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Gas Forming a V-Shape Aluminum Sheet into a Trough of Saddle-Contour

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A sheet metal trough of aluminum alloys is manufactured by gas-forming process at 500 °C. The product with slope walls is of ~1.2 m long and ~260 mm opening width, comprising two conical sinks at two ends. The depth of one sink apex is ~350 mm, which results in the depth/width ratio reaching 1.4. To form such a complex shape with high aspect ratio, a pre-form of V-shape groove is prepared prior to the gas-forming work. When this double concave trough is turned upside down, the convex contour resembles the back of a twin hump camel. The formability of this configuration depends on the gas pressurization rate profile, the working temperature, material's micro-structure, as well as pre-form design. The latter point is demonstrated by comparing two aluminum alloys, AA5182 and SP5083, with nearly same compositions but very different grain sizes.

Keywords camel-back, saddle-contour, SP5083, superplastic, twin humps, V-shape

1. Introduction

Traditionally, airplane skin structures are largely manufactured by the "stretch forming" or "drop hammer forming" techniques. A newer method, superplastic forming (SPF), has been gradually replacing the former ones due to its advantages in overall reduction in structural weight and manufacturing cost and/or post-formed mechanical properties. Usually, SPF employs pressure gas to bulge a blank metal sheet to fill up a die cavity. So, the term, gas forming, is loosely indicative of SPF. Various companies around the world had been using the SPF process for aluminum alloys for different productions before Boeing fabricated the first SPF 7475 aluminum part for commercial airplanes in 1992 (Ref 1). Hefti pointed out that Boeing has focused on developing application for the superplastic (SP) 5083 aluminum alloy rather than the earlier available 7475 and 2004 (Ref 2). Three examples showing the applications of SPF 5083 to 737, 767, and 777 are presented. One of them is the superplastically formed 737 wing outboard leading edge strakelet, approximately 61 cm long by 38 cm wide. This part has a complex geometry without symmetry as sketched in Fig. 1. A proposed manufacturing process for this strakelet is to first gas form a blank sheet into a die cavity, finished as a trough with the contour resembling camel-back with twin humps, then the desired strakelet will be cut out from it. The trough configuration is characterized by sloped side walls, with a high ratio of depth to width. However, this high ratio parameter is likely leading to overstretching when starting from a flat sheet typically. Therefore, a starting shape closer to the desired trough was adopted: the starting sheet was first preformed into a V-shape, and then laid inside a saddle-contour die cavity to be gas formed as depicted in Fig. 2. In this article, the work of gas forming a V-shape sheet into a trough of saddle-contour using SP aluminum alloy AA5083 and commercially available AA5182, is presented. The AA5182 is chosen to be a comparison, as it has been shown to be quasi-SP in making the front fender of an auto body penal by Zeng et al. (Ref 3).

2. Materials and Experimental

Two types of aluminum alloys, SP5083 and commercial AA5182, are used in this study. Both alloys' nominal compositions are similar, with the major alloying element, Mg, comprising 4.0-5.0%. However, their microstructures are very different; the SP5083 is fine-grained (~8 μm, shown in Fig. 3a) while the AA5182 is coarse-grained (~30 μm, Fig. 3b). The resulting uni-axial tensile elongation capabilities at 500 °C are ~380 versus ~200%, respectively. The basic equipment for operating gas forming is a press which can provide a stable and uniform high temperature environment. The press also needs to offer sufficient clamping force, ~150 tons, to hold tight contact between the die cavity, the edge of blank sheet, as well as the cover plate. The large clamping force ensures that the pressurized gas will remain trapped without pushing the cover plate and blank sheet apart, while still allowing the pressurized gas to bulge the sheet toward the die surface to reach the desired configuration, here it is the saddle contour trough. Lubricant, made of boron nitride, was applied to both surfaces of the die cavity and blank sheet to facilitate sliding between them. In this study, a V-shaped

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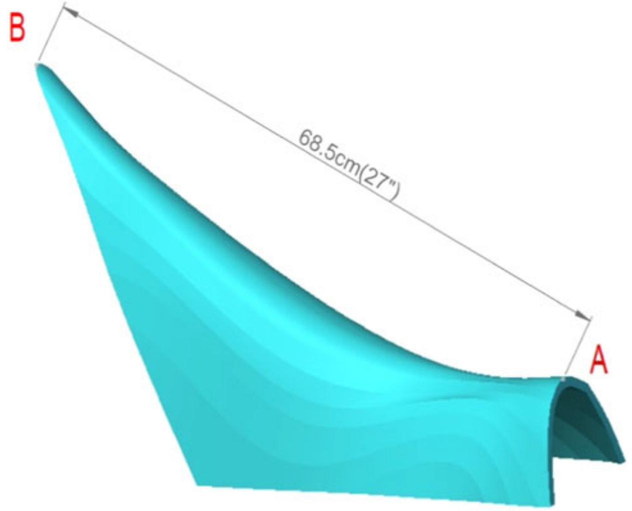

Fig. 1 A computer graph showing the geometry of the strakelet to be formed by SPF

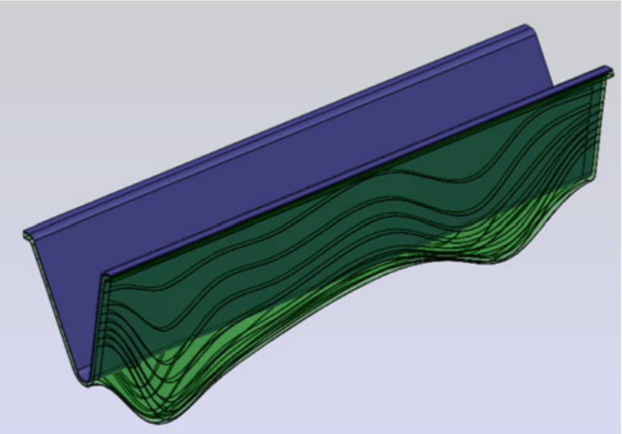

Fig. 2 A schematic drawing shows stacking the pre-bent V groove on top of the saddle-contour die cavity

starting blank sheet was utilized, as it is closer to the final die cavity configuration.

3. Results and Discussion

3.1 Pressurization Rate Profile Estimation Scheme

In gas forming, pressurization rate needs to be manipulated, because its instantaneous magnitude determines the level of flow stress on working material based on the rule of mechanics equilibrium. The induced flow stress is the driving force to cause planar plastic expansion and the stretching rate, fast or slow, is determined by the level of flow stress. Conceptually, there should be an optimal pressurization rate (a function of time) which induces best compromised strain rate distribution over the entire deforming surface, thus resulting maxima surface stretching for a SP material. In early days (~1979), Ghosh and Hamilton (Ref 4) developed an algorithm for obtaining a *p-t* curve starting as a flat sheet assuming under plane-strain condition. In this V-shape case, the same assumption is still valid only that the side walls of the female die will be contacted sooner for the most part in the initial stage of gas bulging so that the Ghosh's 2-D modeling is applied here. At later gas blowing stage, material will be pressed to fill in the cone-like cavity, then the mechanics model by Vulcan et al. (Ref 5) is adopted. So, the above two independent models are employed sequentially for obtaining the *p-t* curve (Fig. 4) in forming a trough with saddle-contour.

3.2 Gas-Formed Camel-Back-Like Trough with SP5083

In Fig. 5, the trough as formed by gas at 500 °C in ~46 min is shown. The product started as an expanded V-groove described above. The manipulated input gas exerts pressure uniformly all over the surface area, but the magnitude of induced flow stress varies from position to position because of geometrical effect. One of the humps, the higher and steeper one, would need higher magnitude of pressure to form, while the other one could be expanded earlier. Conceivably, the

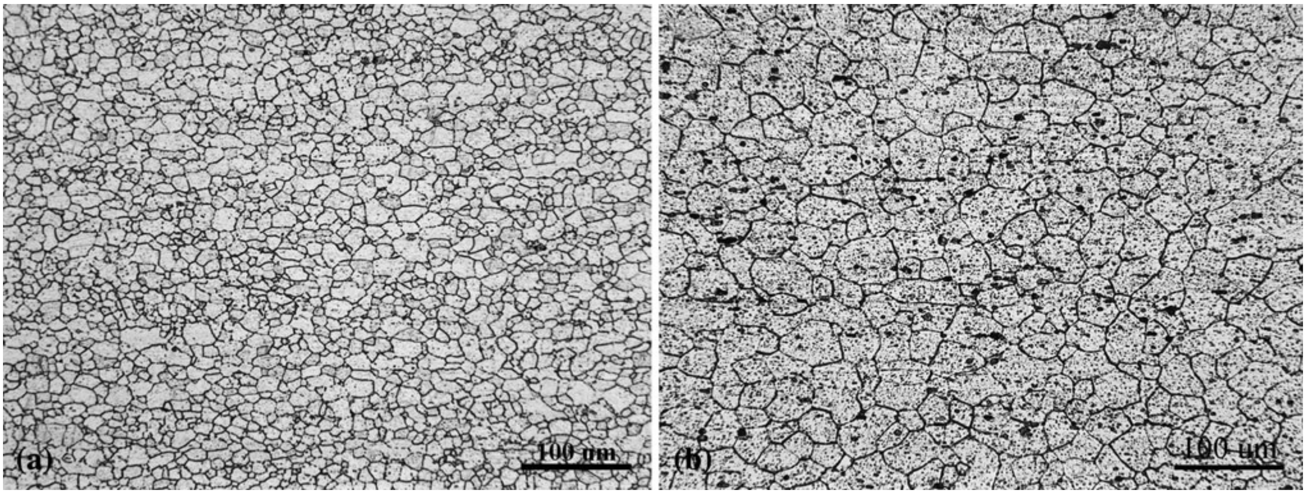

Fig. 3 Microstructures of the SP5083 (fine-grained ~8 μm) (a), and AA5182 (coarse-grained ~30 μm) (b)

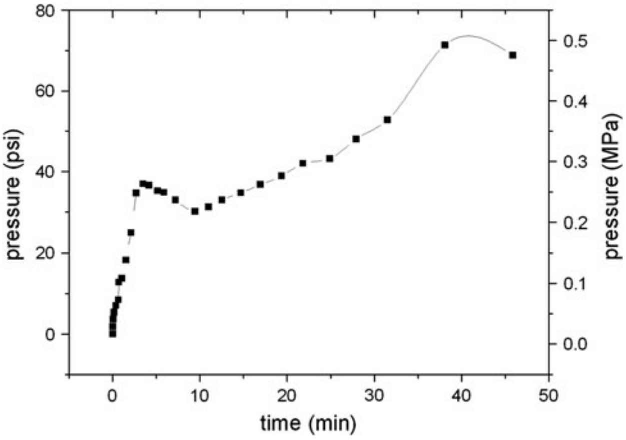

Fig. 4 History of pressure based on the models by Ghosh and Hamilton (Ref 4) and Vulcan et al. (Ref 5)

Fig. 5 The trough bears a contour resembling a camel-back with twin humps, formed at 500 °C by gas pressure in ~46 min

middle part between the two humps should be first finished, followed by the lower hump, then the higher one. It is due to this three sequential forming completion stage that could result in non-uniform thickness distribution. The strakelet cut out from the trough is checked for thickness.

3.3 Thickness Distribution in the Middle Region of the Formed Trough

The measuring route starts from a root point, climbing over the saddle point then descends to the opposite root. The measuring spots on each side are marked as B1, B2, and so on (Fig. 6). The thickness thins down gradually but monotonically from 3.0 to 2.7 mm (B1 to B5, Fig. 7a), indicating that the central region undergoes little plastic stretching. Furthermore, the average thickness thinning ratio (2.75/3.0 mm) is the reciprocal to the ratio of the length of die contour to that of the V-shape, as shown in a typical cross section in this region (Fig. 8). This co-relation reveals a significant fact that materials in the middle region are not stretched in the longitudinal direction. So, it is speculated that a large portion of the expanded V-shape pre-form in the middle region contacts the wall of die cavity early and sticks to the wall thereafter. In other words, a large portion of the V-shape pre-form is not adequately utilized for even thickness distribution.

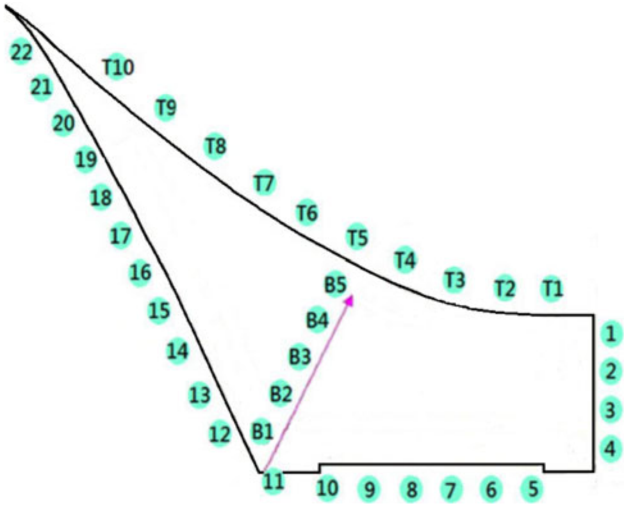

Fig. 6 Locations of thickness measuring on the strakelet used for an airplane fixed wing

3.4 Thickness Distribution Along the Edge of the Strakelet

Measurement around the edge circumference is plotted into two curves as the strakelet is roughly symmetrical, and each side is marked from point 1 to 22 (Fig. 6). Points 1 and 22 correspond to the tops of the two humps of the formed trough, exhibiting thinnest thickness of ~1.7 mm. Point 11 roughly coincides with B1 and can be considered as a datum point preserving the initial thickness, 3 mm. On each side of this datum point 11 (also the root point in B route), thickness decreases monotonically (point 10, 9…1; 12, 13…22) (Fig. 7b). Points 8 and 14 are located at about the same depth as B2 measuring downward from the die entrance, and their individual thickness is the same (~2.8 mm). This fact extends the above postulation that most materials in the V-shape pre-form above the saddle bottom level are not stretched in the longitudinal direction.

3.5 Thickness Distribution Along the Ridge of the Strakelet

This measuring route is along the intersection line between the near-symmetry plane and the back of the saddle, marked as T1…T11 (Fig. 6). T5 approximately coincides with the projected B5 and point 1 is connecting to T0 (extrapolated from T1). Point T5 is slightly thinning just as B5, indicating that further plastic stretching is very limited after the material at this site touches down the surface of the die cavity, which is supposed to occur very early in the gas forming operation. On each side of T5 (Fig. 7c) thickness thinning is moderate, but drops steeply at far ends. This result indicates that the curved bottom is flattened, then stretched one dimensionally in the central region and two dimensionally in the cone regions.

The above analysis regarding thickness distribution in the strakelet shows it is quite uneven and the min./max. ratio in thickness can be <0.6. Besides, large thinning means high plastic deformation, which could cause excess grain boundary sliding leading to cavity formation as to be shown next.

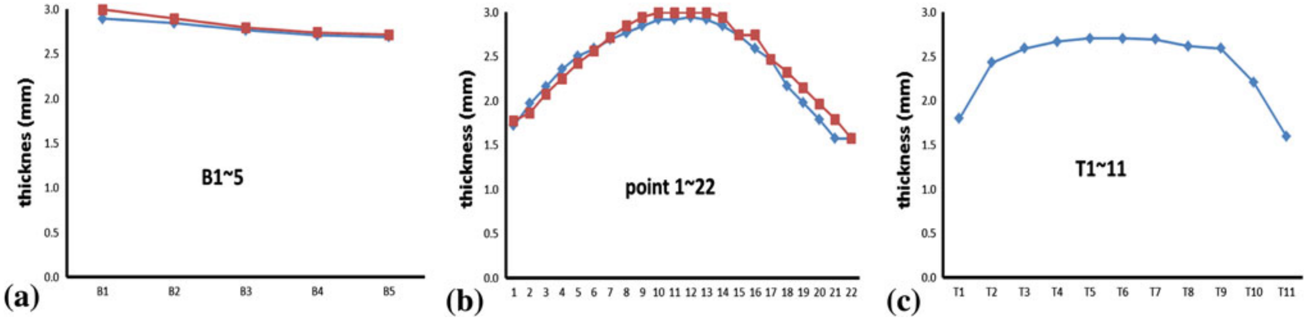

Fig. 7 Thickness distribution. (a) Along B1 to B5, the middle region of the trough, (b) around the edge circumference, and (c) along the ridge

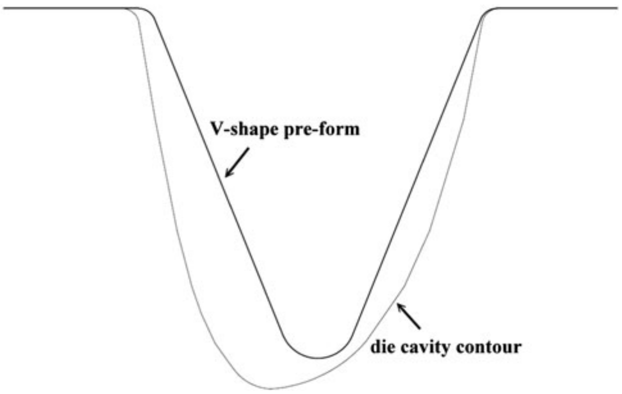

Fig. 8 A cross section in the middle of the trough, corresponding to the B route

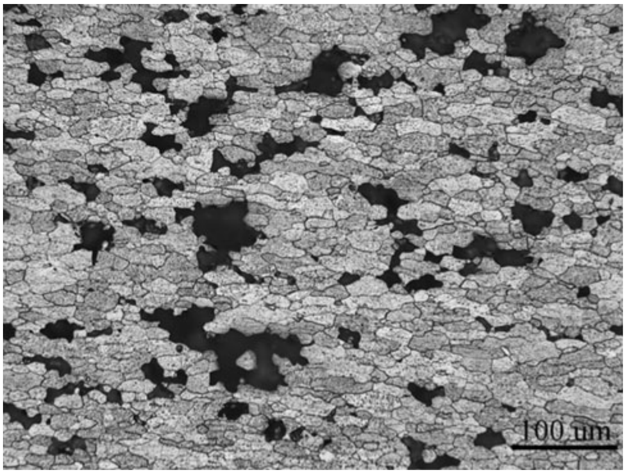

Fig. 9 The optical microstructure at the tip of higher hump (Region 5)

3.6 Micro-structure Variation After Gas Forming

Gas-forming SP material like SP5083 proceeds at high temperature for quite some time, which could transform the working material. The post-formed camel-back-like trough is checked at several sites of microstructures. Specimens from four sites marked 2, 3, 4, and 5 (Fig. 5) are cut out for metallographic examination. The optical micro-structure at site 5 (Fig. 9) is observed with three distinctions: (1) grain growth is minimal after suffering 500 °C for ~46 min, (2) elongated grains run parallel in uni-direction, and (3) severe cavitation exists.

Fig. 10 A gas-formed trough using commercial AA5182, which is far from completion as compared with its counterpart of SP5083

3.7 Formability Comparison Between SP5083 and AA5182

It is shown a gas-formed trough with commercial AA5182 (Fig. 10), which is far from completion as compared with its counterpart of SP5083 (Fig. 5). It is then obvious that formability (ability to be stretched) between fine-grained SP and coarse-grained materials are noticeably different. This point was also mentioned by Luo et al. (Ref 6) that AA5182 is inferior to SP5083 in gas formability. The fundamental theory, grain boundary sliding mechanism, can predict that the fine-grained SP5083 will activate this mechanism more easily.

4. Conclusions

The concept of starting a shape closer to the configuration of desired product is applied in gas forming a trough with a twin-humps camel-back-like contour. A flat sheet of SP AA5083 is first bent into a V-shape groove, aiming at easiness for subsequent gas forming the twin-humps trough. The thickness distribution over the trough surface is uneven to an undesired degree, and the most thinning area at the top of higher hump, is associated with severe cavitation. Thickness thinning analysis along three paths reveals that the present die cavity design is not a good one as most part of the gas-forming sheet only undergoes one-dimensional stretching. Fine-grained SP material is superior to coarse-grained quasi-SP one in formability.

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