Forming of a super plastic sheet metal made of MgAZ31 alloy

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Abstract. Metal forming industries are constantly looking for advanced innovation, economical and energy efficient techniques. Superplastic forming has a great potential to be one of those advanced forming methods. It is a near net shape forming process which uses a unique type of materials where elongation exceeds 200% during a controlled forming conditions, e.g. temperature, pressure, and strain rate. Most of superplastic materials are formed by gas technique at elevated temperature. The main objectives of the research work in this paper were: to study the effects of the forming schemes on the forming time and thickness distribution of the formed and device a method to improve the forming part thickness and its uniformity distribution and the forming time. In this paper, a hydraulic and heating system were designed and manufactured to facilitate the experimental investigation. The superplastic magnesium alloy AZ31, Mg AZ31, was formed at 350°C with different strain rates to investigate the effect of the forming pressure profiles on the thickness uniformity of the superplastic formed part. The pressure profiles were generated based on Dutta and Mukherjee analytical approach. Finally, a variable strain rate method is modified to improve the uniformity of the thickness distribution of the formed part and reduce the forming time; which is a major limitation of superplastic forming.

1. Introduction

1.1 Superplasticity and superplastic Materials

Many superplastic materials follow this constitutive equation:

\[ \sigma = k \varepsilon^n \dot{\varepsilon}^m \]  \hspace{1cm} (1)

Where \( \sigma \) is the flow stress, \( \varepsilon \) is the true strain, \( \dot{\varepsilon} \) is the true strain rate, \( n \) is strain hardening index, \( m \) is the strain rate sensitivity index, and \( k \) is the material constant. In this equation the value of \( n \) is very small, i.e. strain independent and because the increase in strain rate will cause decrease in the strain hardening then the equation becomes

\[ \sigma = k \dot{\varepsilon}^m \]  \hspace{1cm} (2)

The value of \( m \) depends on the material; it can be calculated from the slope of logarithm of stress versus logarithm of the strain rate. The sigmoidal shape can be divided into three regions where different microstructural mechanisms are believed to dominate the deformation behavior, [4]. It is noteworthy to mention that as the grain size increases, the maximum value of \( m \) decreases; which
yields to premature failure during deformation. This is why it is recommended to form fine-grained alloys.

The strain rate can be defined as the change in strain with respect to time.

\[
\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{d[\ln(l/l_0)]}{dt} = \frac{1}{l} \frac{dl}{dt} = \frac{v}{l}
\]  

(3)

Where \( t \) is the time, and \( l \) is the instantaneous length.

2. Material, equipment, and experimental set-up

2.1 Materials

The used specimens were square sheets of the dimension 50 cm x 50 cm x 1.6 mm thickness and made from magnesium alloy, MgAZ31, having the chemical composition shown in Table 1.

| Element | Al | Zn | Mn | Fe | Cu | Ni | Si | Ca | Be | Sr | Ce | Mg |
|---------|----|----|----|----|----|----|----|----|----|----|----|----|
| Wt.%    | 3.1| 1.0| 0.42| 0.006| 0.003| <0.003| <0.1| <0.01| <0.005| <0.005| <0.01| Bal. |

The mechanical behavior of this alloy represented as true stress versus true strain curves at different strain rates and at constant temperature of 350 °C is shown in Figure 1, and the logarithmic stress strain rate diagram at the same temperature is shown in Figure 2.

2.2.1. Hydraulic press

A four-column 100 tons hydraulic press 1 m X 1 m X 2 m dimensions is designed, manufactured and assembled to carry out the experimental work. Figure 3 shows a 3 D drawing of the assembled press. The reason for using a four-column press is to fix and stabilize the working table (component 3) when it slides in the vertical direction. The upper, lower and moving tables are built from hollow steel tubes with 10 mm wall thickness. Details of its design, manufacturing and the different components associated with it are given in, [5].
| Part No. | 1  | 2   | 3       | 4    | 5      | 6          | 7          |
|---------|----|-----|---------|------|--------|------------|------------|
| Part name | Reservoir | Electric motor | Coupling system | Pump | Rod | Piping line | Column |

**Figure 3.** Three dimensional drawing of the hydraulic press and its components

*Figure 4. A photograph showing the hydraulic system*
The hydraulic system, shown in Figure 4, consists of 10 HP electrical motor, two hydraulic cylinders, a pump, a reservoir, and control valve. It allows the compressed oil to travel through the piping system to the rods at a pressure up to 70 bars.

3. Theoretical considerations

3.1 Forming pressure time history

Selection of the forming pressure time history for superplastic forming is very critical as it plays a major role in the thickness uniformity of the formed sheet. In this work, the pressure profile is generated based on the analytical approach given [6]. They derived an equation that relates the required gas pressure to the material parameters such as flow stress, strain rate, and also the sheet and die geometries to form the sheet at a constant strain rate. The equation is as follows:

\[ P = \frac{4S_i}{a} \sigma \exp \left(-\dot{\varepsilon}t\right) \left[\exp \left(-\dot{\varepsilon}t\right) \left(1-\exp \left(-\dot{\varepsilon}t\right)\right)\right]^{1/2} \]  

(4)

Where \( a \) is the radius of the die and \( S_i \) is the initial sheet thickness.

3.2. Forming pressure profiles at different strain rates

In this work, pressure profiles are generated for four constant strain rates, namely: \( 5 \times 10^{-3} \text{ s}^{-1} \), \( 2.5 \times 10^{-3} \text{ s}^{-1} \), \( 1 \times 10^{-3} \text{ s}^{-1} \), \( 5 \times 10^{-4} \text{ s}^{-1} \). Figures 5-8 inclusive show the pressure profiles separately for each strain rate at a magnified scale for clarity. It is worth mentioning that at each strain rate, forming is stopped when the dome height reached 180 mm; which is equivalent to an effective strain of 0.7 at the pole of the dome.

**Figure 5.** Pressure profile for a strain rate of \( 5 \times 10^{-3} \text{ s}^{-1} \)

**Figure 6.** Pressure profile at a strain rate of \( 2.5 \times 10^{-3} \text{ s}^{-1} \)
Figure 7. Pressure profile at a strain rate of \(1 \times 10^{-3} \text{ s}^{-1}\)

Figure 8. Pressure profile for a strain rate of \(5 \times 10^{-4} \text{ s}^{-1}\)

It can be seen from this figure that the pressure increases gradually at the beginning of deformation of the sheet until it reaches its maximum value. This is attributed to the large radius of curvature of the sheet at the initial stages of deformation. Therefore, a small amount of pressure is required to form the sheet at the beginning of deformation. As the radius of curvature decreases, more pressure is required to form the sheet. When more deformation takes place, the thickness decreases at the polar region of the dome. As a result, the forming pressure decreases so that a constant strain rate is maintained in the polar region of the dome.

4. Results and discussion

4.1. Variation of dome height with time for different strain rates

According to reference [7], the dome height (H) can be calculated from the following equation:

\[
H = a \left( \frac{S}{S_i} - 1 \right)^{0.5}
\]  

(5)

Where \(a\) is the radius of the die, \(S_i\) is the initial thickness and \(S\) the instantaneous thickness.

The instantaneous thickness at the pole can be found from the following equation, [6]. (Dutta and Mukherjee, 1992).

\[
S = S_i \exp \left( -\dot{\varepsilon} t \right)
\]  

(6)

The theoretical dome heights as a function of time for strain rates of \(5 \times 10^{-3} \text{ s}^{-1}\) and \(5 \times 10^{-4} \text{ s}^{-1}\) are shown in Figures 9 and 10 respectively.

Figures 11 and 12 show the variation of dome height with time analytically and experimentally at strain rates of \(2.5 \times 10^{-3} \text{ s}^{-1}\) and \(1 \times 10^{-3} \text{ s}^{-1}\) respectively. It can be demonstrated from these two figures that the amount of plastic deformation at the same time is higher at the high strain rate for both theoretical and experimental values. Also shown on the curve, the difference between the experimental and theoretical values obtained from reference [7]. This is due to elastic recovery, which is not considered in the analytical equation. This is why in designing and manufacturing of dies, to obtain the required dimensions, elastic recovery is also considered in the die design process. Furthermore, these two figures indicate that the theoretical equation suggested by Pilling and Ridley overestimates the calculations of dome height.
4.2 Variation of dome height with the distance from the pole

Figures 13 and 14 show the variation of the dome height with the distance from the dome pole at strain rates of $1 \times 10^{-3}\text{ s}^{-1}$ and $2.5 \times 10^{-3}\text{ s}^{-1}$ respectively.

It can be seen from figures 13 and 14 that the height of the dome at the pole at $1 \times 10^{-3}\text{ s}^{-1}$ is higher than that at $2.5 \times 10^{-3}\text{ s}^{-1}$ being 108 mm at $1 \times 10^{-5}\text{ s}^{-1}$ and 92 mm at $2.5 \times 10^{-3}\text{ s}^{-1}$ strain rate. This indicates that the AZ31Mg alloy possesses higher degree of super-plasticity at the lower values of strain rate within the experimental limitations.
To determine the final thickness strain in the formed sheets, the deformed sheets into dome shapes were sectioned along their diameters, ground and polished, and the thickness was measured at the pole of the dome and at locations of 10 mm from each other were measured using a digital micrometer, from which the thickness strain $\varepsilon_t$ distribution along the sheet diameter was obtained using the following equation:

$$\varepsilon_t = \ln \left( \frac{S}{S_i} \right)$$

(9)

Where $S$ is the final measured thickness and $S_i$ is the original sheet thickness which is 1.78 mm in average. This was carried out for the deformed sheet at each strain rate and the results are then presented graphically as thickness strain versus distance from the center. These are shown in Figures 15 and 16 at strain rates of $1 \times 10^{-3} \text{s}^{-1}$ and $2.5 \times 10^{-3} \text{s}^{-1}$ respectively.
It can be seen from Figures 15 and 16 that at the lower strain rate, $1\times10^{-3}\text{s}^{-1}$, the thickness strain is slightly higher than at $2.5\times10^{-3}\text{s}^{-1}$ strain rate, being 65.8% thinning compared to 62.1% i.e. about 3.7% higher. This is explained by the degree of the super-elasticity of the AZ31Mg alloy possessing higher degree of super-elasticity at the lower strain rate. The photographs of Figure 17 show the deformed sheets into domes, and Figure 18 shows a photograph of the dome with crack initiation at the pole. This is expected as the maximum plastic deformation occurred at the pole, where maximum thinning has occurred.

4. Conclusions
The following points are concluded:

I. The superplastic, (SP) forming of the AZ31Mg alloy at 400 °C on industrial and conventional level is proved to be carried out successfully, as this alloy cannot be formed successfully due to its low ductility.

II. The maximum possible successful deformation of this alloy, represented by the maximum polar height and the amount of thinning at the pole, is found to vary with the strain rate in the forming process, being higher at the lower strain rate $1\times10^{-3}\text{s}^{-1}$, the thickness strain is slightly higher than at $2.5\times10^{-3}\text{s}^{-1}$ strain rate, being 65.8% thinning compared to 62.1% i.e. about 3.7% higher. This indicates that the alloy possesses higher degree of superplastic behavior at the lower strain rate values.

III. The height of the dome at the pole at $1\times10^{-3}\text{s}^{-1}$ is higher than that at $2.5\times10^{-3}\text{s}^{-1}$ being 108 mm at $1\times10^{-3}\text{s}^{-1}$ and 92 mm at $2.5\times10^{-3}\text{s}^{-1}$ strain rate. The superplastic forming time of this alloy is high compared to the forming time of the ordinary engineering material. This agrees with the previous findings of other researchers, [8-9].

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6. References
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