revealed that strain rates in the present study are within the range of superplastic regime and no failure of the formed part because of the thinning. Results also revealed that forming time can be reduced by increasing the pressure which in turn increase the strain rate.

*Keywords:*Superplastic forming, Conical shape, Strain, Strain rate

1. Introduction

Superplastic materials are polycrystalline solids which are having the ability to undergo very large and uniform tensile elongations before the failure occurs. Generally elongations higher than 200% indicate the superplasticity.

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Due to this property superplastic forming (SPF) is increasingly used industries like aerospace and automobile to produce complex parts at much lesser efforts and costs when compared with conventional machining [1-3]. Wide varieties of materialsaluminum, magnesium and titanium alloys exhibit the phenomena of superplasticity, when subjected to certain conditions of pressure, temperature and strain-rates [4, 5].The conditions that are necessary for any material to be superplastic material are grain size $\leq 10\mu m$, strain - rates $\leq 10^{-3}\ s^{-1}$ and temperatures $\geq 0.5\ T_m$ where T_m is the melting point of the material under investigation [6].Most often ultra-fine grained materials are obtained by using severe plastic deformation methods like: high pressure torsion (HPT) [7, 8] equal-channel angular pressing (ECAP) [8,9], multiple forging [3], and multi-axis restrain deformation *(Max Strain)* [10] or cyclic extrusion-compression (CEC) [9].Blow forming of single sheet is essentially based on the application of a gas pressure differential on the super plastic diaphragm, resulting in the deformation of the material into a given die configuration. Pressure, typically in the range 10–30 bars, is applied through the injection, via a series of inlet tubes, of either air or a protective gas (typically argon), depending on the affinity to oxygen of the material to be formed. Die and sheet are maintained at the same temperature within a heating press. The gas pressure is imposed over the sheet causing the sheet to form into the lower part of the die. While it is being formed, the sheet simply vents the gas to atmosphere which was initially located within the lower die chamber. The lower die chamber may be held either under vacuum or under some back pressure to control or even to prevent cavitation in the formed material (e.g. aluminum alloys) [11]. The mechanical characteristics of the finished product are very good, because the hardening of material is practically absent and spring-back is zero, with benefit of obtained dimensional accuracy. The surface finish is excellent, so there is no need to make finish operations [12-15].

Nomenclature

A_f	Surface area of the frustum
ao	Original radius of the circular blank
A_s	Surface area of the dome shape at the required instance ($2\pi\rho h_s$)
a	Radius at the smaller end and the cone
ρ	Radius of curvature
l	Slant length of circular blank at the die opening
h_f	Vertical height of the truncated cone
h_s	vertical height of the dome shape in the total deformed components at any instant
h	Total formed height of the component (measured with depth micrometer) ($h=h_f+h_s$)
ε	Strain
$\acute{\varepsilon}$	Strain rate
σ	Stress

2. Methods and materials

Lead –Tin (Pb-40% -Sn-60%) alloy which is used as solders is available in the form of bars was used in the present study. This alloy was cast to slab of dimensions 68mm wide x 720mm long x 30 mm thickness and cold rolled at room temperature to a thickness of 2.45 mm as shown in Fig.1 in a rolling mill at Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad, Telangana, India. The lamellar grains broke down to fine globular grains of average size 8 µm as shown in Fig.2. Cone forming tests were carried out in Low cost experimental setup as shown in Fig 3. Sn-Pb blanks of 80mmΦ x 2.45mm thickness were blown by Argon gas in a conical die of 80mm Φ x apex angle 60^0 as shown in Fig 4. under constant gas pressures 3 bar,6 bar and 8 bar. The progress of deformation of the cone with time was monitored at different stages of forming.

- ❖ Free Blowing (deformation without touching die wall)
- ❖ Free Blowing (max. limit of deformation without touching die wall)
- ❖ Cone wall making tangent to the membrane
- ❖ Cone wall formation + free blowing of dome

These four stages go on repeating further till the cone shape is formed.

Fig.1.Experimental Set Up.

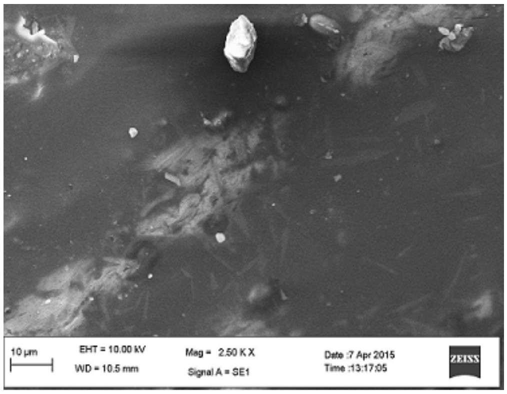


Fig.2. SEM images of Lead –Tin (Pb-40% -Sn-60%) alloy after rolling.

Fig.3. Lead –Tin (Pb-40% -Sn-60%) Alloy sheet thickness of 2.14 mm.

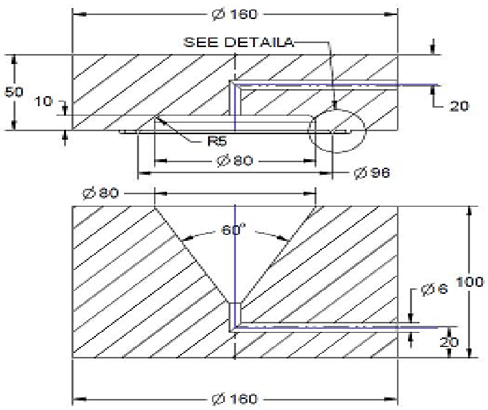


Fig.4. Various stages of superplastic forming in conical die.

As soon as the membrane touches the conical die wall, the thickness freezes and further thinning occurs on the free dome portion.As a result of these dome thickness is less than the cone wall thickness. And finally, in the formed cone the thickness reduces progressively from the base of the cone to the apex.Stress and strains were calculated at different stages of forming for the forming pressures 3 bar, 6 bar and 8 bar.

3. Determination of Stress and Strains at different stages of forming

Stress and strain values of at different stages of forming are calculated. Sample calculations for a forming pressure of 3 bar are shown below

Stage 1. Free Blowing

Original area of the circular blank

$$\text{Ao} = \pi(\text{ao})2 = \pi(40)2 = 5026.5\ \text{mm2}$$

Depth of the formed dome shape = h

$$h = \rho - \frac{(\rho 2 - \text{ao}2)1}{2} = 1.1547\ \text{ao} - \frac{((1.1547)2 - \text{ao}2)1}{2} = 0.578 * \text{ao} = 23.12\ \text{mm}$$

$$\rho = \text{ao}2\frac{h2}{2h}(or)\rho = \text{ao}/\sin 60 = 1.1547\text{ao}$$

Stage 2. Free Blowing (max. limit of deformation without touching die wall)

Surface area of truncated cone = π (r + R) l

= π (a+ao) l

Vertical height of the truncated cone (h_f)

$= l \cos(\theta/2) \quad (\theta=60^0)$

$= l \cos 30^0$

Stage 3. Cone wall making tangent to the membrane

Surface area of the frustum $A_f = \pi$ (ao+a) l

Vertical height of the frustum = h_f

h = Total formed height of the component (measured with depth micrometer)

$h=h_f+h_s \qquad h_f = l \cos 30^0$

$h_s = h- h_f$

Stage 4. Cone wall formation + free blowing of dome

Surface area of the dome shape at the required instance.

$$A_s = 2\pi\rho h_s$$

Where

ρ =radius of curvature of the dome shape.

$$\rho = a^2+h_s^2/2h_s$$

hs = vertical height of the dome shape at that instance.

Total formed area of the deformed components

$$A= A_f+ A_s$$

Strain

$$\varepsilon = \ln (A/A_0)$$

Strain rate:

$$\acute{\varepsilon} = \varepsilon/\text{time}$$

$$\text{Stress,}\sigma = (\frac{\rho}{2t})\text{*P}$$

$$\sigma = ((\frac{A}{2\pi h})/(\frac{Aoto}{A})\text{*P}$$

$$\sigma 3\text{bar} = ((6599.18)2/(4\pi \times 23.4 \times 5026.5 \times 2.45)) \times 0.03 = 0.360\ \text{N/mm2}$$

For dome:

Radius of curvature

ρ = (a2+ h2)/ 2h = (402+22.382)/ (2×22.38)= 46.93 mm

Area of dome

A = 2πρh= 2π×46.93×22.38= 6599.18 mm2

Strain

ε = A/A0= 6599.18/5026.5= 0.272

Strain rate

έ = 0.272/ (50×60)= 9.06×10-5/sec

For Truncated Cone

$h_s = h-h_f$= 46.38-32.04= 14.34 mm

Radius of dome

a = hs/0.578= 24.8 mm

ρ = a/sin60^0= 28.64mm

Area of dome

$A_s = 2\pi\rho h_s$= 2π×28.64×28.64= 2580.48 mm2

Area of frustum

A_f = πl (ao +a)= π × 37(40+24.8)= 7532.28 mm2

A = (As +Af) =10112.76 mm2

Strain

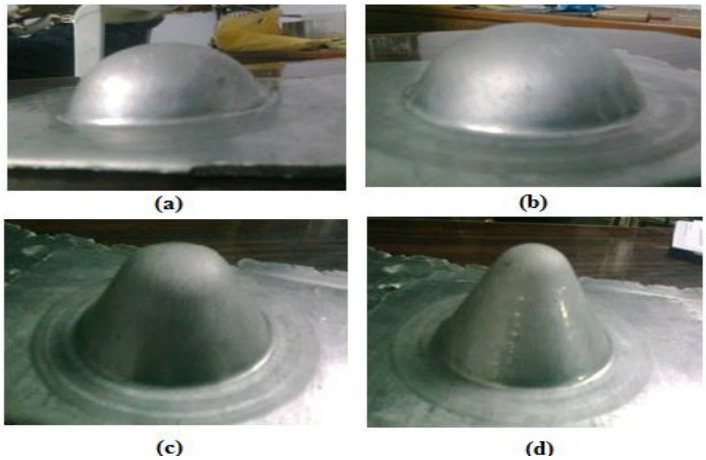
ε = A/Ao= 10112.76/5026.5= 0.699

Strain rate

έ = 0.699/ (80×60) = 1.45×10-4 /sec

4. Results and Discussion

Fig.5 Formation of conical dome at 3 bar pressure at different time intervals in minutes (a) 5 (b) 20 (c) 80 (d) 110



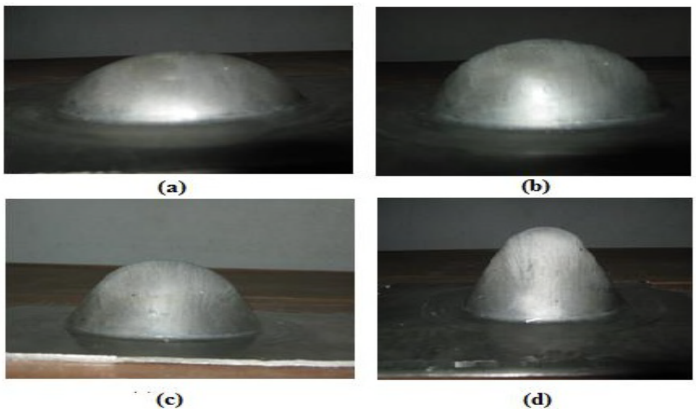


Fig.6 Formation of conical dome at 6 bar pressure at different time intervals in minutes (a) 5 (b) 30 (c) 40 (d) 45

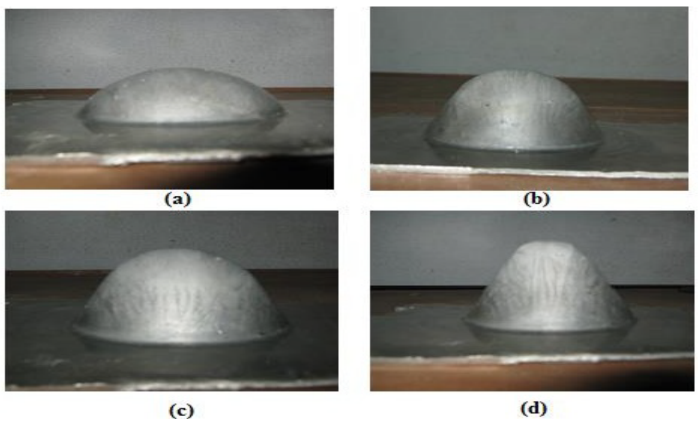


Fig.7 Formation of conical dome at 8 bar pressure at different time intervals in minutes (a) 5 (b) 10 (c) 15 (d) 20

Stress and strain values of at different stages of forming for the forming pressure 3 bar, 6 bar and 8 bar are calculated as per the calculations mentioned in the section.3, and are shown in Tables 1,2 and 3. Conical domes formed at forming pressure 3 bar, 6 bar and 8 bar with different stages are shown Figures 5, 6 and 7.

From the Table 1, one can observe that strain on the material in increasing, but strain rate is decreased in the time interval 5-20 min shows the initial strain hardening of the material, further in the 20-50 min time interval strain rate is increased as the material is free forming without touching the walls of the conical die. After the touching the wall of the die for 80-140 min time interval the strain rate gradually decreasing and remains a constant value.

Table.1. Strain and Strain rates at different stages of forming at a forming pressure of 3 bar

Time (minutes)	Slant height (mm)	Depth (mm)	Radius of Curvature (mm)	Area (mm^2)	Strain	Strain rate /sec
5	0	5.13	158.51	5109.2	0.016	5.43×10^{-5}
20	0	7.00	117.78	5180.2	0.030	2.50×10^{-5}
50	0	22.38	46.93	6599.18	0.272	9.06×10^{-5}
80	37	46.38	28.64	10112.76	0.699	1.45×10^{-4}
110	51.5	54.38	19.53	10404.52	0.727	1.10×10^{-4}
140	58.3	62.50	24.01	12947.30	0.946	1.10×10^{-4}

Table.2. Strain and Strain rates at different stages of forming at a forming pressure of 6 bar

Time (minutes)	Slant height (mm)	Depth (mm)	Radius of Curvature (mm)	Area (mm^2)	Strain	Strain rate /sec
5	0	18.30	52.86	6078.63	0.190	6.33×10^{-4}
10	0	23.40	42.88	6746.75	0.294	4.90×10^{-4}
15	7.07	27.98	43.67	7722.60	0.429	4.76×10^{-4}
20	16.05	32.00	36.13	7702.60	0.426	3.55×10^{-4}
30	22.54	39.27	39.45	10147.88	0.702	3.90×10^{-4}
40	39.25	48.34	28.66	10579.25	0.744	3.10×10^{-4}
45	47.62	54.50	26.49	11623.02	0.838	3.10×10^{-4}

Table.3. Strain and Strain rates at different stages of forming at a forming pressure of 8 bar

Time (minutes)	Slant height (mm)	Depth (mm)	Radius of Curvature (mm)	Area (mm^2)	Strain	Strain rate /sec
5	0	22.45	46.85	6606.56	0.273	9.10×10^{-4}
10	13.20	31.15	39.39	7950.51	0.458	7.63×10^{-4}
15	22.64	38.10	36.95	9412.27	0.627	6.98×10^{-4}
20	43.05	50.41	33.34	12008.32	0.737	6.14×10^{-4}

At higher forming pressures 6 bar and 8 bar (Table 2 and Table 3) strain rate is gradually decreasing and remains a constant value. However, the initial values strain rates are higher when compared to the forming pressure of 3 bar.It is known facts that blow forming of a cone with apex angle nearer to 60^0, under constant strain rate can be achieved by applying a constant gas pressure [13]. In other wards constant gas pressure induces a constant stress in the membrane which in turn produces constant strain rate. In the present investigation similar behavior is observed.

From the Table 2 and Table 3, it can be observed that at higher forming pressures the forming time can be reduced considerably. This is because of higher strains and strain rates. However higher strain rates lead to the local thinning of the formed part. This can be explained as for superplastic deformation, elastic strains are negligible; therefore, constancy of volume can be assumed. From this consideration, the sum of the plastic strains is zero, and tensile strain in one direction must be balanced by compressive (negative) strain in another. The strains are:

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$$

Where ε is the strain and the subscripts indicate the principal directions. For the present sheet forming operation under plane strain conditions, $\varepsilon_2 = 0$ and $\varepsilon_3 = -\varepsilon_1$, the thinning strain ($\varepsilon_3$) is equal and opposite to the longitudinal tensile strain ($\varepsilon_{1)}$ and the thinning will therefore match the tensile deformation. For large tensile strains, the thinning will be corresponding large. Present investigations do not show any failure of the part during forming because of thinning. This shows pressures considered in the study are suitable forming the conical domes. Calculated strain rate values for the different forming pressures at different stages of forming are within the range of superplastic forming regime, which resulted the forming of conical parts without fracture.

5. Conclusions

Conical forming of lead –tin samples at different pressure were carried out in the present study to know the feasibility of forming without failure of the part. The following conclusions are drawn for this study.

- Rolling of the cast slab of lead and tin alloy can reduce the grain size approximately 8 µm, which is suitable for superplastic forming.

- ❖ Calculated strain rate values at different stages of forming at forming pressure are almost a constant which is good agreement with published results.
- ❖ Strain rates are higher at higher forming pressures which resulted in lesser the forming time.
- ❖ Calculated strain rate values for the different forming pressures are within the range of superplastic forming regime, which resulted the forming of conical parts without fracture.

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