Cavity closure during compression between semi-closed dies using superplastic tin-lead alloy

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Abstract. Superplasticity is a feature of a material or alloy, which allows the material to deform plastically to an extremely large strain at low values of stress under certain loading conditions of strain rate and temperature. Eutectic tin-lead alloy is a practical material for research investigations as it possesses a superplastic behavior at room temperature and low strain rate, which makes it a useful tool in simulating the ordinary engineering materials at high strain rate and temperature, and has been extensively used as a model material. In this paper, superplastic tin-lead alloy was used at room temperature to simulate the closure of cavities in steels at high temperatures in the hot region under dynamic loading (high strain rate) under the effect of compressive loads using semi-closed dies (modified dies) with 45° inclination and compare the results from these dies with those of flat platens (open dies) published previously. Hollow specimens having different values of bore diameter (D_b) to outer diameter (D_out), of the same height and volume were investigated under 40% height reduction. The cavity closure for each specimen was determined. Comparison is made between flat platens and semi-closed dies regarding cavity closure based on bore diameter, bore volume, reduction percentage in bore diameter and reduction percentage in bore volume, at the 40% reduction in height. It was found that modifying the platens (45° inclination) resulted in lower values of bore diameters and volume i.e. higher values of reduction in bore diameters and volumes percentages irrespective of the value of bore diameter and the ratio of D_b/D_out.

1. Introduction
Cast ingots normally include some defects, for example; porosity and voids, inclusions and entrapped gasses which tend to reduce their mechanical properties and surface quality. Therefore, it is necessary to get rid of these defects. One recommended method is the free upsetting test for the cast ingots, and it is becoming customary to subject the casts, while hot, into compressive stresses. In the early studies on cavity closure during compression, friction between the workpiece and die interface was considered the main parameter in determining the force, energy, flow of metal and the changes in the cavity dimensions (enlargement or shrinkage) [1,2]. The ring test was also used to determine the changes in the coefficient of friction during compression at room and high temperatures [3,4], and at different strain rates [5]. Void growth in 6061 – aluminum alloy under triaxial stress system was investigated and reported using notched tensile test specimens, to maintain the state of triaxial stress system [6]. The effect of local deformation conditions on the cavitation behavior and cavity growth during open-die hot forging of Ti-6Al-4V was reported by Nicolaou and Semiatin [7]. The effect of strain path reversal on microstructure evolution and cavitation during hot torsion testing of Ti-6Al-4V is given by the same authors. They found that the cavity growth persisted as long as there was a flow-stress.
difference in the regions surrounding a given cavity [8]. The effect of stress and strain path on cavity closure during hot working of an alpha/beta titanium alloy was investigated by Nicolaou et al. Their work indicated that the rate of cavity closure decreases with increasing deformation. This suggests that deformation at very large strains may be required to totally heal damage or complete cavity closure [9].

1.1. Superplasticity and Superplastic Materials
Superplasticity is a feature which allows the material to deform to large strains at low stress if the material is deformed under certain loading conditions. The elongation may be of the order of a few hundred percent up to 2000% [10]. Superplasticity can be induced either in materials possessing a stable, ultra-fine grain size at the temperature of deformation \( \geq 0.4 T_m \), where \( T_m \) is the absolute melting point or in those subjected to special environmental conditions [11]. Superplastic materials are a unique class of metals that have the ability to undergo extra ordinary large tensile ductility where elongations of 200% and more are experienced. The requirements necessary to achieve superplastic behaviour are: i) fine and equiaxed grain size, usually less than 10 microns. ii) Testing temperature that is greater than or approximately half the absolute melting temperature of the subject material. iii) Controlled strain rate [12]. This shows the importance of using superplastic material for investigating cavity closure in ordinary engineering materials during plastic deformation in the forging process. Taylor et al. have investigated the effect of void size and spacing on the ductility and flow stress of superplastic Pb-Sn tensile specimens using experimental testing and Finite Element model [13]. Recently, Ridely et al. have studied and reported the effect of strain rate path on cavitation in superplastic aluminum alloy 5083. The alloy was tested under two different conditions: one in uniaxial tension and the other under constant strain rate. They observed continuous nucleation of cavities in both test conditions. Furthermore, they found that the cavities were associated with inter-metallic particles as observed under metallographic examination. The analysis of their experimental data led to the conclusion that the growth of cavities was controlled primarily by plastic deformation, although diffusion may play a role in the early stages of growth [14]. The deformation behavior of the fine grained tin–lead eutectic alloy was investigated by Soliman and Al-Seif using compression specimens at initial strain rates in the range \( 10^{-5} \) to \( 10^{-1} \) s\(^{-1} \) [15]. Recently, Mulholland et al. have conducted set of parametric experiments on a superplastic material (eutectic tin–lead alloy) with one or more pre-drilled holes in each specimen. They found an increase in ductility with the number of holes up to 10 holes followed with a decrease thereafter [16].

1.1.1. Mechanical Behaviour of Superplastic Materials
Unlike the mechanical behaviour of an ordinary engineering metal or alloy where the flow stress is function of strain, strain rate and temperature. The flow stress of a superplastic material is mainly affected by strain rate at a specified temperature and is strain independent. Steady state flow of structurally superplastic materials invariably shows an increase in flow stress with increasing strain rate. The eutectic tin–lead alloy (61.9% tin and 38.1% lead by weight) has extensively been used as a model material to investigate the deformation characteristics of superplastic materials and ordinary engineering materials at high strains and hot loading conditions [11, 17, 18].

1.2. Effect of Strain Rate on cavity Closure
Recently, Zaid and Al-Tamimi have used superplastic tin-lead alloy at room temperature to simulate the closure of cavities in steels at high temperatures in the hot region under dynamic loading (high strain rate) under the effect of compressive loads using flat platens (open dies). Hollow specimens having different values of bore diameter (\( D_b \)) to outer diameter (\( D_{out} \)), of the same height and volume were investigated under different values of height reduction percentages ranging from 20% to 80%, and the percentage of cavity closure at each reduction percentage was determined and discussed. It was found that the cavity closure percentage increases or decreases at slow rate for reduction
percentage in height less than 40% and increases more rapidly for reduction percentages in height above this value [18].

2. Materials, Equipment and Experimental Procedures

2.1 Materials
High purity, 99.99%, tin and lead supplied in granular form were used for the production of the superplastic tin-lead alloy. Graphite crucibles were used for melting and graphite rods were used for stirring.

2.2 Equipment and experimental procedures
The experimental procedure was carried out in the following sequence: preparation of the superplastic tin-lead alloy, carrying out the extrusion process on the cast eutectic alloy to increase its degree of superplasticity, preparation of specimens from the extruded alloy for the compression test between the semi-closed dies at 40% height reductions and finally sectioning the different specimens along their axis by wire cutting and finally tracing their profiles using the Profilometer, (contracer).

2.2.1 Preparation of the superplastic tin-lead alloy
The preparation process started by placing the pre-calculated amount of pure Tin granules inside a graphite crucible, charged into an electric furnace at 523 °C. After 10 minutes the crucible was taken out of the furnace and the calculated amount of lead (Pb) granules were introduced to the crucible and mixed with Tin (Sn). The crucible was then returned to the furnace for 10 minutes, taken out of the furnace, and the melt was stirred for one minute and poured to solidify in a thick brass hollow cylinder. It is worth noting that the amount of tin and lead were calculated to satisfy the eutectic point of 61.9% tin and 38.1% lead by weight.

2.2 Extrusion process
The extrusion process was carried out at different billets from the prepared tin-lead alloy to increase their degree of superplasticity. The extrusion process was carried at 25 °C which corresponds to a homologous temperature of 0.65 i.e. hot extrusion, using five extrusion dies of different openings to produce hollow cylindrical specimens of bore to outer diameter, \( \frac{D_b}{D_{out}} \), of 0.1, 0.2, 0.3, 0.4 and 0.5 at extrusion ratios of 6.6, 6.4, 6.0, 5.6 and 5. All the extrusion tests were carried out at cross head speed = 5mm/min, and were kept in a freezer at -10 °C to avoid grain growth. Figures 1 and 2 show the designed and manufactured dies in the assembled and exploded conditions.

Figure 1. Photograph of the designed and manufactured dies.  
Figure 2. Extrusion die - exploded manufactured dies.
2.3 Compression between two 45° semi-closed dies test
The compression test between two "45° semi-closed dies" for each specimen was performed using GUNT HAMBURG WP 310 Hydraulic Universal Material Tester of 50 kN capacity at cross head speed of 5 mm/min, which corresponds to strain rate of $4.17 \times 10^{-3}$ s$^{-1}$ at the end of compression (40% reduction in height). The die design allows only 40 % height reduction on specimens of different ($D_b/D_{out}$) namely 0.1, 0.2, 0.3, 0.4 and 0.5 but all having the same solid volume. After the test, the actual bore volume of each specimen was measured by filling water inside the bore using 1-ml Insulin Syringe having an accuracy of ±0.005ml).

2.4 Tracings of the specimens profiles
Five different specimens of 20mm height and with different ($D_b/D_{out}$) ratios were sectioned using a wire cutting process, after which the deformation of the bore was traced using Shadomaster R122 BM Profilometer at a magnification of 10.

3. Results and Discussion
All the following results were obtained for hollow cylindrical specimens of the same volume but of different bore diameters and outside diameters. Furthermore, all the specimens were compressed between the same semi-closed dies with 45° inclination at cross head speed of 5 mm/min, which corresponds to strain rate of $4.17 \times 10^{-3}$ s$^{-1}$, which falls within the range of the rate sensitivity of the tin-lead alloy i.e. when it behaves superplastically.

3.1 Comparison between Flat Platens and Semi-Closed Dies
In this section, comparison is made between flat platens and semi-closed dies with 45° inclined platens based on bore diameter, bore volume, reduction in bore diameter percentage and reduction in bore volume percentage, only at 40% reduction in height. It can be seen from the histograms of Figures. 3, 4, 5 and 6 that modifying the platens (45° inclination) resulted in lower values of bore diameters and volume and higher values of reduction percentages in bore diameters and volumes respectively irrespective of the value of bore diameter and the ratio of $D_b/D_{out}$ . It can also be seen, that the difference is more pronounced at smaller bore diameters and smaller ratios of $D_b/D_{out}$. This means the plastic flow in the radial direction in the radial direction towards the center is more pronounced in case in case of small bore diameters and smaller ratios of $D_b/D_{out}$, i.e. lower friction at the interference as compared to higher ratios of $D_b/D_{out}$, which agree with the previous work of the ring test [1,2]. Furthermore, it can be seen from Fig. 5 that at D1 ($D_b/D_{out} = 0.1$) at 40% reduction in height the diameter closure is 65% in the semi-closed, where is the diameter closure in case of the flat platens die is about 19%. This is explicitly shown in Fig. 6 that at D1 ($D_b/D_{out} = 0.1$) the volume cavity closure is almost completely closed in the semi-closed dies (about 92%) at 40% reduction in height, where is the volume cavity closure in case of the flat platens die is about 58% for the same $D_b/D_{out}$ at the same reduction in height.

3.2 Comparison between Flat Platens and Semi-Closed Dies on the Shape Changes of the Cavity
Comparing the effect of modifying the flat platens to 45° semi-closed die with the flat platens dies when compressing identical specimens at the same reduction in height percentage namely 40%, it can be seen from Figure 7 (a) to (e) inclusive, that the semi-closed dies produced more cavity closure than the flat platens for all the specimens irrespective of their $D_b/D_{out}$ ratio. Furthermore, in case of the flat platens, the bore increased in diameter in certain regions and reduced in others, where as in the case of semi-closed dies reduction of the bore diameter was observed along the whole height of the specimens and being maximum at the middle section of the height except for the specimen D5 ($D_b/D_{out} = 0.5$), Figure 7 (e), where the bore increased in some regions and reduced in others.
Figure 3. Bore diameter after compression (40% reduction in height) flat platten and 45° semi-closed dies

Figure 4. Bore volume after compression (40% reduction in height) flat platten and 45° semi-closed dies

Figure 5. Reduction in bore diameter percentage after compression (40% reduction in height) flat platten and 45° semi-closed dies

Figure 6. Reduction in bore volume percentage after compression (40% reduction in height) flat platten and 45° semi-closed dies
Figure 7. Tracings of the sectioned specimens D1, D2, D3, D4 and D5 along their axes at 0 and 40% reduction in height using flat platens and 40% reduction in height using semi-closed dies (a), (b), (c), (d), and (e) at \( \frac{D_0}{D_{out}} \) of 0.1, 0.2, 0.3, 0.4, and 0.5 respectively.
4. Conclusions
The following points may be concluded:

- Superplastic tin-lead alloy can be used successfully, under certain conditions, as a model material to simulate the behavior of metals at high strain rate and hot conditions in flat and semi-closed dies forging.
- Cavity closure does not depend only on the end friction at the die-workpiece interface as repeatedly reported in the literature, but also depends on other parameters, e.g. strain rate, the geometrical shape of the platen if flat or at angle, reduction in height and bore diameter to the outside diameter ratios of the specimen, \((D_b/D_{out})\).
- Using semi-closed dies during compression by modifying the platen by an angle \((45^\circ\) inclination) resulted in lower values of bore diameters and volume i.e. higher values of reduction in bore diameters and volumes percentages respectively irrespective of the value of bore diameter and the ratio of \(D_b/D_{out}\).

5. References

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