

Development and Validation of an Analytical Seal Bead Design Model for Automotive Superplastic Forming

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ABSTRACT

With the increasing demand for fuel efficient vehicles, technologies like superplastic forming (SPF) are being developed and implemented to allow for the utilization of lightweight automotive sheet materials. While forming under superplastic conditions leads to increased formability in lightweight alloys, such as aluminum, the slower forming times required by the technology can limit the technology to low to mid production levels. One problem that can increase forming time is the reduction of forming pressure due to pressurizing (forming) gas leaks, during the forming cycle, at the die/sheet/blankholder interface. Traditionally, such leaks have been successfully addressed through the use of a seal bead. However, for advanced die technologies that result in reduced cycle times (such as hot draw mechanical performing, which combine aspects of mechanical preforming of the sheet metal followed by SPF), the use of seal beads can restrict the drawing of sheet material into the forming die. Therefore, it is desirable to design and implement a bead that can provide the required sealing at the interface, yet allow for the material to flow past the seal bead and into the die. The objective of this paper is to develop and validate an analytical method of determining the required seal bead geometry that is capable of allowing material to draw over the bead while sealing and eliminating leaks during forming. Comparisons between numerical and analytical methods are presented along with a seal bead which was developed based on the analytical method and tested on a pre-existing die.

INTRODUCTION

The room temperature formability of many lightweight metals, such as aluminum sheet, is limited, especially when compared with drawing quality steels, which have been the traditional sheet metal used in automotive applications. However, the formability of light alloys can be significantly increased by forming them at elevated temperatures. One of the elevated temperature deformation modes is superplasticity, which can be exploited by deforming a fine-grained metal (grain size $< 10^{-6}$ m) at an absolute temperature above half of its melting temperature at low strain rates (typically 10^{-3} s⁻¹ or less). Superplastic alloys typically require special processing to refine grain size, which can add significant cost; however, they have been observed to achieve elongations of 200-1000 percent [1, 2]. Superplastic forming (SPF) is a manufacturing technology that capitalizes on this deformation mode. In conventional SPF, a blank is loaded within a hot die and allowed to preheat (Fig. 1(a)). The press then acts with sufficient force to close the die halves and create a seal between the perimeter of the upper die half, blank, and lower die half (Fig. 1(b)). A controlled gas pressure cycle is applied to one side of the blank stretch forming it into conformance with the cavity in the opposing die half (Fig. 1(c)). The pressure cycle is engineered to maintain a target strain rate typically equal to or less than 10^{-3} s⁻¹; hence, superplastic forming cycle times often exceed 20 min.

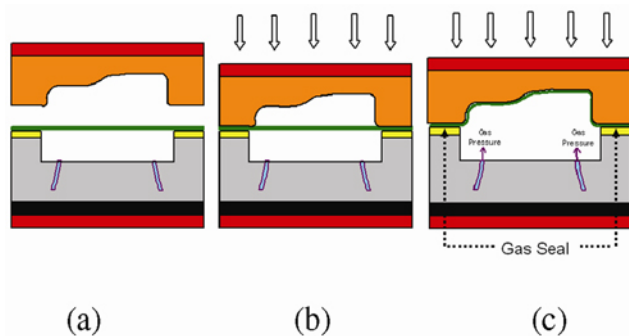


Figure 1. Schematic of a basic SPF process. (a) Blank is placed into elevated temperature SPF die for preheat, (b) die halves close onto blank, and (c) gas pressure is applied to one side of the blank to stretch form the sheet into the die cavity.

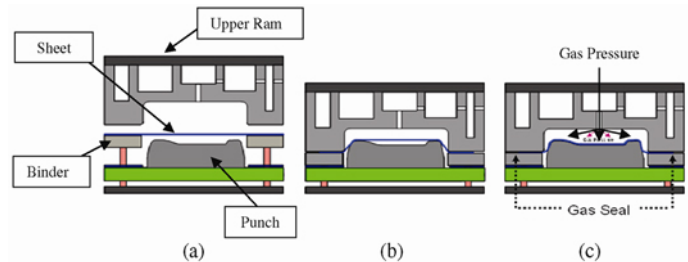


Figure 2. Schematic of the HDMP two-stage process. (a) Preheated blank is placed into die, (b) blank is preformed around the punch, and (c) gas pressure is applied to one side of the blank to stretch form the sheet onto the male punch.

The ability to form complex parts coupled with a low investment / high variable cost business case has made SPF a main stream manufacturing technology in the low volume aerospace, niche automotive, public transportation and architectural industries. To increase the volume for which SPF is cost competitive, a novel die technology referred to as hot draw mechanical preforming (HDMP) has been developed that combines aspects of conventional stamping with SPF to expand the forming envelope of conventionally processed, lightweight alloys and to lower the forming cycle time [3]. HDMP is a two stage, single die, elevated temperature forming operation. The first stage serves to draw-in metal from the perimeter of the sheet and preform the blank, thus resulting in less thinning of the material and less time to complete the gas forming operation. As shown in Fig. 2, the heated upper die and punch are fixed to the upper and lower platens, respectively. The heated lower binder rides on cushion pins and travels between the die positions shown in Fig. 2(a) and (b). After a preheated blank has been loaded between the upper die and binder (Fig. 2(a)), the upper ram travels down for blank close-out. When completed, the downward stroke of the upper ram actuates the binder cushion providing a restraining force for drawing the sheet over the punch. The position of the binder at the conclusion of the draw is shown in Fig. 2(b). The press then acts on the perimeter of the blank creating a seal between the upper die, blank, and binder (Fig. 2(c)). Immediately thereafter, gas pressurization is applied and controlled to perform the second forming stage which completely forms the sheet into the die.

In conventional SPF (Fig. 1) and HDMP (Fig. 2), delivering a quality part with an optimal cycle time is contingent on maintaining a seal between the die and blank. Unfortunately, gas leaks can occur in SPF, often due to imperfections and out-of-tolerance conditions at the mating surfaces on the die perimeter. These defects can be the result of die machining but may also develop due to thermal distortion caused by repeated heat cycling [3]. A solution to gas leaks is a seal bead which follows the perimeter of the blank and slightly penetrates (upsets) the thickness of the sheet [4]. Seal beads are commonly used in the SPF industry; however, the geometry of the seal bead has been mostly based on experience and trade.

Seal bead design can be an unknown variable for researchers and manufacturers with limited SPF experience. It also represents a significant challenge for the HDMP process. A gas seal is needed for the second, gas forming stage; however, the bead can not impair the metal draw-in during the first stage of the mechanical pre-forming. Obstructing the material flow into the die cavity during pre-forming would lead to excessive thinning of the blank in the entry region of the die and cause sheet splitting. In this work, an analytical model based on slab-analysis has been developed to engineer SPF and HDMP seal beads. The model considers the elevated temperature material properties and SPF process parameters to predict the optimum seal bead design.

2. INVESTIGATED SEAL BEAD GEOMETRY

The rectangular seal bead shown in Fig. 3(a) is a common design used in the SPF industry [5]. It is an effective design, but without proper engineering or experience, can penetrate excessively into the sheet thickness and impair the release of part from the die. Difficulty in removing a part from a die can result in the dimensional distortion of the part. There are many alternative seal bead designs such as the concept shown in Fig. 3(b). Developed for automotive SPF manufacturing, the cusp shape achieves a gas seal with minimum through-

thickness deformation of the sheet serving to promote part release from the die. This cusp shape, along with other alternative seal bead designs, can be more difficult and expensive to machine than the rectangular bead, especially when the bead height is limited to a fraction of a millimeter. Hence, the rectangular bead has been used in this work due to the relatively simple shape, lower cost of machining and extensive industrial use.

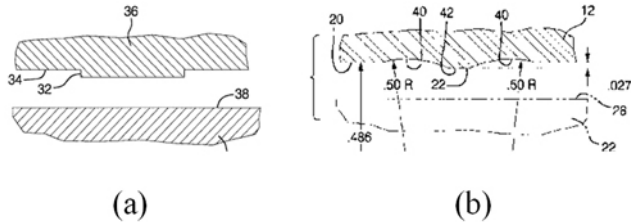


Figure 3. (a) Common rectangular seal bead design and (b) example of an alternative bead design [5].

3. MATERIAL MODELING

This work has focused on the seal bead design for dies used to form two aluminum alloys; namely, AA5182 and AA5083. Each of these two alloys has been used in automotive sheet metal applications and can be formed under superplastic conditions (i.e. using SPF dies). The power law model for rate sensitive materials, presented in Eq. (1), has been employed in this study:

$$\bar{\sigma}_{flow} = K \bar{\epsilon}^m \quad (1)$$

where $\bar{\sigma}_{flow}$ is the effective flow stress, $\bar{\epsilon}$ is the effective strain rate, K is the strength coefficient, and m is the strain rate sensitivity factor. Uniaxial tensile testing at 475°C for a range of strain rates between 10^{-4} and 10^{-2} s^{-1} were carried out to determine the values for K and m for each material [6]. The experimentally determined material parameters are shown in Table 1.

Table 1. Material model coefficients for AA5182 and AA5083 at 475°C for strain rate between 10^{-4} and 10^{-2} s^{-1} .

AA5182		AA5083	
K (MPa)	53.4	K (MPa)	155.14
m	0.26	m	0.39

4. FEA SEAL BEAD MODEL

Finite element analysis has been used for the development and validation of the analytical seal bead model. The FE model for the seal bead can be seen in Fig. 4. The sheet has

been defined using the ABAQUS/Standard CPE4R element [7], with 4 elements through the thickness and 280 elements along the length. The sheet thickness was assumed to be 1.5mm. The lower die half die is labeled “Rigid bottom surface” and the upper die half labeled “rigid seal bead”. Both surfaces were meshed as R2D2 elements and defined as rigid bodies.

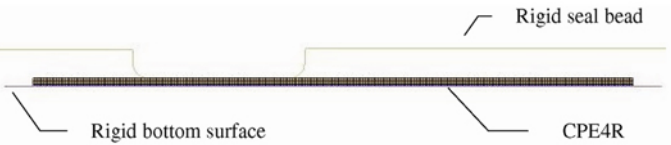


Figure 4. Schematic of finite element seal bead model.

Contact between the sheet and the die was modeled using a soft contact definition between the slave sheet and rigid die surfaces. The coefficient of friction applied in this study was 0.2 unless otherwise noted.

Loading was applied to the rigid seal bead reference node as a concentrated force which in turn acts as a distributed load across the seal bead profile. The load ramp time is 2 sec. and was held constant for an assumed SPF forming time of 120 sec. An additional load was applied on the nodes on the right hand edge of the sheet (Figure 5) representing the force imposed as material stretches and/or draws into the die during forming. A boundary condition was established to pull the nodes a total of 10 mm in 120 seconds which is indicative of the behavior of the sheet during forming.

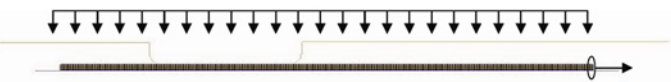


Figure 5. Schematic of boundary conditions for finite element seal bead model.

5. ANALYTICAL SEAL BEAD MODEL

Plane strain slab analysis was used as the theoretical basis for the analytical model. It was assumed that the seal bead width (w_c) represents the most critical parameter influencing seal bead penetration into the sheet. The schematic for this model and force balance is shown in Fig. 6. The pressure on the seal bead, P_n , is assumed to be constant throughout the process and evenly distributed across the seal bead width (w_c). Contact between the sheet and the seal bead is represented by the friction coefficient (μ).

<figure 6 here>