Designing gas pressure profiles for AA5083 superplastic forming

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Abstract

The use of the superplastic forming in high production applications has been substantially hindered by the process required long cycle times. It has been indicated by a number of researchers that the applied gas pressure profile can be designed in such a way as to reduce the forming times. In this paper, time varying pressure profiles were designed based on various sheet deformation rate schemes. Key advantages and disadvantages of the different approaches to pressure profile design were examined relative to the Al-Mg alloy AA5083 forming time and thinning. The present effort represents a necessary step toward designing optimum gas pressure profiles for shorter cycle times without sacrificing the integrity of the formed parts.

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1. Introduction

The superplastic forming process is currently used to form certain lightweight sheet material into components with complex geometries in one manufacturing step. However, the slow nature of the process compared to other forming processes hinders it from being used in high volume applications. The process is carried out by applying pressurized gas on one side of a sheet forcing it to take the internal shape of a preheated single-piece die. It has been indicated by a number of researchers that the applied gas pressure profile can be designed in such a way as to reduce the forming times. For example, Yang et al. (1996) used a step-change variable pressure which involves...
steps of isobaric forming with a non-constant strain rate within the superplastic region for bulge forming of Al 7475 alloy at 505 °C. They reported reducing the forming times compared with single-step constant pressure forming while achieving satisfactory thickness profiles. In another example, Ding et al. (1997) considered a pressure profile that generates a variable strain rate path in Ti-6Al-4V high-temperature bulge forming based on a linear stability criterion.

Up to date there are four main types of gas pressure cycles for superplastic forming that can be identified in research and industrial applications. These are: isobaric forming, multiple steps of isobaric forming, varying pressure according to a constant maximum strain rate, and varying pressure according to necking mitigation. The purpose of this study is to compare the forming efficiency of the different types of pressure loading in the superplastic forming of AA5083.

2. Material constitutive model

The fine grain Al-Mg alloy has been used in various applications such as the forming of body panels of the GM Malibu and the Ford GT (Barnes, 2007). The AA5083 alloy is weldable with moderate strength and good corrosion resistance.

In general, superplastic materials undergoing the superplastic forming process exhibit viscoplastic deformation, in which the flow stress is highly sensitive to the strain rate. The superplastic forming process is carried out under isothermal conditions and the stress-strain rate relationship can be described by the phenomenological model:

\[ \bar{\sigma} = k \bar{\varepsilon}^m \dot{\varepsilon}^n, \]  

where \( \bar{\sigma} \) is the effective flow stress, \( k \) is a material constant, \( \bar{\varepsilon} \) is the effective strain, \( \dot{\varepsilon} \) is the effective strain rate, \( m \) is the strain rate sensitivity exponent, and \( n \) is the strain hardening exponent. A high value of strain rate sensitivity \( m \) is responsible for the superplastic properties of the sheet material, and thus the delay in the localized thinning.

In this study, we will be using the material model developed by Kappes and Liewald (2011) for forming an AA5083 superplastic sheet at 500 °C. Based on the extended power law in Eq. (1), they reported experimentally calibrated values of 0.402, 0.123 and 161.009 for \( m, n \) and \( k \), respectively.

3. Finite element model

The implicit solver in the commercial finite element code ABAQUS™ was used to simulate the superplastic bulge forming of an AA5083 sheet, as shown in Fig. 1. Due to the symmetry of the problem, an axisymmetric model was used in the simulations. The 100-mm diameter circular die with a die entry radius ER of 5 mm was modeled as an analytical rigid surface. The 1.4-mm thick sheet was modeled using four layers of axisymmetric elements. Each layer contained 300 solid elements. The sheet elements between the die and the blank holder were assumed to be fixed, as shown in Fig. 1. This was necessary in order to simulate the pure stretching condition in the superplastic forming process. Finally, a coefficient of coulomb friction of 0.1 at the die-sheet interface was considered in the simulations.
4. Results and discussion

4.1. Uniform pressure

Isobaric profiles are easy to apply; however, they produce an undesigned time varying strain rate profile. For a low forming pressure, the resulting strain rate will vary within the required range to sustain the superplastic properties for most of the cycle time. For higher values of pressure, the superplastic properties are not maintained and thus the quality of the formed parts will be jeopardized. Therefore, the application of isobaric forming is suitable only for low values of pressure and thus the corresponding cycle times might be long.

4.2. Multiple steps of uniform pressure

Superplastic forming with multiple isobaric steps is easy to implement in practice, however, there are many possibilities for the number of steps and their duration. In this paper it is suggested to have a maximum of four relatively long isobaric steps which are based on the results of another controlling criterion such as maintaining a maximum strain rate.

4.3. Varying pressure according to a maximum strain rate

An attractive alternative is a time varying pressure profile that maintains an approximately constant value of the maximum effective strain rate at certain regions of the deforming sheet. Forming at a constant maximum strain rate that provides the highest strain rate sensitivity is expected to produce the best obtainable forming quality or thickness distribution. However, this method requires long forming times and sophisticated gas pressure control equipment. If the choice is made to sacrifice some of the quality in order to reduce the forming time, then there is no reason why the superplastic forming process must be conducted under constant strain rate control.

4.4. Varying pressure according to necking mitigation

In this section, we consider a time varying pressure profile that generates a designed strain rate path that mitigates necking based on certain sheet stability criteria such as the nonlinear long wavelength stability analysis (Hutchinson and Neale, 1977). This criterion is basically a one-dimensional simplification of the method introduced by Marciniak and Kuczynski (1967). In their analysis, Hutchinson and Neale (1977) examine the deformation of a long cylindrical solid bar subjected to a time dependent load and containing a geometric nonuniformity. A constant strain rate condition is assumed in the uniform section of the bar. As deformation
proceeds, the ratio of the strain in the local region to the strain in the uniform region is closely monitored. When this ratio starts growing rapidly, instability is assumed to have occurred.

For example, Jarrar et al. (2012) combined the nonlinear long wavelength stability analysis with a creep mechanism material model that accounts for hardening/softening. A series of stability curves, which denote combinations of strain and strain rate for unmitigated thinning and, ultimately, rupture of an AA5083 bar, were computed. The associated uniaxial strains and strain rates were expressed in terms of von Mises effective strains and strain rates, and pressure profiles were computed. The main disadvantage of using the nonlinear long wavelength analysis is that the value of the geometric nonuniformity in cross-sectional area of the model bar on which the instability analysis is based, is not known a priori.

In general, having pressure profiles based only on necking mitigation, is not expected to generate practical improvements in the process for the following reasons:

- It is known that superplastic behavior of the material exists within a certain narrow range of strain rates. Within this range stable deformation extends to relatively very large strains before failure. The transition from the non-superplastic region to the superplastic one happens also in a narrow region of strain rates. Therefore, the critical strain to failure is not expected to be gradually increasing but rather almost abruptly changing with strain rate.

- Applying high pressures that are expected to reduce the forming time without causing failure do not guarantee that the resulting thicknesses are acceptable. The sheet thinning depends on the strain rate during deformation, which makes it more crucial to consider the thinning-strain rate behavior rather than merely to mitigate failure.

- The theoretical critical strain values computed from tension or bulge tests are based on deformation paths different than those resulting from simulation generated pressure profiles that mitigate failure.

- Critical strain values from sheet failure theories such as Neal and Hutchinson (1977) or Marciniak and Kuczynski (1967) depend on assuming a value for an initial geometric nonuniformity in the sheet. The value of such a nonuniformity is difficult to measure experimentally.

4.5. Comparing pressure profiles with respect to forming time and thickness uniformity

The black solid line in Fig. 2 represents the pressure profile for AA5083 high temperature bulge forming while maintaining a maximum strain rate of 0.0011/sec during deformation. This gas pressure profile was computed (rather than prescribed at the outset of the simulation) using an algorithm internal to ABAQUS™. The algorithm does not precisely meet the target strain rate and results in a stepwise temporal variation in the generated pressure profile. A detailed overview of this algorithm with comparison to an alternative smoothly varying algorithm can be found in (Jarrar et al., 2010).

In the early stages of bulge forming, there is minimal contact with the die surface. Thus, a relatively high starting pressure provides a reasonable substitute for the linearly ramped starting pressure which is generated by the constant maximum strain rate profile. Accordingly, Fig. 2 shows three suggested multi-step profiles. The two-step pressure profile, shown in blue, consists of two steps of isobaric forming: the first involves forming at a pressure of 0.286 MPa for 13.9 minutes, and the second involves a pressure of 0.238 MPa for 2.9 minutes. The three-step pressure profile, shown in green, involves isobaric forming at a pressure of 0.238 MPa for 7.4 minutes, followed by a second step of forming at 0.286 MPa for 6.5 minutes and finally forming again at a pressure 0.238 MPa for 2.9 minutes. The four-step profile, shown in red, involves isobaric forming at 0.2, 0.238, 0.286 and 0.238 MPa for 5.6, 1.8, 6.5 and 2.9 minutes, respectively. Notice that these multi-step pressure profiles all merge with the constant maximum strain rate profile at some point in time before the end of forming.
Table 1. shows the predicted forming times for the different types of gas pressure profiles considered in the study. It took 16.4 minutes to form a bulge with a dome height of 50 mm at an isobaric pressure of 0.238 MPa. The 0.238 MPa isobaric forming provided the same thickness distribution, shown in Fig. 3, compared to forming at a constant maximum strain rate of 0.0011/sec. However, the forming time was only 23 seconds shorter. On the other hand, isobaric forming at 0.286 MPa provided comparable thickness uniformity to the 0.238 pressure. However, its forming time was 6.4 minutes shorter than that for constant maximum strain rate forming. The two-step pressure profile showed exactly the same results as those for the 0.286 MPa isobaric forming. That was due to the fact that forming ended before the second step started. The three-step and four-step pressure profiles showed better results than those from forming at constant maximum strain rate of 0.001 1/s. However, their results are less favourable compared to isobaric forming at a pressure of 0.286 MPa. Forming at a constant maximum strain rate of 0.0005 1/s or at an isobaric pressure of 0.2 MPa was shown to be impractical due to the relatively very long forming times involved.

| Pressure Profile | Forming time to a 50 mm dome height, minutes |
|------------------|---------------------------------------------|
| P = 0.2 MPa      | 25.3                                       |
| P = 0.238 MPa    | 16.4                                       |
| P = 0.286 MPa    | 10.4                                       |
| \( \dot{\varepsilon} = 0.0005 \) 1/sec | 36.8                                       |
| \( \dot{\varepsilon} = 0.001 \) 1/sec  | 16.8                                       |
| Two-step         | 10.4                                       |
| Three-step       | 13.2                                       |
| Four-step        | 14.8                                       |
Fig. 3. Finite element resulting thickness distribution of half of fully-formed AA5083 dome as function of position along dome surface. The zero position corresponds to the pole of the dome. The small abrupt change between 72 and 82 mm corresponds to the region directly after the die entry radius.

5. Conclusions

In this study, three sets of finite element simulation runs of AA5083 high-temperature bulge forming were conducted. In the first set, an isobaric pressure was prescribed during bulge forming. In the second set of simulations, the gas pressure profile was computed (rather than prescribed at the outset of the simulation) using an algorithm internal to ABAQUSTM in a way that an approximately constant effective strain rate was kept at the pole during forming. In the third set, multi-steps of uniform pressure were prescribed during forming. The predicted forming times were presented for these sets of simulation runs. Results suggest that, for free bulge forming of AA5083 at 500 °C, single, two- and three-step isobaric forming produces the same part thickness uniformity within shorter forming times compared to forming at a constant maximum strain rate. In fact, pressure profiles that consist of relatively long isobaric forming steps are easier to apply in production-forming processes than the small pauses or steps required by the pressure profiles generated by the constant maximum strain rate forming from ABAQUSTM. In addition, it was concluded that a proper evaluation of any claimed benefits from applying pressure profiles varying according to necking mitigation should consider comparing the results with those of a full range of values of isobaric and constant strain rate forming.

The present effort represents a necessary step toward designing optimum gas pressure profiles for shorter cycle times without sacrificing the integrity of the formed parts. In future work, a more accurate microstructure based material model will be implemented in the finite element simulations. In addition, extensive bulge forming experiments will be conducted to validate the simulation results.

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