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Influence of the Initial Blank Geometry on the Final Thickness Distribution of the Hemispheres in Superplastic AZ31 Alloy

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Featured Application: This paper presents the design of the thickness of a blank to manufacture a formed product with a more uniform thickness. A more uniform thickness in a formed product allows to avoid thinning that may involve early breaks of the part. Moreover, the obtained product is lighter and it is formed in lower time.

Abstract: This work deals with the design of the thickness of an AZ31 alloy blank, which is a superplastic magnesium material, to manufacture a hemisphere with a uniform final thickness. The finite element technique was used for the design process. The superplastic free-forming manufacturing was simulated for a part whose initial thicknesses were made to vary through two independent design parameters to obtain a linear thickness decrease from the pole to the end of the blank to form. This is because a linear thickness decrease is easily obtained through a machining process. The optimized blank, that is, the blank with a non-constant thickness that leads to the most uniform thickness distribution of the formed product, allows the manufacturing of a hemisphere with more uniform thickness values with a reduction in forming times and in weight in comparison with that formed by a constant initial thickness blank. At the same time, experimental tests confirmed the results highlighted by the finite element technique.

Keywords: free-forming test; finite element method; uniformity of the final thickness distribution; magnesium alloy AZ31; simulation; blank initial thickness; process time reduction; product weight reduction

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1. Introduction

Superplastic metallic materials allow reaching tensile elongations (>1000%) which are much higher than those due to conventional materials. They are characterized by a fine grain size that keeps them stable during the forming process (approximately 10 μm). Furthermore, to reach very high elongations, these materials must be deformed at high temperatures ($T > 0.5\ T_f$ with T_f absolute melting temperature of the material) that must be kept constant during the forming process and at low strain rates (between 10^{-3} and $10^{-5}\ s^{-1}$) [1,2]. Industrially interesting superplastic materials are aluminum-based [3], titanium-based [4], and magnesium-based alloys [5].

The superplastic forming (SPF) processes of sheet metal are generally known as blow forming processes, that is, stretching processes that use a pressurized gas instead of the classic punch. The technological scheme of an SPF process is shown in Figure 1; it consists of 4 steps: (1) a superplastic blank is locked on the die through a blank holder; (2) the die (and, therefore, indirectly the sheet metal) is heated up to the desired/optimal temperature value; (3) a pressurized gas pushes the sheet metal up to copy the internal geometry of the die and, at the end of forming once the die is cooled; (4) the obtained part is removed from the die.

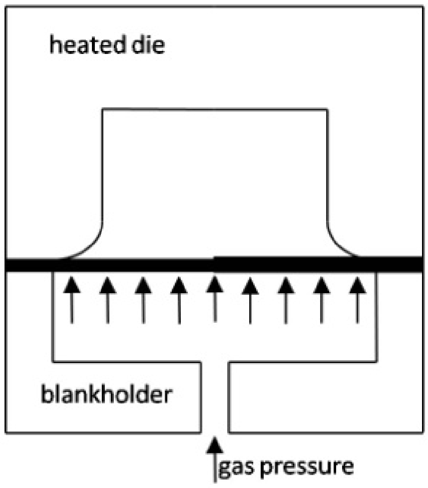

Figure 1. Scheme of the blow forming process.

The design of the superplastic forming processes involves the finite element method to determine the optimal load curve, that is, the curve which, by correlating the forming pressure to the forming time, can deform the sheet through the optimal values of strain rates [6,7]. Since forming times are very long (in the order of tens of minutes), researchers have recently oriented towards faster hot sheet metal forming processes by using the blow forming process with a decreased forming temperature and an increased pressure, thus the superplastic conditions arise [8,9]. To obtain a hemisphere, the superplastic forming process of a disc with a constant initial thickness was extensively studied in the past [10]. These studies show that the manufactured hemisphere presents thickness gradients from the axis of symmetry to the edge of the sheet and, therefore, non-uniform distribution of thicknesses. This thickness non-uniformity is as much greater as smaller as the value assumed by the strain rate sensitivity index, m [10,11].

To yield the final distribution of the thicknesses as uniformly as possible, two approaches can be followed:

- Use multiphase superplastic forming;
- Use blanks with an initial variable profile of thicknesses.

Multi-phase superplastic forming generally involves the first step of sheet forming to obtain a pre-shape that is afterwards submitted to a final forming step to achieve the final product. In this way, it is possible to obtain a more uniform final distribution of the thicknesses, but the technique involves long forming times because it requires different forming steps [12–14]. Conversely, the forming times are reduced if a blank with an initial variable profile of the thicknesses are used. In [15–17], how to prepare the blank with an initial variable profile of the thicknesses was not investigated. Moreover, the optimization of the initial profile of the blank thicknesses gives rise to profiles that follow laws that are difficult to actually achieve (such as parabolic laws or with discontinuous variations). In [11], the influence of a sheet with an initial variable profile of thicknesses, obtained by machining an aluminum alloy sheet with a constant initial thickness, on the material formability was investigated for a hot gas sheet metal forming process.

This work aims to optimize the initial variable profile of blank thicknesses to make more uniform the thickness of the product manufactured through a free-forming process. The free-forming process constitutes the first step of a superplastic forming process. Furthermore, it represents a suitable process to characterize the behavior of the material. A more uniform thickness in a formed product allows the avoidance thinning that may involve early breaks of the part; therefore, it leads to greater strength of the product. The starting point was a disc with a radius of 40 mm and a constant thickness of 1 mm made of a superplastic AZ31 magnesium alloy. It was submitted to gas blow forming, such as in [18], where the authors studied the microstructure of the material once formed by starting from a constant thickness. They looked for a profile involving a linear thickness decrease that is easily obtained by a machining process. The finite element analysis was used to design the optimal initial variable profile of the disc thickness by simulating the free-forming process of the considered superplastic material. The optimal profile was used to carry out some experimental tests to validate the design considerations.

2. Materials and Methods

The finite element analysis was carried out starting from a circular disc with a radius of 40 mm and a thickness of 1.0 mm. The material of the disc was an AZ31 magnesium alloy whose chemical composition by weight is Mg-3% Al1% Zn. The material has superplastic performances at a temperature of 440 °C [19]. Under these conditions, the hardening law follows the power law of the type:

$$\overline{\sigma} = C\overline{\varepsilon}^{n}\,\dot{\overline{\varepsilon}}^{m}, \tag{1}$$

In Equation (1), $\overline{\sigma}$ is the equivalent stress, $\overline{\varepsilon}$ is the equivalent strain, $\dot{\overline{\varepsilon}}$ is the equivalent strain rate while m, n, and C (i.e., the strain rate sensitivity index, the hardening index, and the strength coefficient respectively) are material constants. These constants have a value of m = 0.407, n = 0.12, C = 289.9 MPa respectively, that were experimentally identified, as reported in [19], and used to simulate different superplastic forming processes using the AZ31 alloy [20]. These values characterize a material affected by a little strain-hardening [20]. The material constants were obtained by free forming tests performed at different pressure levels (0.275 MPa and 0.4 MPa) by using the inverse analysis technique to minimize the differences between the numerical data and the experimental measurements [19].

Both the use of an analytical model [21] and the experimental data [22] showed that a free-forming process of a sheet with an initial constant thickness produces a trend of the final thickness, s, along the arc length, l, varying according to a parabolic relationship such as:

$$s(l) = s_p + \frac{s_e - s_p}{L^2} l^2, \tag{2}$$

where the subscripts e and p refer to the edge and the pole of the hemisphere respectively, while L is the arc length.

Subsequently, in [11], the correlation between the thickness at the edge, s_e, and the thickness at the pole, s_p, was established through the same simple analytical model for both an initial blank with a constant thickness and an initial blank with a variable thickness. However, this result is affected by the use of an analytical model with simplifying hypotheses. Therefore, this work used the finite element analysis to optimize the initial profile of blank thicknesses to manufacture a hemisphere in superplastic AZ31magnesium alloy (whose geometry is characterized by H = h/a = 1 with a = initial radius of the disc and h = height of the hemisphere) with a final distribution of the thicknesses as uniformly as possible.

The simulation of the free-forming test, starting from an initial variable profile of thicknesses, was carried out using the non-linear finite element software package MARC® by MSC. The rigid-plastic flow formulation was used for the superplastic forming analysis. Due to the axisymmetric nature of the problem, an axisymmetric simulation model was used. The scheme of the simulated free-forming test is shown in Figure 2. The disc was discretized through two rows of 128 continuous 4-node iso-parametric elements commonly used for axisymmetric applications. The nodes on the symmetry axis are constrained in such a way that they cannot move orthogonally to this axis. Moreover, to simulate the presence of a blank holder, the nodes placed on the periphery of the blank were constrained. The die is modeled as a rigid body. The disc is deformed by a gas at a constant pressure that is applied uniformly to the upper edges of the disc.

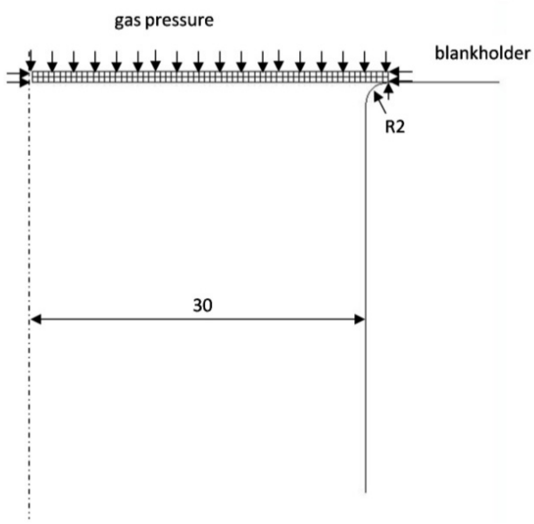

Figure 2. FEM schematization of the blow forming process.

The initial profile of the blank thickness was varied by appropriately modifying x and y parameters as shown in Figure 3 and Table 1. In detail, in the first phase, simulations were carried out by setting x = 0.9 mm and varying y parameters between 0 and 20 mm (see Figure 4). It was observed that, for each value of x, between 1 mm and 0.8 mm, the uniformity of the product thickness increases as the value assumed by the y parameter decreases (the maximum is therefore achieved for y = 0). Once y = 0 was chosen, the smallest value of x able to involve a maximum equivalent deformation at the pole of the hemisphere was identified. It is necessary to point out that the values x = 1 mm and y = 0 represent the reference situation; that is, the initial profile of the thicknesses is constant and equal to 1.0 mm.

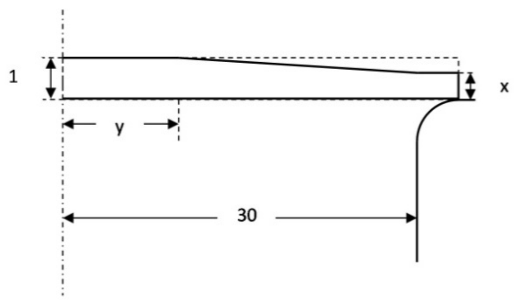

Figure 3. Considered initial profiles of blank thicknesses.

Table 1. Values of x and y parameters considered to design the initial profile of the blank.

x [mm]	y [mm]	y [mm]	y [mm]	y [mm]
0.90	0	10	15	20
y [mm]	**x [mm]**	**x [mm]**	**x [mm]**	**x [mm]**
0	0.95	0.90	0.85	0.80
15	0.95	0.90	0.85	0.80

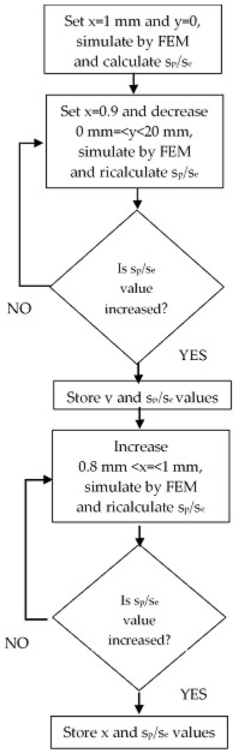

Figure 4. Flowchart of the proposed numerical approach.

3. Results and Discussion

Tables 2 and 3 show the results of the optimization process that was carried out to achieve more uniform thickness values of the formed hemisphere. In these tables, the s_p/s_e ratio is used to evaluate the thickness uniformity. Table 2, built for H = 1 and x = 0.90 mm, shows how, with decreasing y value, the s_p/s_e ratio tends to increase up to 0.669 for y = 0. This value is higher than that obtained for a blank with a constant initial thickness (s_p/s_e = 0.508) by 31.7%. Therefore, the value 0 represents the optimal condition for the y parameter. Table 3, drawn up for H = 1 and y = 0, shows that as x decreases, the s_p/s_e ratio increases by achieving the highest values. However, the numerical simulation shows that the maximum equivalent strain, for x = 0.85 and x = 0.80 mm, is placed on the edge of the sheet, unlike what happens for the other conditions, where the maximum equivalent strain is placed on the pole of the sheet. Therefore, to avoid the sheet breaking on the edge, only the simulations that produce a maximum equivalent strain on the pole of the sheet were considered to reproduce processes feasibly. This consideration shifts the optimal value of the parameter x from 0.85 mm and 0.8 mm to 0.9 mm. In the end, to achieve more uniform thicknesses in the formed hemisphere made of superplastic AZ31 magnesium alloy, the optimal values of the geometric x and y parameters are 0.90 mm and 0 mm respectively; they involve a value of s_p/s_e ratio equal to 0.669.

Table 2. FEM optimization analysis for different values of y parameter.

x = 0.9 [mm]	s_p [mm]	s_e [mm]	Max Equivalent Strain	s_p/s_e
y = 0	0.437	0.653	at pole	0.669
y = 10	0.427	0.643	at pole	0.664
y = 15	0.420	0.639	at pole	0.657
y = 20	0.413	0.634	at pole	0.651
x = 1.0 y = 0 constant thickness	0.385	0.757	at pole	0.508

Table 3. FEM optimization analysis for different values of x parameter.

y = 0 [mm]	s_p [mm]	s_e [mm]	Max Equivalent Strain	s_p/s_e
x = 0.80	0.487	0.526	at edge	0.926
x = 0.85	0.460	0.609	at edge	0.755
x = 0.90	0.437	0.653	at pole	0.669
x = 0.95	0.410	0.706	at pole	0.581
x = 1.00 constant thickness	0.385	0.757	at pole	0.508

The simulation evidence shows how a blank with a linear non-constant thickness from 1 mm at the pole to 0.9 mm at the edge involves an s_p/s_e ratio equal to 0.669 which is 31.7% greater than that due to a blank with a constant thickness of 1 mm (0.508). This is because a smaller thickness of material at the edge involves an increase of the strain rate at the edge that makes the material flow plastically from the edge to the pole. This plastic flow of material happens while the material at the pole, free from constraints due to the die, is characterized by a high value of strain rate that makes the material flow plastically from the pole to the edge. These two flows imply a more uniform thickness from the pole to the edge of the resulting product.

To validate the obtained optimization values, some experimental free-forming tests were carried out at a constant pressure of 0.4 MPa on two circular blanks in superplastic AZ31 magnesium alloy. The first one was a disc-shaped blank with a constant thickness of 1.0 mm, while the second was a circular blank with a variable initial thickness, that is, its thickness varies linearly from the axis of symmetry, where it is equal to 1.0 mm, up to the edge where it reaches a value of 0.90 mm, according to the optimal value obtained during the previous design stage. Three replicates for each type of blank were considered.

The blank with a variable initial thickness was manufactured by removing chips from a sheet with a constant initial thickness of 1.0 mm. In this way, the machined blank had a volume of 4618 mm^3 which is about 8% lower than that of the blank with a constant initial thickness (5026 mm^3). Therefore, the forming time measured for H = 1 (t = 1490 s) is reduced by 12% if it is compared to that needed to form a blank with a constant initial thickness (t = 1700 s).

The free forming test was performed using the experimental equipment designed at the Technology and Manufacturing Systems Laboratory of the University of Cassino at Cassino, Italy. It has an interface, to acquire data, made up of a PC, a multimeter KEITHLEY 2700 and a power supply ATTEN TPR3003T—an interface to manage the test parameters and to translate the punch, a mold creeper, a punch, and a load cell LUNITEK FT; a crossbar actuated by a rotating screw jack and an electric motor. This equipment allows the submission of discs with a radius value of 40 mm to hot forming tests. Before carrying out the test, the die needs to be uniformly heated in such a way as to bring the disc to a temperature of 440 °C. This is possible using a system to heat and control the temperature of both the die and the sheet. To carry out the test, once the test temperature is reached, gas is introduced at the predetermined pressure. The control phase of the test involves recording the h-t curve (i.e., displacement at the apex of the dome h depending on the forming time t) through the use of a measurement laser. Moreover, when the forming process ended, the thickness of the deformed disc was measured using a Prismo Vast MPS coordinate measuring machine of Zeiss®. The adopted measuring method of the sheet thickness is reported in [23].

Figure 5 shows the final thickness versus the distance from the symmetry axis for H = 1. It is possible to see that, by using a blank with initial variable thicknesses, the final thickness values are more uniform than those due to a blank with a constant initial thickness. Moreover, the curve due to a blank with a variable thickness shows that the thickness of the formed hemisphere at the pole is larger than that due to a blank with a constant thickness. This means that the blank with a variable thickness will deform more than the blank with a constant thickness before breaking. This means that the blank with a variable thickness has greater formability than the blank with a constant thickness. In particular, from Figure 5, the s_p/s_e ratio value (for experimental limits s_e value is measured at a distance of 25 mm from the symmetry axis) obtained for a blank with variable initial thicknesses is 20% higher than that of a blank with a constant initial thickness.

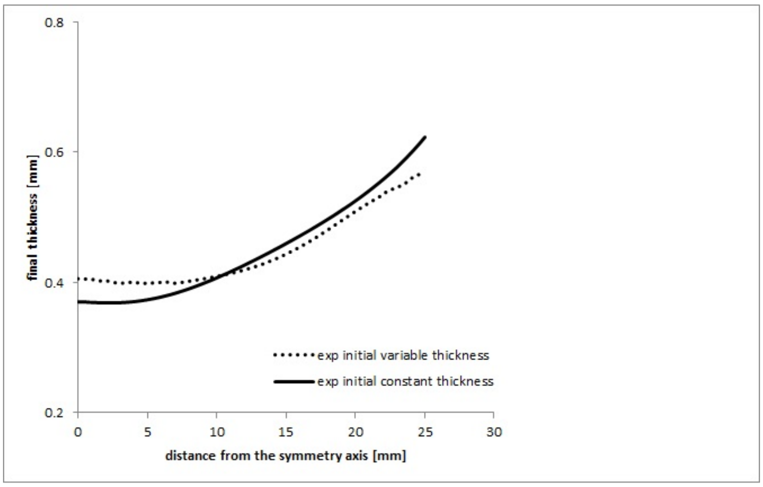

Figure 5. Experimental results for blank with variable and constant thickness.

The experimental evidence shows that a blank with a non-constant thickness from 1 mm at the pole to 0.9 mm at the edge involves a weight reduction of the formed hemisphere weight of 8% and a forming time decrease of 12% in comparison with a blank with a constant thickness of 1 mm. Moreover, it involves an s_p/s_e ratio 20% less than that due to a blank with a constant thickness of 1 mm. The difference between the percentage reductions of the s_p/s_e ratio values obtained numerically and experimentally (31.7% and 20% respectively) is because the s_e value was measured at a distance of 25 mm from the symmetry axis since it was not possible to experimentally measure that at the edge.

4. Conclusions

The work showed the optimization process of the initial blank geometry to obtain a superplastic AZ31 magnesium alloy hemisphere characterized by a greater uniformity of the final thicknesses. In particular, it was found that the initial blank must have a linearly variable thickness profile from a value at the pole s_p of 1 mm to a value at the edge s_e of 0.90 mm. A linear thickness decrease of the initial blank is wanted since it is easily machined starting from a blank with a constant thickness. The obtained hemisphere presents a greater uniformity of thicknesses, it is about 8% lighter than that due to a blank with a constant initial thickness, and it is formed in a time that is 12% shorter than that required by a blank with a constant initial thickness.

Moreover, the curve due to a blank with a variable thickness shows that the thickness of the formed hemisphere at the pole is larger than that due to a blank with a constant thickness. This means that the blank with a variable thickness will deform more than the blank with a constant thickness before breaking. This means that the blank with a variable thickness has greater formability than the blank with a constant thickness. No effects have the proposed approach on the formability of the material too.

The distribution of the thickness of a formed product, which was investigated in this paper, is directly correlated to the product strength. A more uniform thickness distribution would avoid unwanted local thinning, where the material typically breaks.

Moreover, the proposed approach reduces the forming time and the product weight and, therefore, the final costs.

The proposed approach realizes lighter products, which means a higher product quality in some fields. The proposed approach has no effects on the geometric accuracy or on the roughness of the product surfaces, which are other ways to define the quality of a part.

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