Comparison of Advanced SPF Die Technologies in the Forming of a Production Panel

Y. Luo, S.G. Luckey, W.B. Copple, and P.A. Friedman

Superplastic forming (SPF) is a manufacturing process that can facilitate increased use of aluminum in automobile body structures. Despite considerable advantages with regards to formability and tooling costs, the process has been mostly limited to low volume production due to relatively long cycle times and the need to use specially processed sheet alloys. To address these issues, advanced processes such as two stage gas forming (TSGF) and hot draw mechanical pre-forming (HDMP) have been developed. Advantages of these processes have been demonstrated on the forming of a complex dash panel part. Final thickness distribution and forming time on this part manufactured with these two processes were compared to that of the same panel produced with conventional SPF. The HDMP technology which combines hot stamping with SPF was found to have the capability of forming a complex shaped component with a superior thickness profile and faster forming cycle than that formed with a conventional single stage or two stage forming cycle. Additionally, the HDMP process proved to be a robust process with a wide temperature window and allowed for the forming of lower-cost, non-spf aluminum, and magnesium sheet alloys. Finally, analysis of the post-form microstructure indicated that there was essentially no cavitation in panels formed with the HDMP process and that material with a coarse grain structure could be successfully formed.

1. Introduction

Superplasticity is a term used to indicate the exceptional ductility that certain metals can exhibit when deformed under specific conditions of strain rate and temperature. The tensile ductility of superplastic metal typically ranges from 200% to 1000% elongation, but ductility of 5000% has been reported (Ref 1). Superplastic forming (SPF) is a manufacturing process that takes advantage of a material's superplastic response. Typical SPF takes places in a simple one-sided, single action tool. The blank is clamped in a heated die and then blow formed with gas pressure into a female die (Ref 2).

Conventional SPF (CSPF) offers several advantages over traditional stamping processes including increased formability, zero springback and low tooling costs. However, there are limitations in the commercial feasibility of this process. First, SPF is a rate sensitive process typically encompassing slower deformation rates, which result in a relatively slow cycle time. Second, SPF is a stretch forming process with no draw-in of material into the die cavity, which may result in tears or non-

uniform wall thickness in the formed part and limit the ability to form complicated components.

To overcome these limitations, two novel SPF processes were developed utilizing pre-forming: two stage gas forming (TSGF) and hot draw mechanical pre-forming (HDMP). TSGF is a new multi-stage SPF approach which utilizes two stages of gas forming within one die (Ref 3). During the first stage of forming the material is forced into an engineered pre-form cavity. This is followed by a reverse of gas pressure during the second stage that forces the material into the final part cavity. This technology is based on the early work of Nakamura and Fischer (Ref 4, 5). A novel SPF process utilizing a HDMP process that uses a blank holder to control the material flow into the die during the pre-forming step was recently developed. This new die concept is based on the patent of Friedman (Ref 6) and has been referred to as hot draw mechanical pre-forming (HDMP).

In this article die design and forming trials were performed on a complex-shaped production panel using CSPF, TSGF, and HDMP. Advantages of the newly developed SPF processes were evaluated by comparing final thickness distribution of the panel and forming time. The HDMP technology was found to have the capability of forming a complex component with a superior thickness profile and faster forming cycle than either of the other two processes. Additionally, the HDMP process allowed for the forming of lower-cost, non-SPF grade, commercial aluminum, and magnesium alloys. The influence of forming temperature on HDMP was also investigated in this work to establish the robustness of the process.

2. Complex-Shaped Production Panel

The panel formed in this work is part of the dash panel assembly used on a current vehicle model. A CAD rendering of
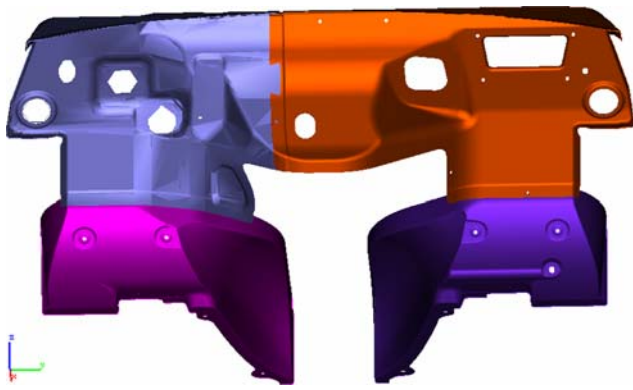
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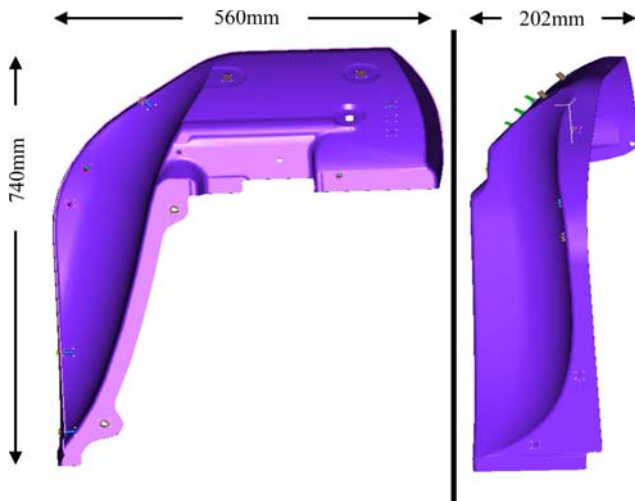**Fig. 1** CAD rendering of the dash panel assembly

Fig. 2 CAD rendering of the part formed in this work with some approximate dimensions

this assembly is shown in Fig. 1, with the panel of interest in the lower left hand corner. Approximate dimensions of the part are shown in Fig. 2. Presently, all four of these parts are being manufactured via CSPF.

Due to the panel's geometry a double-attached formation comprising two identical parts was used. By forming these two parts together, an efficient deep draw panel geometry could be used which offers very good material utilization. A layout of the panels in die position is shown in Fig. 3. While forming of the left hand and right hand parts in one formation instead of two identical panels would have been a lower tooling investment option, the geometry of this panel did not lend itself to this approach.

3. Die Design

3.1 Conventional SPF

In CSPF, gas pressure only needs to be controlled on one side of the sheet to form the part. As shown in Fig. 4, this type of die consists of two die halves where one die half contains the forming surface and the other contains inlet holes for the gas to

be introduced into the die. The die halves are secured via die clamps to the heated platens of the SPF press. With the application of gas pressure, the sheet is forced into the forming cavity.

3.2 Two Stage Gas Forming

The two-stage SPF die design for the panel includes a die half containing the part cavity and a second die half with the pre-form cavity. To initiate the design of the pre-form cavity surface, several cross-sections of the final part cavity were generated in CAD, which represent the deepest portions of the cavity, as well as the locations of the worst localized necking after the entry radius. For each two-dimensional (2D) cross-section of the final forming cavity, a pre-form section was designed to pre-thin material in local regions of the sheet to minimize thinning in other regions. By locally pre-thinning regions that experience the least thinning in the part cavity, material can be made available to increase thickness in more critical regions (Ref 4, 5). Hence, pre-form sections were engineered to optimally redistribute metal thickness within the final part cavity. The pre-form sections were used to generate a wire frame, and surfaces were applied to the wire frame to complete the pre-form design shown in Fig. 5. The pre-form surface was then evaluated with three-dimensional (3D) FEA using LS-DYNA.

The development of a complex three-dimensional (3D) pre-form surface that pre-thins a blank such that the final part thickness profile is improved and without wrinkles would be a difficult and for some part geometries an impossible task without numerical methods to guide the design of the pre-form. This design was driven by 10 iterations of design and finite element analysis to achieve the appropriate thinning distribution without the development of wrinkles in the final formed part.

3.3 Hot Draw Mechanical Pre-Forming

The HDMP die utilizes a punch and a blank holder to draw material into the forming cavity prior to superplastic gas pressure forming. To initiate the design of the punch, an analysis was performed using CSPF and hot stamping to find out critical locations on the panel. In this design, the punch was offset from the forming cavity by a minimum of 5 mm to ensure the die was not matched while also drawing the material as deep as possible. The radii of the pre-form were made as large as possible to reduce localized thinning in the sheet. For critical areas, the pre-form shape was designed to limit metal from sliding along the die surface and prevent excessive thinning during pre-forming. FEA was applied to investigate the influence of the pre-form punch design and produce an optimized pre-form shape. The final punch shape is shown in Fig. 6 and a photograph of the die in Fig. 7.

4. Material for Study

A 5083 aluminum alloy specially processed for SPF (referred to as SPF5083) was provided by SKY Aluminum and used in most of the forming trials to compare advantages of these three processes. To expand the advantages of the HDMP process, trials were also conducted with the lower-cost, commercially available aluminum alloy AA5182 and magnesium alloy AZ31.
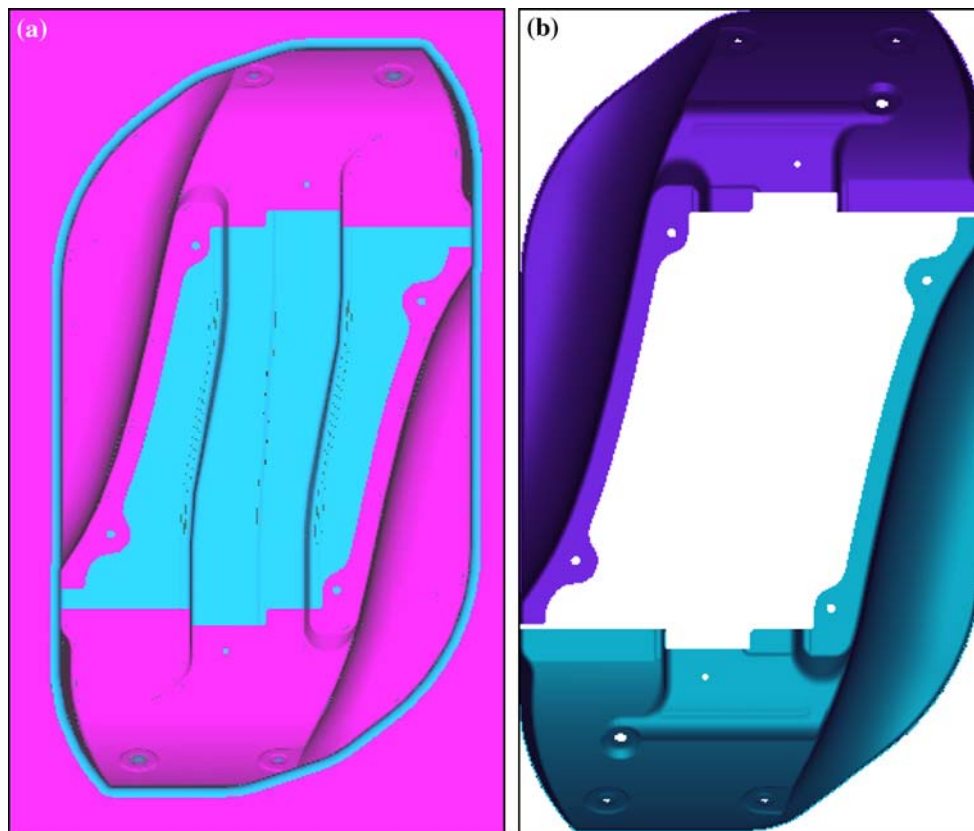
Fig. 3 Schematic illustration of the packaging strategy to produce two parts within one deep draw forming (a) before and (b) after trimming

Fig. 4 Photograph of the CSPF die cavity for forming the panel

The SPF 5083 sheet had a nominal thickness of 1.6 mm and was received in the fully hard (H19) condition. The chemical composition of the 5083 alloy is listed in Table 1.

The AA5182 and AZ31 sheets had nominal thicknesses of 1.6 mm and 1.75 mm, respectively. The AA5182 was received in the fully annealed (O temper) condition while the AZ31 was received in the H24 temper. Chemical compositions of these two alloys are listed in Table 2 and 3.

5. Experiment Set-up

All forming trials were performed in an 800-ton hydraulic SPF press. The die was secured between the platens of the press with the forming cavity located on the upper platen. The platens contained cartridge heaters which heat the SPF die through conduction. The die temperature was monitored using two Type K thermocouples placed within the die 25 mm from the forming cavity. For the CSPF process, blanks sheared to 1250 mm × 1030 mm were loaded between the die halves and a clamping force was applied to seal the forming cavity. Gas pressure was then introduced into the lower die half forcing the sheet into the upper forming cavity. Blanks for TSGF were also sheared to 1250 mm × 1030 mm. During the first forming stage of TSGF, the material was forced into an engineered pre-form cavity, which was followed by a reverse of gas pressure during the second stage that formed the final part cavity. The blank size used for the HDMP process was 1250 mm × 980 mm. The HDMP process began by placing the sheet onto the blank holder, which was supported by a movable cushion system. The upper die was lowered until it contacted the sheet. The upper platen continued moving lower as the sheet was formed over the punch. As in a normal stamping die, the amount of material flow into the cavity can be controlled by the blank holder force. After the upper die reached the lower die the press force was increased to seal the die and gas pressure introduced into the lower die cavity to complete the part.

It is essential in automotive SPF applications that forming time be minimized. A novel analytical technique (Ref 3) was
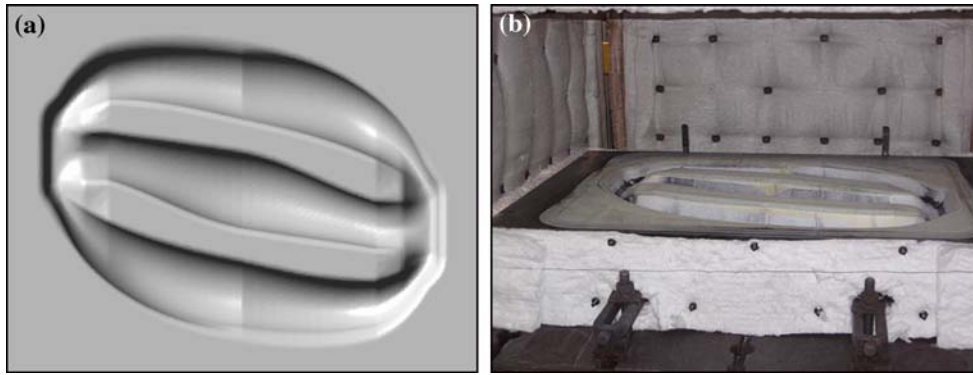
Fig. 5 (a) CAD model and (b) photograph of the pre-forming die half used in TSGF of the panel
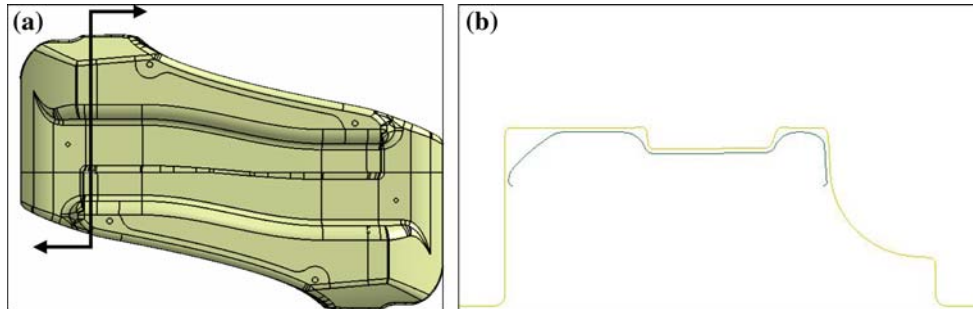

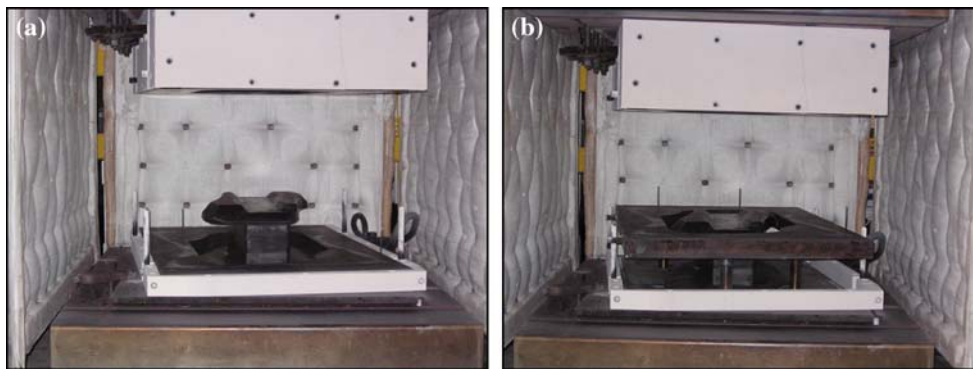**Fig. 6** Pre-forming design of HDMP die showing (a) the punch design and (b) one critical section

Fig. 7 Photograph of the HDMP die for the panel with the blank holder in the (a) down and (b) up positions

Table 1 Nominal chemical composition (wt.%) of SPF5083 alloy

Material	Mg	Mn	Fe	Si	Cr	Cu	Ti	Al
SPF5083	4.8	0.53	0.23	0.08	0.08	0.07	0.03	Rest

Table 3 Nominal chemical composition (wt.%) of AZ31 alloy

Material	Al	Ca	Cu	Fe	Mn	Zn	Mg
AZ31	2.8	0.02	0.03	0.002	0.43	1.1	Rest

Table 2 Nominal chemical composition (wt.%) of AA5182 alloy

Material	Mg	Mn	Fe	Si	Al
AA5182	4.6	0.26	0.22	0.1	Rest

introduced which combines the FEA predicted constant strain rate pressure history with experimental forming trials to establish an optimized pressure cycle. Gas pressure curves predicted with simulation for all three SPF processes were programmed into the press control software. The gas management system was able to control pressure within ±2% of the target pressure.

6. Results and Discussion

6.1 Development of Gas Pressure Cycles

SPF5083 panels were completely formed into the die cavity using the CSPF process with a maximum strain rate of 4×10^{-3} s^{-1}. The pressure cycle and strain rate profile determined from FEA that was applied in CSPF are shown in Fig. 8. The dashed line represents the target strain rate and the solid line is the gas pressure. A formed panel completed with this cycle is shown in Fig. 9. The two troughs on either side of the panel were designed to suppress wrinkling that could occur in the two-stage process. Attempts to increase the strain rate to decrease the forming time below 400 s resulted in failure at the bottom radii.

A maximum strain rate of 5×10^{-3} s^{-1} was achieved with the TSGF process. The forming cycle and strain rate profile applied in TSGF are shown in Fig. 10. Photographs of the side and top of pre-formed panels are shown in Fig. 11. The fastest forming cycle achieved for TSFG process was over 700 s. This was the result of a having radii that were too small in the pre-form.
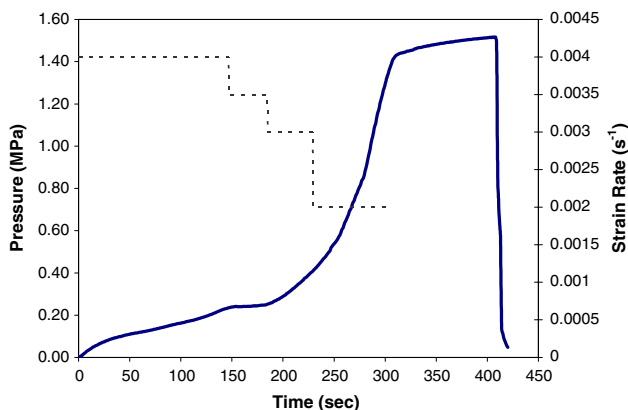
These radii caused a local thinning or defect which then resulted in a split during final forming at faster strain rates. TSGF is believed to have the potential to reduce the forming time to less than 300 s with the proper pre-form design. Note that even with very low strain rate and long cycle time, it was not possible to form parts using the CSPF or TSGF process using the lower cost AA5182 aluminum sheet or AZ31 magnesium sheet.

SPF5083, AA5182, and AZ31 panels were all completely formed into the die cavity using the HDMP process. Due to the deep draw of this design, the panel did not require extensive gas pressure forming. Additionally, since the pre-form is mostly a drawing operation the panels experienced minimal thinning in the first stage of forming. This allowed for the use of very high
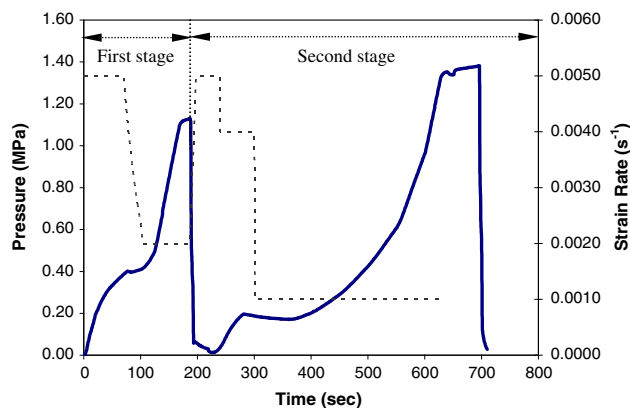

Fig. 10 Gas pressure forming cycle with a maximum strain rate of 5×10^{-3} s^{-1} predicted with LS-DYNA for the TSGF process

Fig. 8 Gas pressure forming cycle with a maximum strain rate of 4×10^{-3} s^{-1} predicted with LS-DYNA for the CSPF process

Fig. 9 A photograph of a fully formed panel using the CSPF process
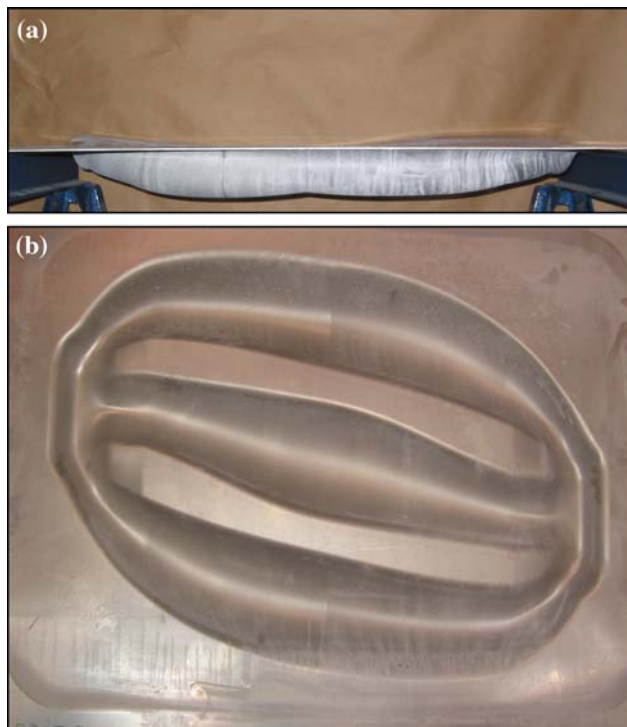

Fig. 11 Photographs of the pre-formed panel from the TSGF process showing the (a) side view and (b) top view

strain rates in the second stage of forming. Hence, in this present work, the gas pressure forming cycle applied in the second forming stage was designed to form the panel as quickly as possible with the available equipment. The gas pressure forming cycle used in these trials is shown in Fig. 12. Examples of fully formed SPF5083, AA5182, and AZ31 using the HDMP process are shown in Fig. 13. Note the gas forming cycles of the parts were accomplished in approximately 140 s.

6.2 Process Comparison

Cycle time is an important factor in determining overall cost for the production of automotive products. Gas pressure time for the forming of this panel for three different alloys is shown
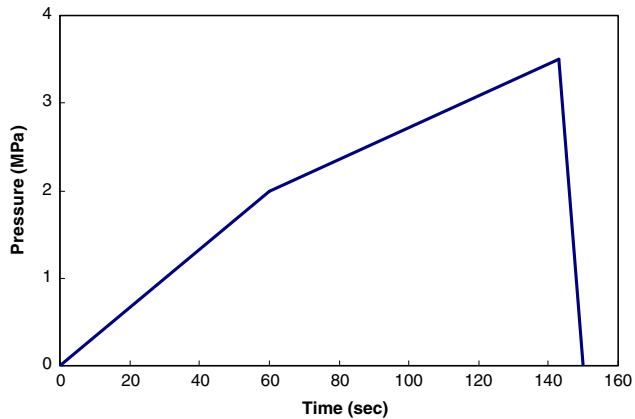
Fig. 12 Gas pressure forming cycle applied with the HDMP process

in Table 4. The application of HDMP can offer a significantly faster forming time of 140 s compared to 420 s with CSPF. The very long time of 700 s for the TSGF process was due to the excessively small radii on the pre-form. These radii created a defect on the part that would result in splitting during the subsequent gas pressure stage unless a very low forming rate was applied. As noted above, it may be possible to reduce this forming time to approximately 300 s by re-designing the pre-form shape.

Blank thickness was measured for three panels respective of each process at the locations identified in Fig. 14 of the formed part. Thickness was measured with an ultrasonic thickness gage with a 3.5 mm diameter probe. On the basis of thickness measurements, the percent thinning was calculated and averaged respective of location. Figure 15 shows the experimental results for parts formed with CSPF, TSGF, and HDMP processes using SPF5083. It appears that with the HDMP process, maximum thinning is approximately 45%, as compared to 65% with CSPF for the same material and forming temperature.

Table 4 Forming times in seconds for three different alloy sheets

	SPF5083	AA5182	AZ31
CSPF	420	N/A	N/A
TSGF	700	N/A	N/A
HDMP	140	140	160

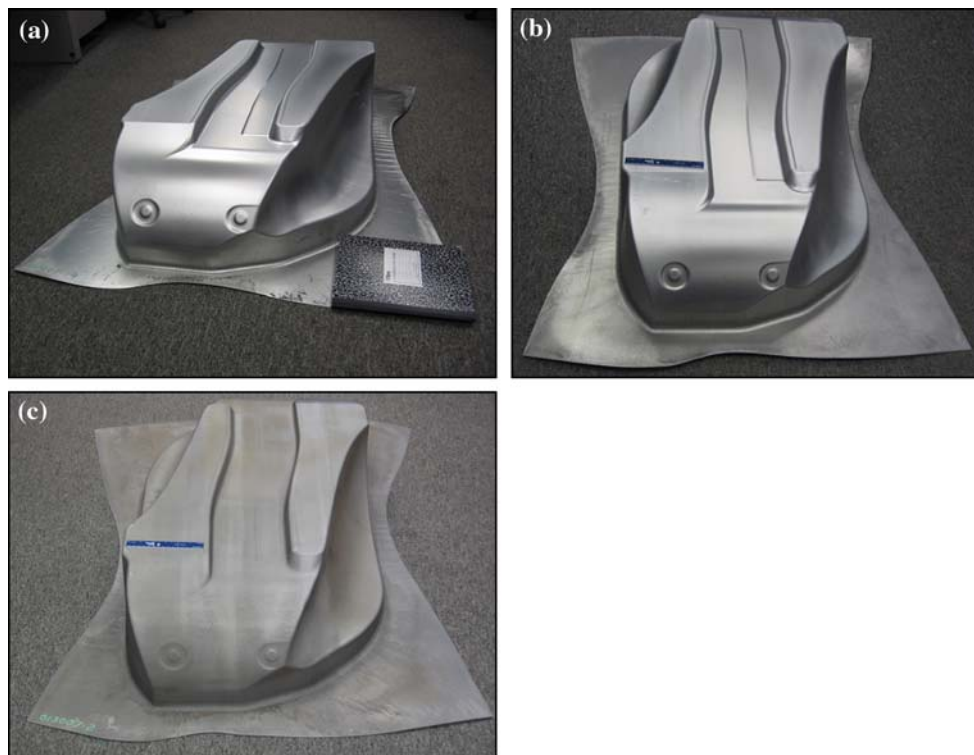Note the CSPF and TSGF processes required the use of the specially processed SPF5083 alloy.

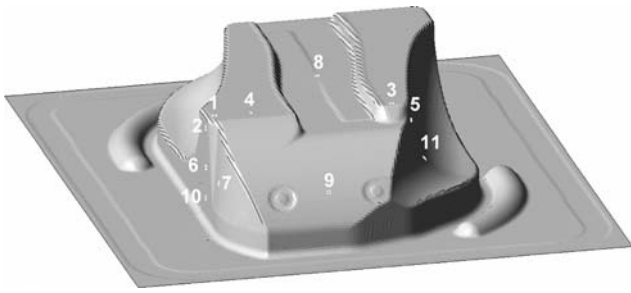**Fig. 13** Photographs of panels formed with the HDMP process for (a) SPF5083, (b) AA5182, and (c) AZ31

Fig. 14 Location of thickness measurements to compare forming experiments of different SPF process
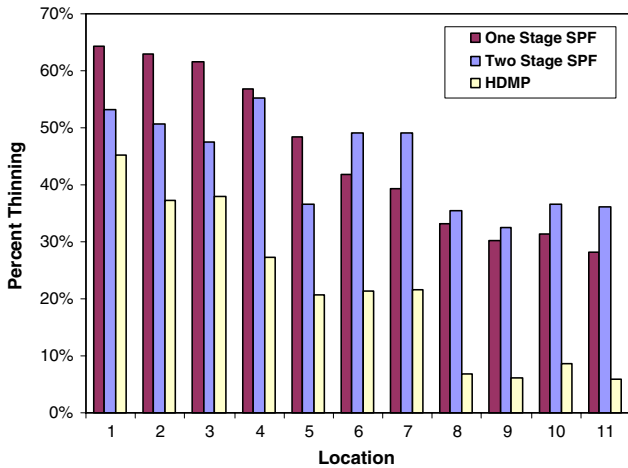

Fig. 15 Thinning percentage at the locations identified in Fig. 14 for different SPF processes. Forming trials were all conducted at 475 °C with SPF5083 alloy

Fig. 16 Thinning percentage at the locations identified in Fig. 14 of HDMP forming trials on three different alloys at lower temperatures

Fig. 17 Schematic representation of the part showing the three areas that were studied with optical microscopy

While the HDMP process resulted in significantly improved thinning behavior at 475 °C, forming trials at lower temperatures showed even superior thinning behavior for all three alloys tested. The percent thinning at the locations identified in Fig. 14 using HDMP with commercially available AA5182 and AZ31 alloys as well as SPF5083 at lower temperature is shown in Fig. 16. Note that the maximum thinning in SPF5083 decreased from approximately 45% to 35% by lowering the temperature to 426 °C. Additionally, forming trials with the lower-cost alloy AA5182 showed similar thinning characteristics at under 400 °C. This is a significant result since forming at lower temperature is often preferred since it facilitates material handling and dimensional stability.

6.3 Microstructural Analysis

To better understand the effect these forming processes had on the material, a microstructural analysis was conducted. Samples were extracted from the formed parts at two locations (noted in Fig. 17) and investigated with an optical microscope. The grain structure of parts formed with the HDMP process at two forming temperatures of 410 °C and 475 °C were investigated. As shown in Fig. 18 and 19 parts formed at 410 °C with both the SPF5083 and AA5182 alloys do not contain cavitation in sections A or B, which is often observed in parts formed with CSPF (Ref 7). The absence of cavitation in the HDMP parts is believed to be a result of the differences in the
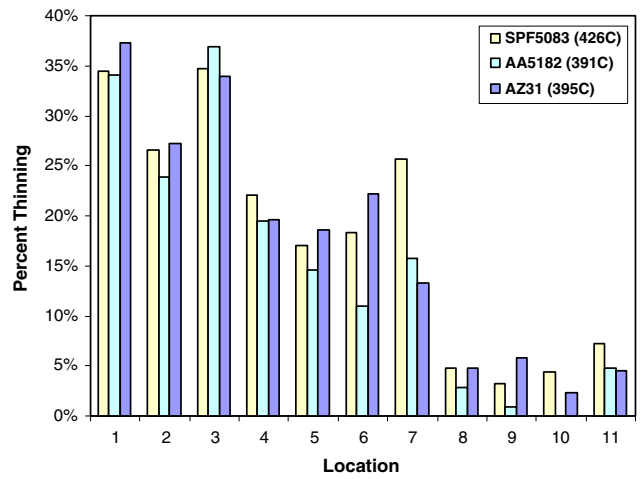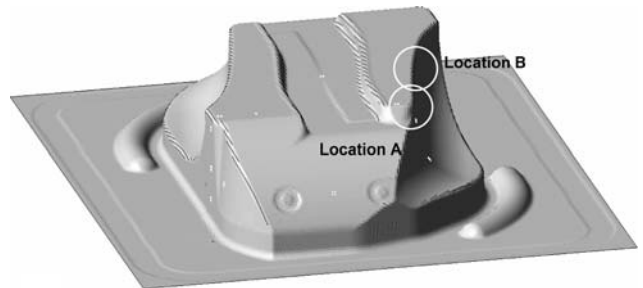
strain level and strain rate. The HDMP process imparts lower strain levels in the material and forming is performed at significantly faster rates. Cavitation does not occur in these alloys until a certain threshold strain is reached (Ref 7). In the case of HDMP, the strain levels are well below this threshold. Additionally, it is believed that a faster forming time results in the deformation being controlled by dislocation processes rather than grain boundary sliding which, in turn, changes the failure mechanism from internal cavitation to external necking (Ref 8).

This same result can also be observed from micrographs of parts formed at 475 °C using HDMP, as shown in Fig. 20 and 21. The grain size of each material was relatively unchanged from the forming process staying at approximately 10 μm and 50 μm for the SPF5083 and AA5182 alloys, respectively. Given the forming results found in this work, it appears the HDMP process is not dependent on having a fine grain size and can tolerate the coarser grain size found in commodity-grade alloys.

6.4 Influence of Temperature

As noted in Fig. 15 and 16, the final thickness distribution can be improved with the HDMP process by decreasing the forming temperature from those that are typical of CSPF. To further investigate the influence of temperature on HDMP,
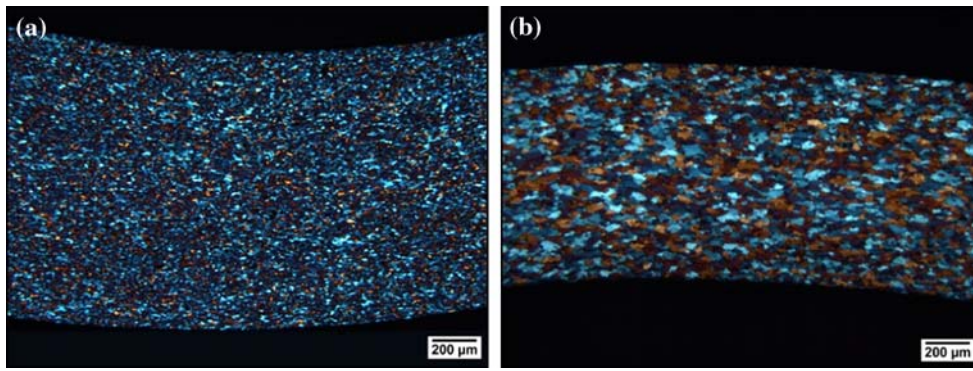
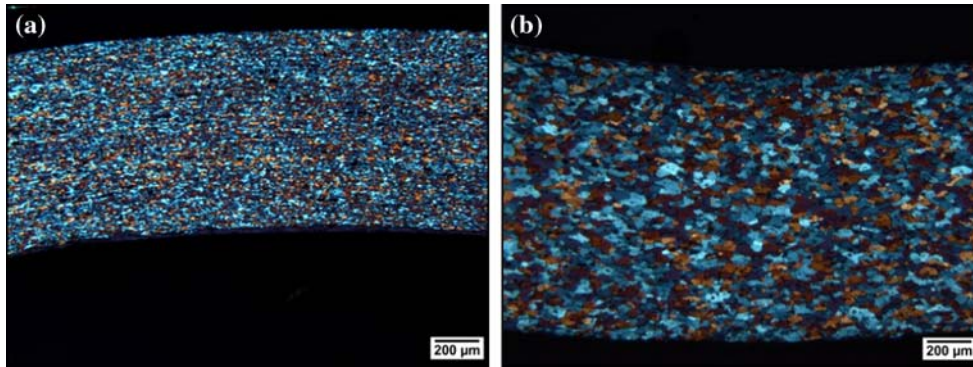**Fig. 18** Micrographs from section A of parts formed at 410 °C for (a) SPF 5083 and (b) AA5182 using the HDMP process

Fig. 19 Micrographs from section B of parts formed at 410 °C for (a) SPF 5083 and (b) AA5182 using the HDMP process
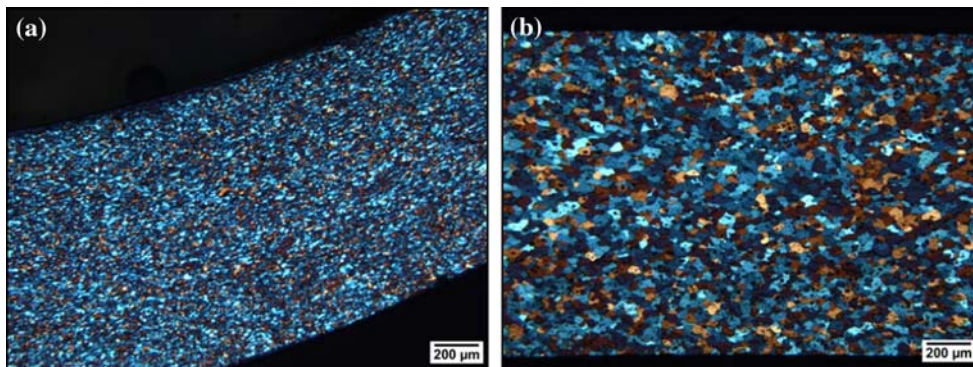

Fig. 20 Micrographs from section A of parts formed at 475 °C for (a) SPF 5083 and (b) AA5182 using the HDMP process
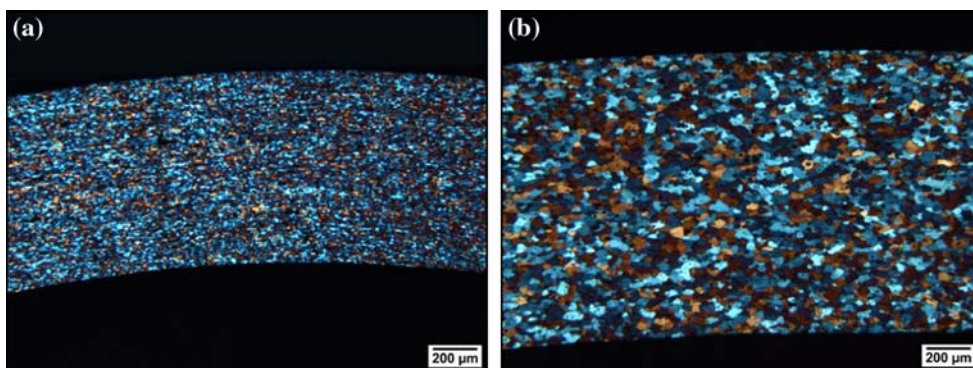

Fig. 21 Micrographs from section B of parts formed at 475 °C for (a) SPF 5083 and (b) 5182 using the HDMP process

forming trials were carried out while allowing the tool temperature to decrease. All panels were fully formed and a large forming window with respect to temperature was demonstrated: 426-475 °C for SPF5083, 391-470 °C for AA5182, and 395-420 °C for AZ31. Since, all of the panels were successfully formed in these trials, these results do not capture the absolute forming limits with respect to temperature but rather demonstrate the robustness of the process. Further trials will be needed over a wider range of temperatures to determine the actual forming window.

Similar to before, part thickness was measured at the locations noted in Fig. 14 with an ultrasonic thickness gage and the percent thinning cal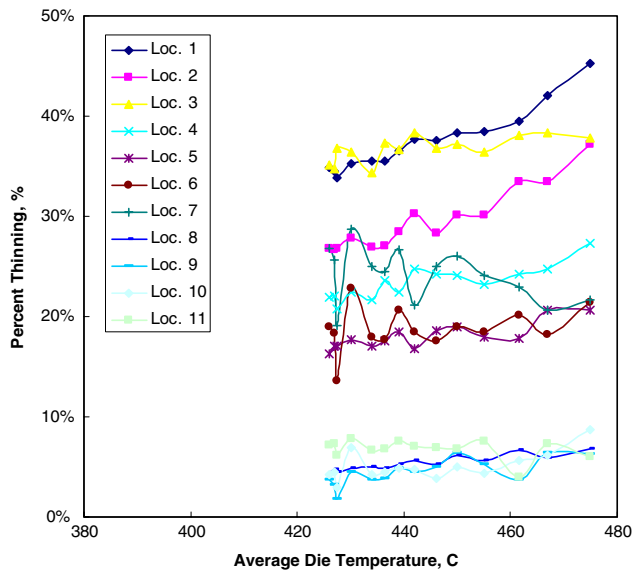culated. The relationship of percent thinning on SPF5083 and AA5182 with temperature is shown in Fig. 22 and 23, respectively. For both SPF5083 and AA5182, percent thinning generally decreases with lower temperatures. As noted above the maximum thinning of SPF5083 improves from 45% at 475 °C to 35% at 426 °C. This trend can be explained by measuring the material draw-in from these same panels. This was performed in two locations as noted in Fig. 24.

The value of L1 is plotted as a function of forming temperature in Fig. 25 for both the SPF5083 and AA5182
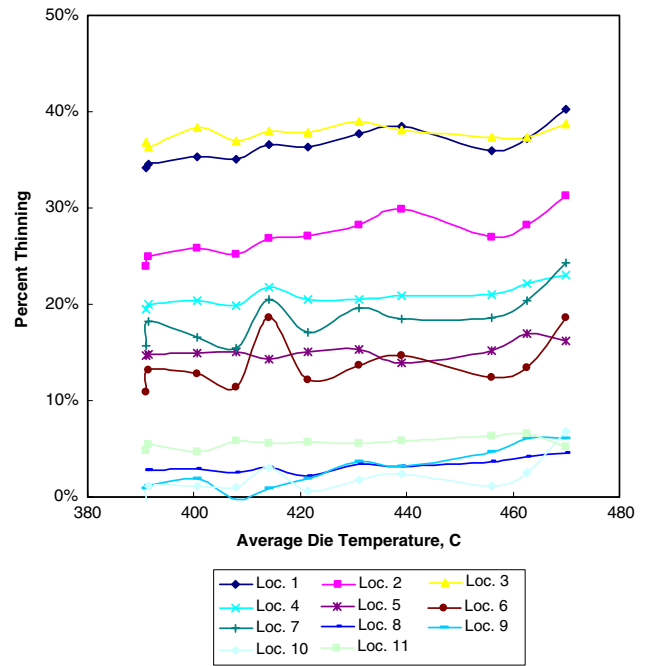

Fig. 22 Experimental percent thinning at the locations identified in Fig. 14 for HDMP plotted as a function of temperature for SPF5083

Fig. 23 Experimental percent thinning at the locations identified in Fig. 14 for HDMP plotted as a function of temperature for AA5182
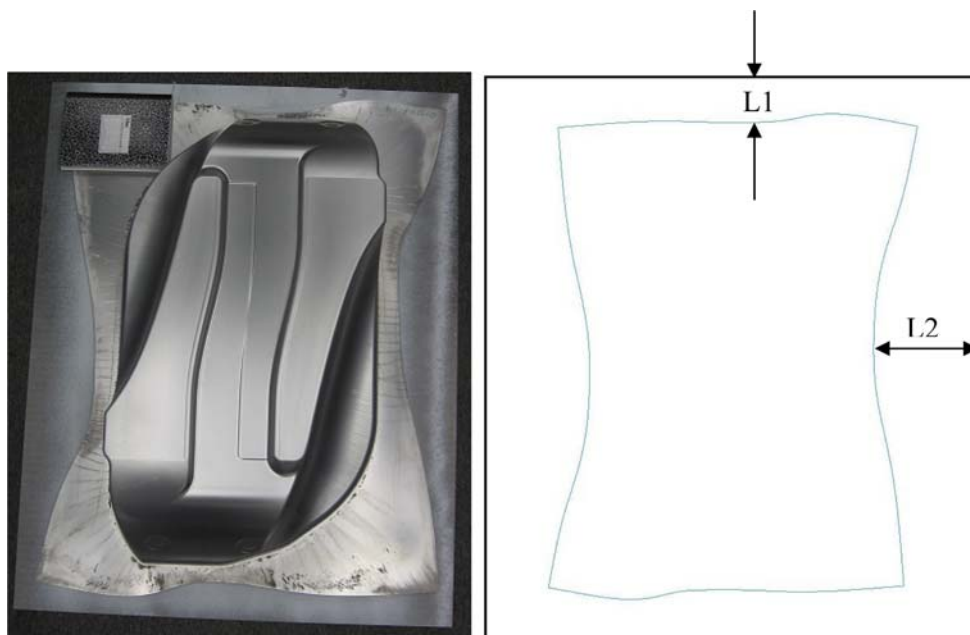

Fig. 24 Location of material draw-in measurements to compare forming experiments under different temperatures
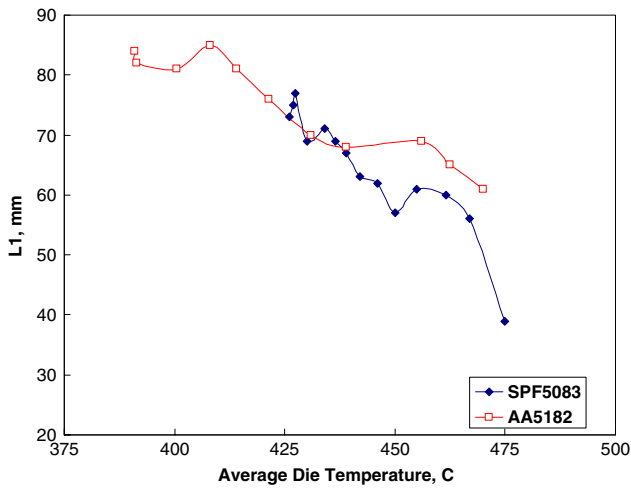
Fig. 25 Material draw-in as measured by L1 (Fig. 24) as a function of temperature

alloys. The material draw-in was found to decrease with increased temperature over the entire range of forming temperature. This is believed to be caused by the decrease in flow stress with increased temperature and therefore inability of the material to draw-in as much material. The difference in material draw-in is the reason for improved thickness with lower temperature as more material was drawn into the forming cavity during the pre-forming operation.

6.5 Correlation with Simulation

Figure 26 shows the experimental and simulation predicted thickness profiles for panels formed with CSPF, TSGF, and HDMP processes at the locations identified in Fig. 14. It can be seen from Fig. 26 that FEA can predict thickness distribution for all three processes with high accuracy. The maximum difference between FEA and experimental result are 3.2%, 3%, and 5% for CSPF, TSGF, and HDMP, respectively. Information on how the simulations were performed can be found in Ref 9, 10.

7. Summary and Conclusions

The HDMP technology which combines hot stamping with SPF was found to offer a superior thickness profile and faster forming cycle than what could be achieved with either the conventional single stage or two stage forming cycle. Additionally, the HDMP process proved to be a robust process with a wide temperature window and allowed for the use of lower-cost, non-spf aluminum and magnesium sheet alloys. Analysis of the post-form microstructure indicated that there was no cavitation in panels formed with the HDMP process and that material with a coarse grain structure could be successfully formed. Specific conclusions include:

- HDMP process achieved a gas pressure forming time of 140 s as compared to 420 s with CSPF. Faster times may be possible with improved equipment.
- Successful forming trials were conducted on commercial grade AA5182 and AZ31 alloys with similar thinning pro-
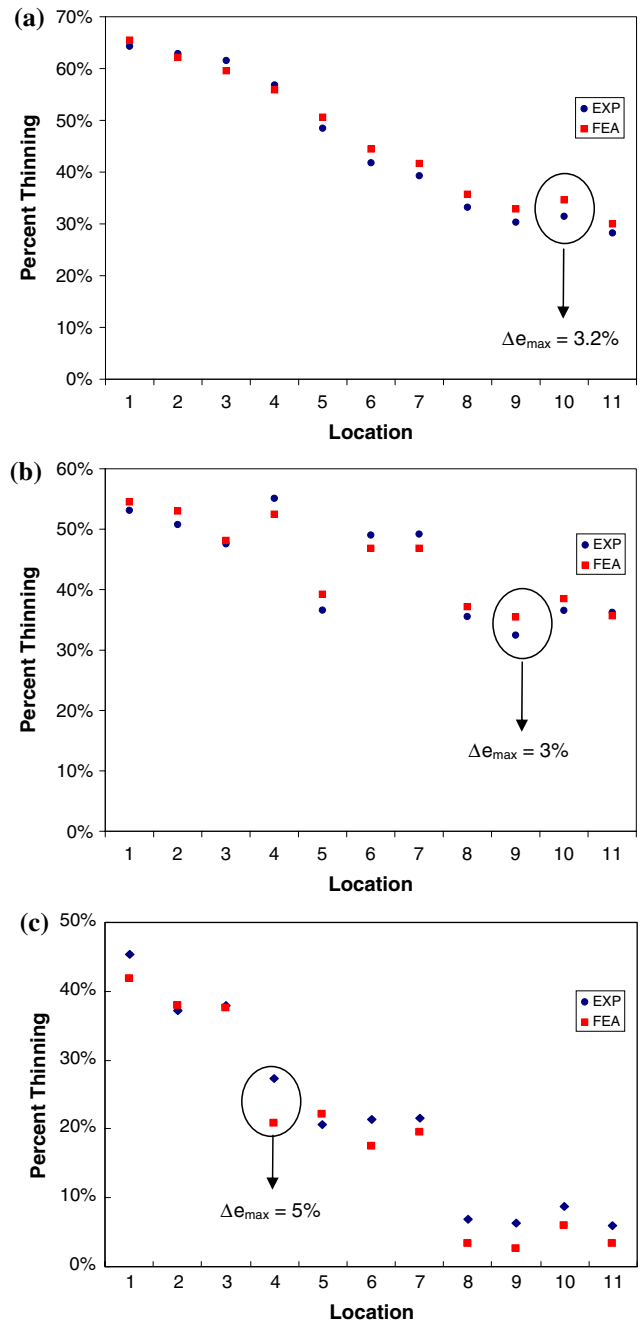

Fig. 26 Experimentally measured and FEA predicted thickness at the locations identified in Fig. 14 for (a) CSPF, (b) TSGF, and (c) HDMP processes

files and forming times to what was achieved with SPF5083.

- Material thinning was reduced in SPF5083 from a maximum of 65% to approximately 35% with the use of HDMP. Similar thinning results were found for the lower-cost A5182 and AZ31 alloys with the HDMP process.
- Successful parts were formed over a wide range of temperatures (426-475 °C for SPF5083, 391-470 °C for AA5182, and 395-420 °C for AZ31) indicating a robust process with respect to temperature.
- There was no evidence of cavitation in any of the parts formed with the HDMP process.

Acknowledgments

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