Superplastic Forming Characteristics of Fine-Grained 5083 Aluminum

R. Verma, P.A. Friedman, A.K. Ghosh, C. Kim, and S. Kim

Superplastic forming characteristics of a fine-grained 5083 aluminum sheet have been investigated by means of gas-pressure forming of a rectangular pan. This part geometry lends itself to a simple representation in terms of nearly one-dimensional sheet stretching and permits reasonably rigorous control of strain rate throughout the forming cycle. This study followed a study of the uniaxial tensile properties carried out on this alloy. A two-stage forming cycle, which comprised a short, rapid prestraining stage followed by a stage of slower rate of superplastic straining, was used because the uniaxial tensile work showed enhancement of superplastic response of this alloy under this condition. The study examined the effect of process parameters such as initial gas pressurization rate, level of hydrostatic pressure, and lubricants on the thinning characteristics of the sheet, especially along the die entry radii. The gas pressure/time cycle was suitably modified to avoid premature sheet failure due to excessive sheet thinning or cavitation. Cavitation under the biaxial forming condition and the effect of hydrostatic pressure on cavitation suppression were evaluated. A defect-free pan with sharp corners was formed.

Keywords
aluminum alloys, cavitation, gas-pressure forming, metal forming, superplasticity

1. Introduction

SUPERPLASTIC forming is becoming an important industrial process for the manufacture of complex metal parts. The large tensile elongations and low flow stresses that are characteristic of superplasticity permit the use of gas-pressure forming to produce complex shapes. In this method, a sheet of superplastic metal is blow formed in a die by applying gas pressure from one side, rather than by stamping between mated steel dies.

In the automotive industry, an ongoing need to reduce vehicle weight and improve fuel efficiency has led to considerable interest in replacing steel with aluminum in sheet metal body parts. The need for improved corrosion resistance has further suggested that a leaner alloyed variety of aluminum, such as aluminum-magnesium alloys, would be more desirable for such applications. A typical aluminum-magnesium commercial alloy is 5083 aluminum (Al-4.7Mg-0.7Mn), which is widely used as a structural material in applications that require corrosion resistance and moderate to high strength (155 to 300 MPa) and which has potential as an automotive body-sheet alloy. Conventional stamping of aluminum alloys into sheet metal parts is limited by their lower formability, as compared to drawing-quality steels; therefore, superplastic gas-pressure forming of aluminum sheet parts is of considerable interest.

A fine-grained 5083 aluminum sheet (available from Alusuisse Company, Shelbyville, KY, under the trade name Formall 545) was investigated for gas-pressure forming. The optical micrograph shown in Fig. 1 reveals a fine grain structure with an average grain size of 6.5 μm. The as-received alloy was shown to have an essentially equiaxed microstructure without subgrains and a uniform dispersion of submicron particles. Chemical analysis with transmission electron microscopy (TEM) identified the dispersoid particles as Al_6Mn (Ref 1).

Initial superplastic characterization of the material is usually carried out by conducting tensile tests (Ref 1) to determine the strain-rate sensitivity index, m ($d \log \sigma / d \log \dot{\varepsilon}$), as well as tensile elongation to failure. Certain aluminum alloys have been shown to exhibit larger superplastic elongations in a two-

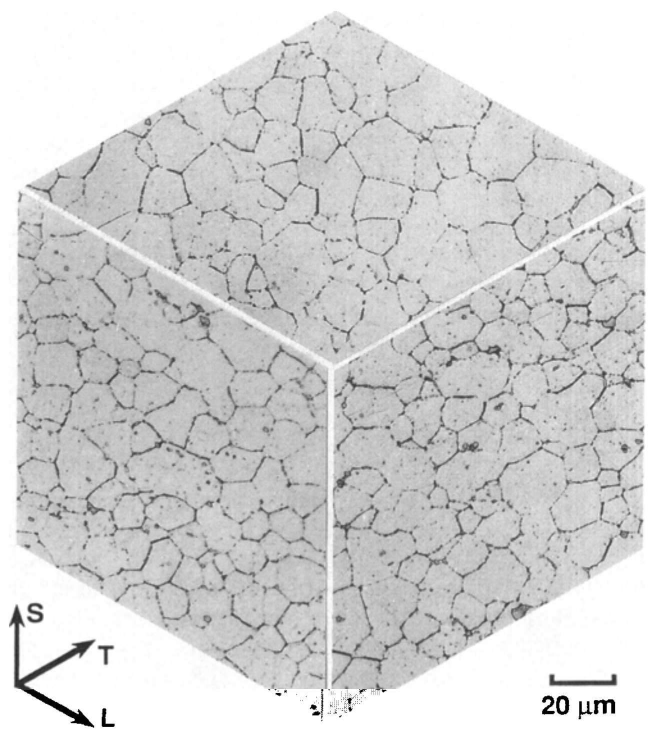

Fig. 1 Microstructure of superplastic 5083 aluminum after solutionizing at 525 °C for 15 min followed by water quenching and aging at 150 °C for 24 h

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step strain-rate deformation cycle in which the sheet is first rapidly strained to a strain level of 0.6 to 0.8, followed by a slower rate of deformation (Ref 2). It has been shown that during the rapid straining stage aluminum-lithium alloys develop a recrystallized grain structure by "continuous recrystallization"—a process of gradual conversion of subgrains into a high-angle fine-grained structure (Ref 2). A tensile elongation as high as 600% was recorded in 5083 aluminum using a two-step straining schedule comprised of a relatively rapid rate of 10^{-2}/s up to a strain of 0.5, followed by a slower strain rate of 8×10^{-4}/s to failure (Ref 3). It has been suggested that negligible grain growth during the first stage of deformation helps to enhance overall formability. These uniaxial test results became the basis for selecting optimum superplastic forming conditions for this material.

Commercial superplastic forming operations generally involve multiaxial stress states. Effective utilization of uniaxial superplastic test parameters in an actual forming process involving a complex stress state requires a mathematical model. A number of attempts to model blow forming of sheet metal have been reported (Ref 4-12). Several previous models considered the forming of a spherical dome shape. These analyses either ignored the existence of different stress states in different regions (Ref 4) or simplified the problem to a "balanced biaxial" state of stress at the pole and "plane strain" at the equator (Ref 8). Ghosh and Hamilton (Ref 12) modeled blow forming of a long rectangular box section or channel section, a shape common to many actual parts. This shape permits a simple plane strain state to be assumed to exist in most of the part. The problem is reduced to one-dimensional stretching along the minor axis of the channel. For simple geometries, such as a rectangular pan, this approach allows a less expensive and numerically more accurate analysis than a three-dimensional finite-element model and thus permits better understanding of the effect of different process parameters on the thinning characteristics of the sheet.

The present work investigates the blow-forming characteristics of fine-grained 5083 aluminum sheet into a rectangular pan shape. Even though the selected pan geometry has a finite length, the simplified plane strain analysis was used to calculate the necessary gas-pressure cycle. A two-stage forming cycle consisting of a rapid prestraining stage followed by a normal superplastic forming stage, as developed in the uniaxial tests, was utilized for the forming runs.

2. Process Modeling

The blow-forming process model of a long rectangular pan by Ghosh and Hamilton (Ref 12) has been used for this work. The large length-to-width ratio presents a situation where sheet stretching occurs essentially along the pan width direction. This permits a plane strain state to be assumed throughout the unsupported sheet section. Die entry radius is ignored, and sheet is assumed to be clamped at the edge of the rectangular die opening. With these assumptions, the thinning gradient is absent in the sheet until the sheet touches the die walls or bottom. The free forming region (i.e., prior to sheet contact with die walls) is assumed to have a circular cross section with a radius of curvature that decreases with increasing strain.

One-dimensional membrane analysis yields a relationship between gas pressure, flow stress, sheet thickness, and the radius of curvature of the sheet. The radius of curvature is related, through simple geometry, to strain rate and time. The optimum superplastic strain-rate and flow-stress values from uniaxial test data are used to compute optimum strain-rate and flow-stress values in the biaxial stress state of the sheet by using von Mises effective stress and strain concepts. Using these relationships, the appropriate pressure/time curve is developed. This curve is useful until the sheet touches the walls or the bottom of the die. After contact is established between the sheet and the die, strain is calculated in individual regions assuming complete sticking between sheet and die (i.e., no further thinning is assumed to occur in the contacted region). The forming process is controlled by maintaining a constant effective strain rate in the unsupported (free) region. An appropriate pressure/time curve is computed to control the sheet forming operation.

3. Die for Pan Forming

A schematic of the two-part die for forming the rectangular pan is shown in Fig. 2. The gas inlet for applying the forward (forming) pressure is in the center of the top piece. The back (hydrostatic) pressure is applied through two inlets in the main die. The die was machined from RA 330 superalloy, which has excellent oxidation resistance.

4. Gas-Pressure Control System

A pressure-regulating system was used to control the forward (forming) gas pressure. The system consisted of these components:

- Electropneumatic pressure controller (TESCOM ER-2000, Tescom Corp., Elk River, MN)
- Computer interfaced to the controller for entering the pressure cycle
- Pressure transducer to provide pressure feedback to the controller
- Digital pressure display
- Gas inlet valves to the die

Superimposed hydrostatic pressure was used in some of the forming runs to help control cavitation. This was applied by maintaining a gas pressure on the back side of the forming sheets. No pressure controller was used for this back-pressure control; instead, the back-pressure side was connected to the forward-pressure system through a valve. Initially, the back pressure was applied by manually opening both the forward- and the back-pressure valves and equilibrating the forward and back pressures, and then closing the back-pressure valve once a steady pressure was attained. The back pressure was then maintained at this level by manual control of the leak valve as needed. At this point, the pressure controller can be used to apply a forward differential pressure (per calculated pressure/time cycle) to form the pan.

5. Gas-Pressure Cycle

A gas-pressure cycle for blow forming of a 50 by 150 mm rectangular pan (25 mm deep) was computed based on the plane-strain model described previously. In order to make use of the enhanced superplastic response of this alloy in the blow-forming operation, a two-stage forming cycle similar to the uniaxial two-step straining schedule was developed. The computed cycle, which comprised a rapid prestraining stage at 10^{-2}/s strain rate to a strain of 0.5 followed by a superplastic forming stage at 8×10^{-4}/s strain rate, is plotted in Fig. 3.

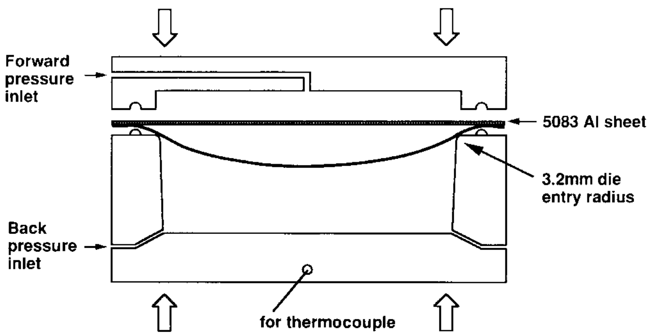


Fig. 2 Schematic of 50 by 150 mm rectangular die (25 mm deep) with 3.2 mm die entry radius for pan forming with the initial and partially formed sheets as indicated

6. Forming Test

Rectangular pieces, 100 by 200 mm, cut from the 5083 aluminum sheet were used for pan-forming runs. A coating of boron nitride powder slurry was applied as lubricant on both surfaces of the aluminum piece. Boron nitride has been shown to be a good lubricant for high-temperature deformation (Ref

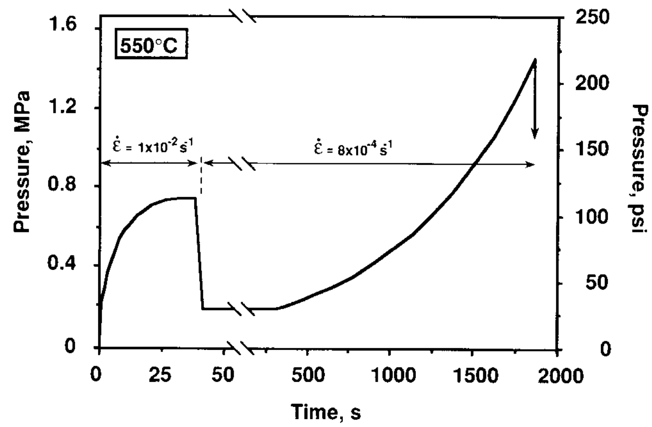
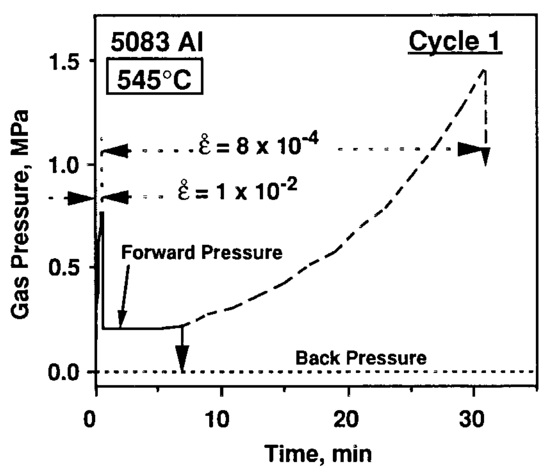
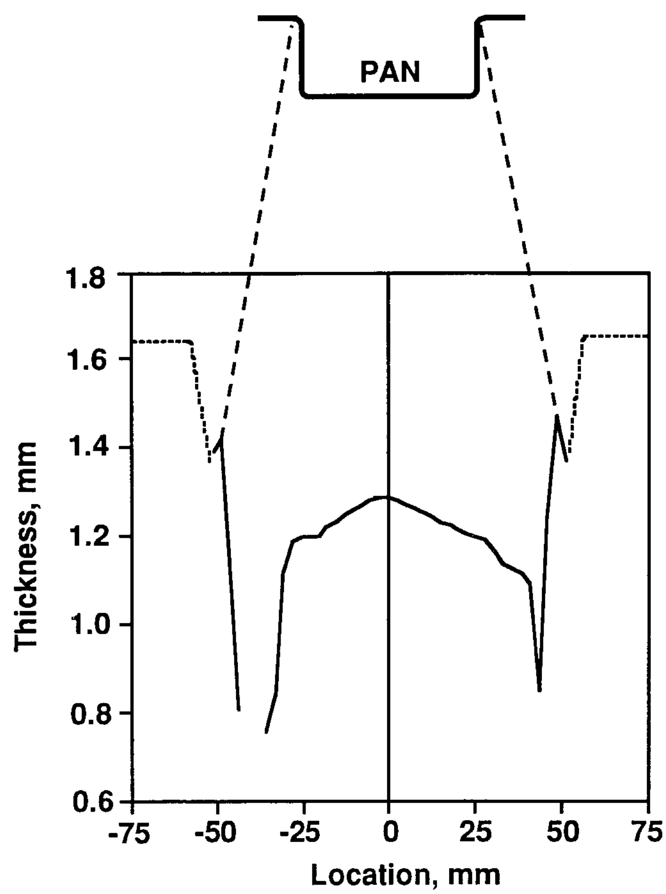


Fig. 3 Computed pressure/time cycle for forming a 50 by 150 mm rectangular pan (25 mm deep) from 1.6 mm thick 5083 aluminum sheet



(a)

(b)



(c)

Fig. 4 Cycle 1. (a) Pressure/time cycle. (b) Formed pan. (c) Sheet thickness profile in mid-transverse section of pan

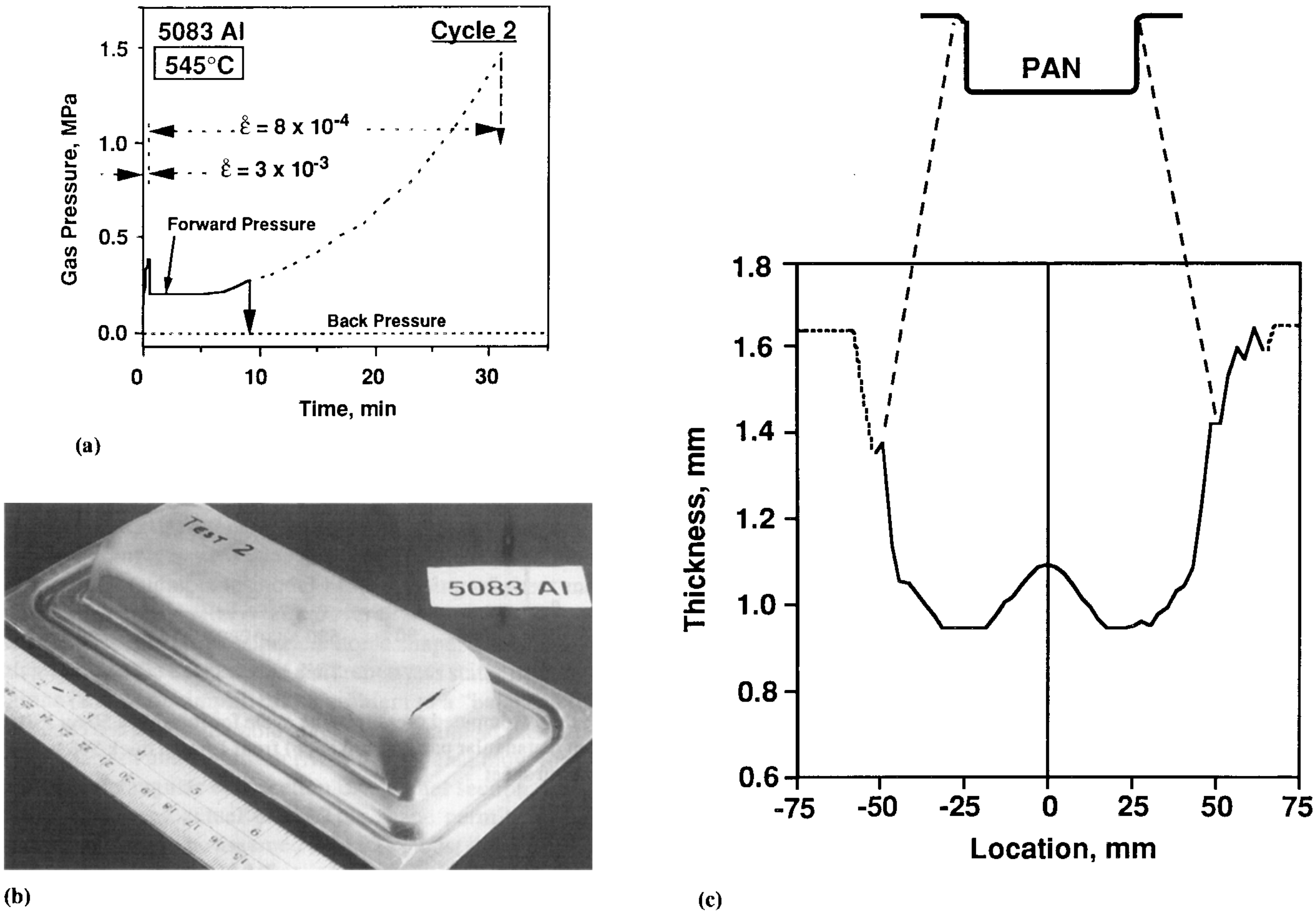


Fig. 5 Cycle 2. (a) Pressure/time cycle. (b) Formed pan. (c) Sheet thickness profile in mid-transverse section of pan

12). The die set was placed between the heated platens of the press, and the temperature was stabilized at the forming temperature. The aluminum sheet was then placed in the preheated die, and a blank clamping load was applied in order to grip the plate and seal the die. A flange load of 49 kN during the first stage of the cycle and a load of 147 kN during the second stage of the cycle were required in order to prevent leakage from the die. Increasing the blank clamping load much past these limits resulted in thinning and premature fracture of the sheet at the die entry radii. This problem is not viewed as a real limitation for the process but simply a function of the sharp die entry radius used in this study.

All pan-forming runs were made at 545 to 550 °C. The following runs summarize the development of an optimum pressure cycle for complete forming of the pan shape with very little cavitation.

6.1 *Cycle 1*

The pressure/time cycle used for this run is shown in Fig. 4(a) (the same cycle as in Fig. 3). The forward (forming) pressure was controlled through a computer, with the back-pressure inlet open to the atmosphere (no back pressure). The cycle had to be interrupted soon after the first stage, as indicated in Fig. 4(a), because of premature failure of the pan as evidenced by rapid gas flow and pressure instability. The failed pan (Fig. 4b) exhibited a crack at the die entry edge along the length. A transverse section was cut from the failed pan, and thickness measurements were made at a number of locations along the pan width. The thickness profile plotted in Fig. 4(c) shows sharp thinning out of the sheet at the die entry radii.

During the early stage of forming (i.e., before the sheet had contacted the die walls), the force of gas pressure on the sheet was supported almost entirely at the die entry edges. The edges cut into the sheet thickness due to a local through-thickness compression. The extent of sheet thinning depended on the magnitude and the rate of increase in the gas pressure. The net pressurization rate during the first stage was 0.77 MPa (112 psi) in 40 s. It is obvious that this sharp rise in gas pressure during the first stage of the forming cycle (Fig. 4a) was sufficient to completely thin out and crack the sheet along the die entry edges.

6.2 *Cycle 2*

The pressure/time cycle used for this run is shown in Fig. 5(a). The net pressurization rate during the first stage was reduced to half that in cycle 1: 0.39 MPa (56 psi) in 40 s. Again, no back pressure was applied during this cycle. A few minutes into the second stage of the cycle, premature failure of the pan was indicated by pressure instability, and the cycle was interrupted. The failed pan (Fig. 5b) showed no cracks along the die

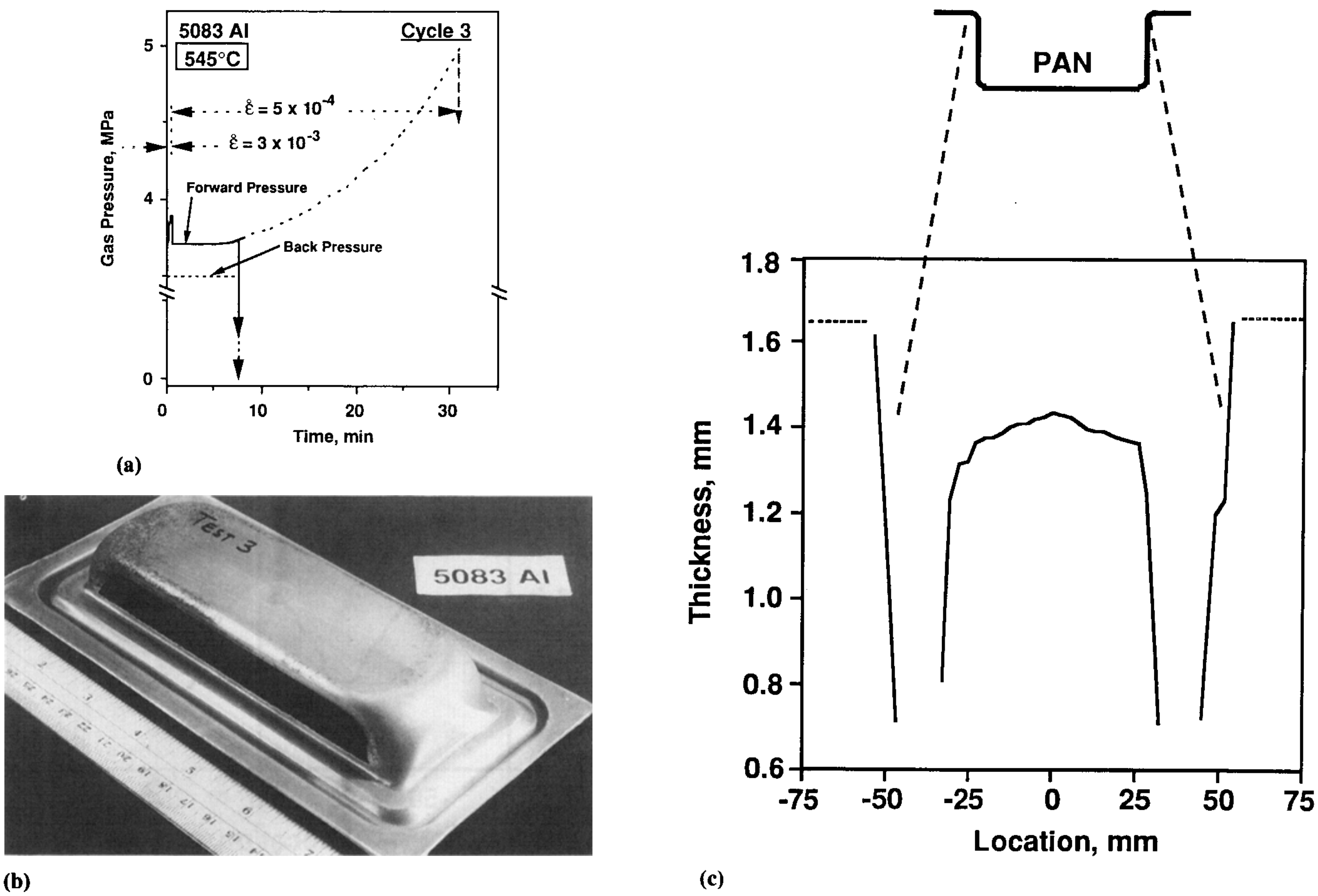


Fig. 6 Cycle 3. (a) Pressure/time cycle. (b) Formed pan. (c) Sheet thickness profile in mid-transverse section of pan

edges, but exhibited small fissures in its bottom near the short edge, which was indicative of excessive strain and concurrent cavitation-induced failure.

A transverse section of this pan was cut and thickness measurements made along its width. The thickness profile (Fig. 5c) shows no excessive sheet thinning except in the failed section.

6.3 *Cycle 3*

In order to suppress pan failure by cavitation, cycle 2 was modified by combining it with a 3.5 MPa (500 psi) hydrostatic pressure. This was achieved by applying a constant 3.5 MPa back pressure from the start of forming and increasing the forward pressure by 3.5 MPa throughout the cycle, over and above the calculated pressure level (Fig. 6a). This cycle had to be interrupted because of premature sheet failure in the first stage itself. The failed pan (Fig. 6b) showed die entry-edge cracks similar to those seen in cycle 1 (Fig. 4b). The thickness profile along the pan width (Fig. 6c) indicated failure due to excessive sheet thinning at the die entry radii.

It is clear that along the die entry edges the sheet experienced extremely high through-thickness compression aided by reaction force against high forward pressure. Combined with tensile membrane stresses, this forward pressure caused excessive through-thickness thinning. The sheet along the die edges thinned out completely very early during the first stage of the forming cycle. Thus, it was concluded that application of back pressure during the first stage of the forming cycle is not prudent for a material such as 5083 Al, which has only marginal superplasticity, particularly when a sharp die entry radius is used.

6.4 *Cycle 4*

This test (Fig. 7a) was designed with no hydrostatic component during the first stage of the cycle (in order to avoid die entry cracks) and with a 3.5 MPa hydrostatic pressure during the second stage (to suppress cavitation failure). The forming cycle was completed without failure. The fully formed pan with sharp corners and edges is shown in Fig. 7(b). The thickness profile determined along the pan width (Fig. 7c) shows sheet thinning at the bottom edges, which are last to form. This thickness variation, however, can be further reduced by lowering friction between the sheet and the die walls through increased lubrication of the sheet.

6.5 *Summary*

The test conditions and results of the four pan-forming runs are summarized in Table 1. It is concluded that, if die entry radius cannot be enlarged, premature failure during pan forming can be avoided by using a somewhat slower forming rate during the first stages (i.e., 3×10^{-3}/s instead of 10^{-2}/s) and by

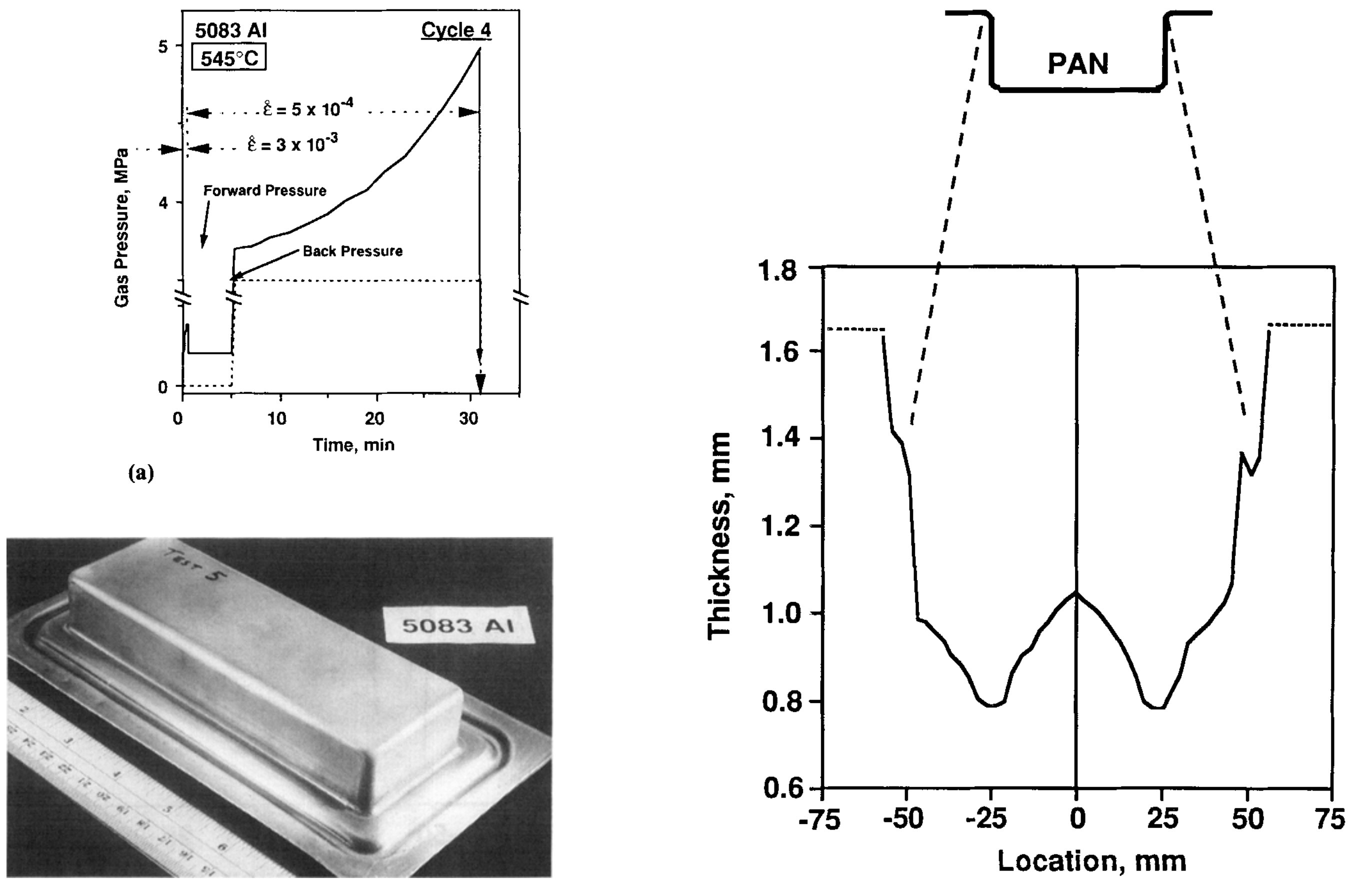


Fig. 7 Cycle 4. (a) Pressure/time cycle. (b) Formed pan. (c) Sheet thickness profile in mid-transverse section of pan

Table 1 Gas-pressure forming of a 50 by 150 mm pan (25 mm deep) from 5083 aluminum sheet at 545 °C

Cycle	Strain rate, s^{-1} Stage I	Strain rate, s^{-1} Stage II	Back pressure, MPa	Load on flange, kN	Remarks
1	10^{-2}	8×10^{-4}	0	49	Cracks along die entry radii
2	3×10^{-3}	8×10^{-4}	0	49	Improved forming cavitation failure
3	3×10^{-3}	5×10^{-4}	3.5	147	Cracks along die entry radii
4	3×10^{-3}	5×10^{-4}	0	49	Fully formed pan
			3.5	147	

avoiding hydrostatic pressure during the first stage of the forming cycle. A hydrostatic pressure of 3.5 MPa can be used during the second stage to suppress cavitation. It is believed that this complex forming cycle is a result of the very small die entry radius and short flange region used in the present work. Increasing die entry radius would perhaps be the best solution, allowing use of the original pressurization cycle.

7. Cavitation in Formed Pans

Cavitation in blow-formed aluminum is of interest not only because it is an important factor that limits the superplastic stretching of aluminum (Ref 13), but also because it can have deleterious effects on the mechanical properties of the formed parts (Ref 14, 15). It is also necessary to determine whether cavitation under biaxial stress state is different from cavitation under uniaxial conditions. Transverse sections cut from pans formed under 0, 2.0, and 3.5 MPa hydrostatic pressures were mounted, polished, and examined metallographically. The optical micrographs in Fig. 8 show cavitation in the three pans at a strain of 0.5. Cavitation rate diminishes with the application of hydrostatic pressure. The voids resulting from cavitation were examined under several different magnifications to ensure that the black images were in fact cavities, and not precipitates. Based on this examination, the very small, dark features in Fig. 8 were not counted as cavities forming in the material.

Quantitative assessment, in terms of volume percent cavitation, was made with the help of an image analyzer. The optical image is first transformed into a binary (two-tone) video image. The number of pixels in the black (cavity) area are counted and divided by the total number of pixels in the image to give cavity

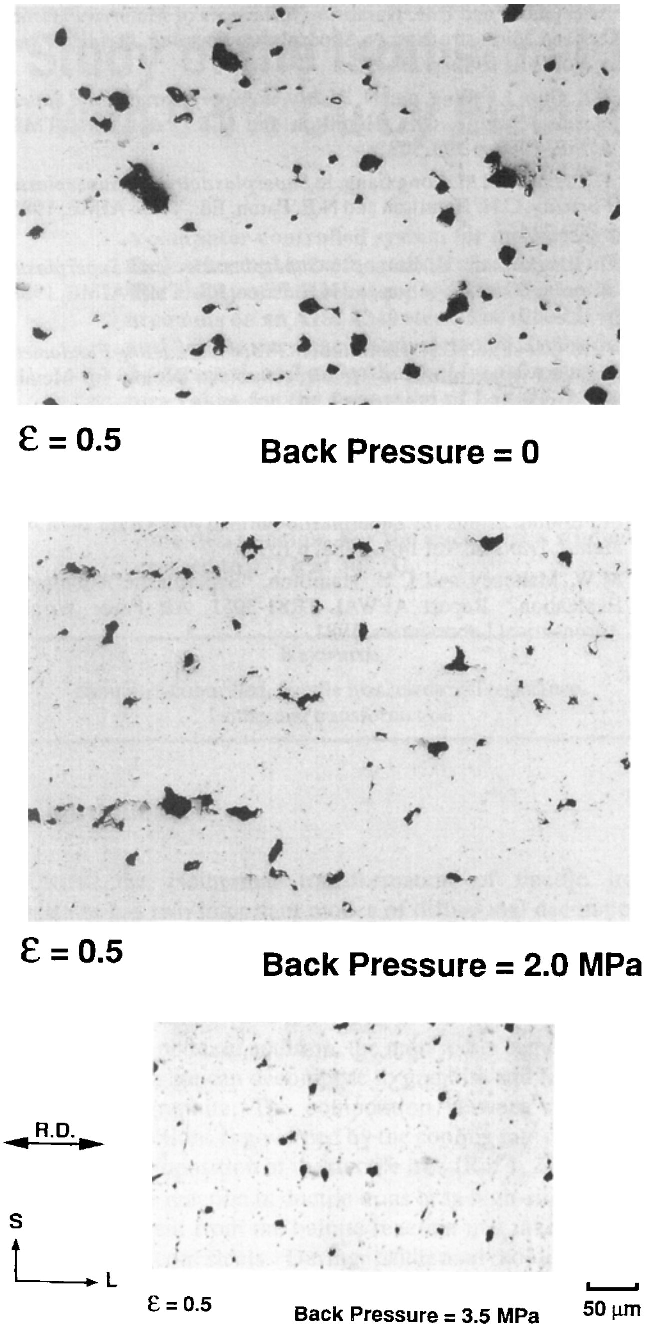


Fig. 8 Optical micrographs showing cavitation in pans formed with superimposed hydrostatic pressure at the midsection of the major or minor axis at 540 °C along the pan bottom

volume fraction in the material. The results are plotted in Fig. 9 along with cavitation data for the uniaxial two-step tensile tests taken from Ref 3. It is seen that the rate of cavitation under biaxial stretching (no hydrostatic pressure) is higher than that under uniaxial stretching (550 °C two-step test). Incubation strain for cavity initiation in the case of biaxial stretching is 0.4, compared with 0.5 in the case of uniaxial stretching (Ref 3). Furthermore, under the biaxial stress state, the cavitation rate decreases with the application of hydrostatic pressure.

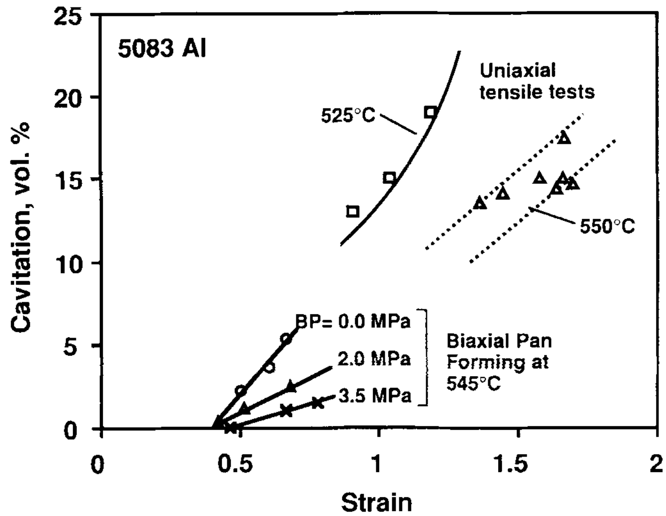


Fig. 9 Cavitation as a function of strain along the pan bottom at the midsection of the major axis in pans formed at 540 °C with 0, 2.0, and 3.5 MPa hydrostatic pressures. For comparison, cavitation under uniaxial tension (without hydrostatic pressure) is also included.

8. Conclusions

To achieve superplastic forming of 5083 aluminum sheet into a rectangular pan, a two-stage gas pressure versus time cycle has been developed based on a plane-strain deformation model. The cycle consists of a rapid prestraining stage followed by a superplastic forming stage for the blow forming of a 50 by 150 mm rectangular pan (25 mm deep) from a fine-grained 5083 aluminum sheet. Premature failure by excessive sheet thinning at the die entry radii can be avoided by suitably reducing the gas pressurization rate (and thus the sheet deformation rate) during the first part of the straining cycle and by minimizing the initial hydrostatic pressure level.

Cavitation begins earlier in the forming process (lower incubation strain) under a biaxial stress state and proceeds at a faster rate than for uniaxial deformation. Cavitation also leads to premature sheet failure, which can be avoided by cavitation suppression through the use of hydrostatic pressure during forming. It was found that a hydrostatic pressure of 3.5 MPa was adequate to avoid failure from cavitation.

Hydrostatic pressure can aggravate sheet thinning at the die entry radii, especially when the radius is small and the pressure is high during the initial stage of gas pressurization. The problem can be solved by delaying application of hydrostatic pressure, or perhaps by increasing the die entry radius.

Production of fully formed rectangular pans with a die bottom edge radii of 3 mm and a minimum of cavitation has been successfully demonstrated using a two-step strain-rate forming technique.

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