Greener manufacturing: Superplastic-like forming

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Abstract. Conventional superplastic forming (SPF) is normally conducted at a slow forming rate ($10^{-3}$ s$^{-1}$ or slower) and high temperatures (typically 773 K or higher for aluminum alloys), which is not attractive for wider applications. Recently, SPF has revived as an attractive process in the automotive and aerospace industries, especially for forming of excellent precision, large, and complex-shaped work pieces. A hybrid superplastic forming process has exploited the usage of superplastic forming for faster times, lower temperatures, and also for use by non-superplastic materials by designing a process that combines stamping and gas blow forming in one operation to establish an energy-saving technology. With recent developments in these areas, the light-weight, yet inexpensive aluminum alloys are promising candidates for green manufacturing. In comparison with the conventional SPF process, the forming time has been shortened (typically from 30 min to 8 min), and the forming temperature has been lowered down (from 773 K to 673 K). Furthermore, as a greener manufacturing process, it uses the non-superplastic grade materials, which is more compatible with existing manufacturing processes with less material preparation time and expense cost.

1. Introduction

Superplastic forming (SPF) is a high-temperature process by which sheet metals are deformed by gas pressure in a single-side die cavity to produce parts of complex shape by taking advantage of the superplastic flow behavior of the material. Conventional superplastic forming was conducted at slow forming rate ($10^{-3}$ s$^{-1}$ or slower) and high temperature (typically 773 K or higher for aluminum alloys), which have limited it for wider applications. SPF can also be combined with a joining operation involving diffusion bonding (SPF-DB) between several sheets of material [1]. New emerging superplastic developments also include superplastic tube forming [2]. No matter how the conventional SPF has been developed, it is only a perfect fit for the low production volumes. Recently, SPF has revived as an attractive process in the automotive and aerospace industries, especially for forming of excellent precision, large, and complex-shaped work pieces in one operation. With these developments, the light-weight, yet inexpensive aluminum alloys are promising candidates for green manufacturing.

In this paper, the superplastic-like forming process has been examined, expanding the usage of SPF for non-superplastic materials, lower temperatures, and faster times by designing the process that combines drawing and gas blow forming to establish an energy-saving technology.
2. Superplastic-like forming
Most of the prior SPF processes were conducted at a high temperature near the melting point, which also introduced many problems, such as reduced tool life, high heating demands etc. In addition, the mechanical properties of the product are poor due to higher amounts of cavitation introduced. Another big disadvantage is the slow forming rate. Cycle times vary from 30 min to 2 hr in the conventional SPF [3-6].

2.1. Materials usage
For industrial applications, the superplastic materials most commonly associated with conventional SPF are aluminum (5083, 7475) and titanium (Ti6Al4V) alloys with applications in the aerospace and automotive sectors. Other materials such as INCONEL 718 or magnesium alloys (AZ31B, ZK10) are also progressively entering the market. These kinds of materials largely complies with the SPF process requirements, such as fine grain size, high structure stability with respect to grain growth, and high purity of the structure. SPF5083 products have been implemented on various Boeing commercial airplanes [7]. Usually, the superplastic materials are thermal-mechanically prepared to meet the requirements for superplastic forming. However, for some alloys such as AA6xxx series [8], it is complicated and difficult to be processed, which also have not yet suited the commercial application for SPF. Therefore, the cost and preparation of raw materials is very high.

In order to reduce the material cost, the non-superplastic grade of AA5083 was employed in the hybrid SPF process. The lightweight and inexpensive alloy was only rolled and had a maximum elongation-to-failure of 93% [9]. Results indicate that it is possible to use the hybrid SPF process to form into 3-stepped die cavity at 673 K. Dry graphite was applied as lubricant, and evenly sprayed on both surfaces of the aluminum pieces. Compared to the superplastic materials, the non-superplastic alloys offer cost savings in the range of 20-50% [10]. As a greener manufacturing technology, the using of non-superplastic grade materials make it more compatible with existing forming process with less material preparation time and expense cost.

2.2. Process development
The technique studied in this paper is a combination of drawing (mechanical pre-forming) and superplastic forming (gas blow forming). This process, hereby named “superplastic-like forming”, will overcome some of the problems that are encountered during the conventional superplastic forming. It will take advantages of the benefits of both drawing and gas blow forming. Initially, the sheet was mechanically drawn into the die cavity, and as a result some materials at the flange area flowed into the deformation area as shown in Figure 1. The two-stepped punch with length of 43 mm was used in the drawing phase. The punch dimension was designed in accordance with simulation and die cavity geometry. Experimental work has also shown that even a small amount of material can significantly improve the following forming performances not only in cycle times but also for forming temperature [11]. The pressure cycle was applied on the sample to keep the target forming strain rate at 0.002 s⁻¹. The whole gas blow forming process was conducted in only 8 minutes.

Figure 1. Forming sequence of the hybrid SPF of non-superplastic AA5083 sheet (a) clamping stage, (b) drawing and sealing stage, and (c) gas blow forming stage [11].
2.3. Forming temperature

Normally the temperature for SPF is in the range of 0.5 to 0.75 times the melting temperature ($T_m$). At these temperatures, some of the materials may encounter some problems such as oxidation at the grain boundary that reduces the ductility (e.g. for titanium alloys (Ti6Al4V)) or grain growth that causes unstable forming behavior (e.g. for magnesium alloys (AZ31B) or aluminum alloys (AA6xxx)).

In the hybrid forming of AA5083, the level of bulging into the 3-stepped die cavity after mechanical pre-forming was obtained for a series of experiments conducted within the temperature range from 300 to 500ºC, as shown in Figure 2. Comparing these bulge heights, there is little variance between the temperatures of 673 and 773 K [11]. Therefore, it indicates the possibility of forming the sheet metal at 673 K. The changes of the microstructural features, such as less grain growth, less cavitation and dynamic recrystallization, can be obtained at the relatively lower temperatures. Furthermore, lower forming temperature will also inevitably lead to a lower carbon footprint by establishing an energy-saving technology.

![Figure 2. Bulge height profiles of formed parts at different forming temperatures[11].](image)

2.4. Forming time

One of the reasons that hindered the conventional superplastic forming process not widely applied in industries is the low production rate. The typical forming time for superplastic process lies in between 30 to 120 min depending on the parts (the strain rate is in the range of $10^{-3}$ to $10^{-1}$ s$^{-1}$). This limitation implies that the technique is only suitable for low product volumes, e.g. for aerospace, prototype parts or niche cars. In the hybrid SPF process, the gas blow forming time has been shortened to 8 min. The pressure cycle obtained from prediction at a constant strain rate of 0.002 s$^{-1}$ is plotted in Figure 3.

It is commercially viable to apply the SPF to high volume products such as automotive parts or aerospace components. Considered as essential in hybrid SPF, it utilizes the stretch-forming at a constant thickness, and also adopts advantages of superplastic forming of excellent precision and little springback. Therefore, the new design of hybrid process has revived as an attractive technology, but with time and energy savings.

![Figure 3. Pressure schedule predicted at a forming strain rate of 0.002 s$^{-1}$.](image)

3. Finite element modeling (FEM)

The flow stress behavior of AA5083 during the hybrid superplastic forming has been represented by the power law given in ref. [12]. Figure 4 shows the thickness distributions at the end of forming phases. The simulation followed the experimental sequence and has been divided into two processing
phases. The punch, which was modelled as a rigid tool, firstly moved down at a constant speed until it reached a total displacement of 43 mm. In this phase, the new punch has been changed into a two-stepped punch using the FEM design. For the second phase of gas blow forming, the punch was inactive and the workpiece was deformed due to the applied pressure only.

![Figure 4. The predicted thickness contour of the workpiece in the phase of (a) mechanical pre-forming, and (b) gas blow forming.](image)

The influences of process parameters, including of holder force, friction and punch geometry, have also been studied to facilitate process [12]. The conventional flow stress and the physically based material model related to the underlying behavior will be implemented in the simulation as well.

4. Summary
Non-superplastic grade of AA5083 has been used in the hybrid superplastic forming. As a greener manufacturing technology, it conducts the forming process at faster forming rate and lower temperature in one hybrid operation. It utilizes both the advantages of drawing and gas blow forming, and makes it more attractive for industry applications by forming the non-superplastic grade materials. The non-superplastic material is a promising candidate to be used in this green manufacturing with less cost, time, and energy consuming. Therefore, it is commercially viable to apply the hybrid SPF to high volume production, especially for the energy-saving technology to establish a more sustainable low carbon earth. Finite element modeling is a convenient method that can be used to facilitate the process design.

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