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Cold and Warm Hydroforming of AA754-O Sheet: FE Simulations and Experiments

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Abstract. The sheet hydroforming with punch (SHF-P) process offers great potential for low and medium volume production, especially for forming: (1) lightweight sheet materials such as aluminum (Al) and magnesium (Mg) alloys and (2) thin gage high strength steels (HSS). Mg and Al alloys are being increasingly considered for automotive applications, primarily due to their lightweight and high strength-to-weight ratios. However, there is limited experience-based knowledge of process parameter selection and tool design for SHF-P of these materials. Thus, there is a need for a fundamental understanding of the influence of process parameters on part quality. This paper summarizes analyses of the SHF-P process of AA5754-O sheet using finite element (FE) simulations. FE simulations and preliminary experiments of SHF-P were conducted to determine the process parameters (blank holder force versus punch stroke and pot pressure versus stroke) to form a challenging shape (a cylindrical cup with a reverse bulge) successfully at room and elevated temperature (~150°C). The material properties of the sheet material were obtained from tensile tests at room temperature up to 260°C as presented by [1]. The FE model was established using PAMSTAMP 2G, Version 2009. SHF-P experiments were conducted in order to (i) evaluate the formability of the part at room and elevated temperatures and (ii) validate FE simulation results. This study shows that the SHF-P at elevated temperature can form a cup with larger cup height and better reverse bulge profile than SHF-P at room temperature. Moreover, the FE predictions of part profiles and thinning distributions matched reasonably well with the experimental results.

Keywords: sheet hydroforming, AA5754-O aluminum sheet, counteracting pressure, optimal pressure profile, finite element simulation
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INTRODUCTION

Manufacturing technology development of materials and processes for automotive body and structural applications has been focused on mass reduction to improve vehicle fuel economy and emissions. While advanced high strength steels provide significant opportunity to optimize mass with performance for the passenger compartment structure, lighter weight materials such as aluminum (Al) and magnesium (Mg) offer potential for significant mass reduction of body and closure panels. For example, it was reported that a 10% weight reduction could improve the fuel efficiency by 6-8% for an average automobile [2]. Krajewski et al. described opportunities for implementing wrought, cast and extruded Al and Mg materials throughout the automobile [3]. However, fabrication methods with such wrought materials can be challenging because they are difficult to form into complex shapes at room temperature. Since the deformation behavior of some Al sheet alloys is greatly enhanced at elevated temperatures of 150-300°C [1], development of warm forming technologies for Al and Mg sheet alloys could enable production of complex panels requiring deep draws. Warm stamping and warm hydroforming are two such processes that have received considerable attention recently [4, 5].

For the sheet hydroforming with punch (SHF-P) forming method, a sheet blank is deep drawn against a counter pressure from compressed fluid inside the pot, as presented in **FIGURE 1**, rather than against a female die as in conventional stamping operations. The medium in the pressure pot can be either “passive” (pressure generated due to incompressibility of the medium during forward stroke of the punch) or "active" (pressure generated by an external pump) as defined by [6].

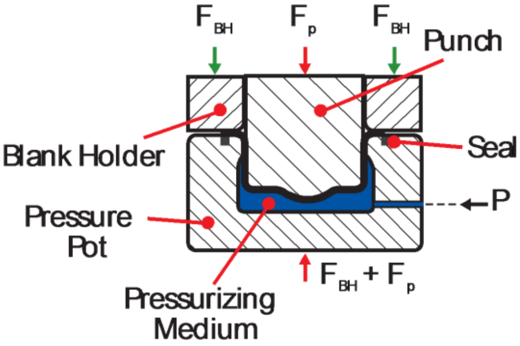


FIGURE 1. Schematic illustration of the SHF-P process [6]

For the warm hydroforming method, the sheet and the flange portion of the die and the blank holder are heated to the required temperature. The pressurizing fluid may be maintained at slightly higher than room temperature, while the punch is cooled. During the process, the lower temperature of the punch cools the portion of the sheet that is in contact with the punch and increases its load carrying capacity. Thus, failure caused by excessive thinning is postponed and the process yields a higher limiting draw ratio (LDR) than those obtained from deep drawing at room temperature [4, 5]

The most common defects encountered during the SHF-P process are wrinkling, excessive thinning (leading to fracture) and leaking of the pressurized fluid during forming. Conventionally, the process parameters are estimated by performing trial and error experiments which requires considerable time and effort. Therefore, the present research focuses on the use of finite element (FE) simulations along with physical experiments to estimate the optimum blank holder force (BHF) vs. punch stroke and optimum pressure vs. punch stroke that is needed to form a part successfully. This preliminary study assumes isothermal conditions in the analysis of SHF-P at elevated temperatures (meaning all tooling components, blank and fluid were heated to approximately the same temperature). The benefit of a cooled punch was not investigated in this study.

OBJECTIVE / APPROACH

The objective of this study was to improve the hydroforming process of aluminum and magnesium alloys using FE simulations and validated by experimentation. More specifically, the objective was to establish an efficient method for estimating the process parameters (BHF, pot pressure, punch velocity) that are used for room and elevated temperature SHF-P processes to produce defect-free parts. The following tasks were included in the approach to determine the process parameters:

1) Fluid pressure and temperature control systems of the machine setup were evaluated for accuracy and sensitivity to control pressure and temperature during a forming operation.

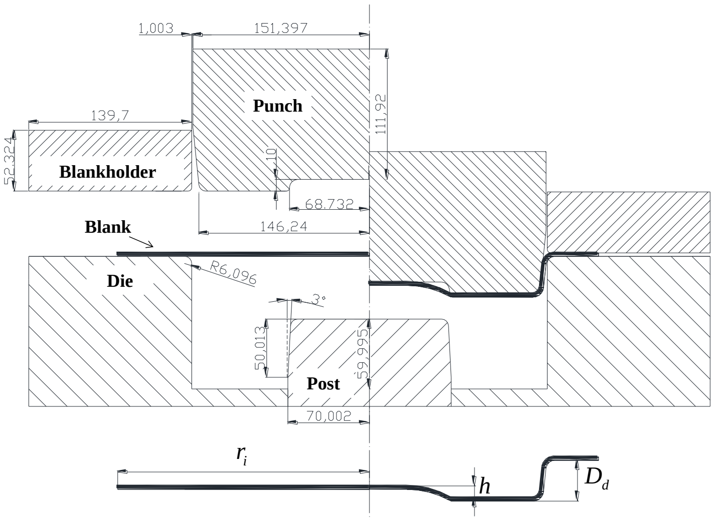
2) SHF-P experiments were conducted at room and elevated temperatures.

3) Formed samples were measured using a coordinate measuring machine (CMM) and height gauge measurement devices.

4) A FE model was created to determine the effects of various SHF-P process parameters and validate replacing the experimental trial and error with simulation.

EXPERIMENTAL APPARATUS

The schematic of the tooling is presented in **FIGURE 2**. The lower die consisted of three main components including the pressure pot, lower post (fixed in the center) and blank holder. The upper die consisted of the punch and the spring setup which allowed the punch to travel to a maximum stroke of 1.5 in (38 mm). The purpose of the lower post was to create a reverse bulge at the center of the deformed part when forming a part by conventional deep drawing without using fluid pressure. However, necessary modifications of the deep drawing tooling restricted the travel distance of the punch. In these SHF-P tests, the lower post did not touch the sheet and the fluid pressure can be considered as the only active force that forms the reverse bulge into the center recess of the punch.



(a)
Initial setup

(b)
After Deformation

FIGURE 2. Schematic of the tooling for SHF-P experiments: (a) initial setup (b) after deformation, where r_i = initial blank radius, D_d = draw depth and h = bulge height.

A Mokon heating system was used to control the forming fluid temperature. With the fill and vent valves open, fluid will circulate through the tool. The system includes a reservoir that maintains fluid at temperature and available for filling and draining the tool cavity through the fill and vent valves. Dynalene 600, a synthetic oil, was used as the fluid for building up forming pressure in the pot cavity.

Prior to forming tests at room and elevated temperatures, preliminary FE simulations were conducted to establish initial test parameters (BHF, punch velocity, and pot pressure) that could be used as experimental inputs. The sheet material was AA5754-O with an initial diameter, d_i, and thickness, t_i, of 17 in (432 mm) and 0.039 in (1.0 mm), respectively. Table 1 lists the input parameters for the room temperature experiments.

TABLE 1. Input parameters for SHF-P tests at room temperature (punch velocity=0.075 in/sec)

Sample #	BHF (kip)	Pot Pressure (psi)	Punch stroke (inch)
5	5.6	300	1.35
6	5.6	300	1.13

In the preliminary FE simulations of the room temperature SHF-P process, the pot pressure was maintained at approximately 300 psi (2.07 MPa) for various BHF of 5.6, 11.25 and 33.8 kip (25, 50 and 150 kN). With the downward movement of the punch, the punch displaced oil causing an increase in counter pressure. As this pressure approached the set limit of 300 psi (2.07 MPa), the relief valve cycled to maintain a steady pot pressure.

In the case of elevated temperature deformation, the maximum pot pressure input for the relief valve was set to limiting pressure levels as listed in Table 2. Initially, a pot pressure of 300 psi (2.07 MPa) and BHF of 5.6 kip (25 kN) were used similar to room temperature SHF-P, but the part consistently failed around the punch corner region. Therefore, new process conditions were used by applying a lower BHF, around 1 kip (4.45 kN), and increasing pot pressures.

A set of samples were formed at a constant BHF and draw depth of 0.56 in (14 mm), but with variable pressure limits of 500, 1000 and 2000 psi (3.4, 6.9 and 13.8 MPa), to study the effect of forming pressure on the part shape.

For the pressure limit of 2000 psi (13.8 MPa), the sample parts were further drawn to depths of 0.7, 1.0 and 1.5 in (17.8, 25.4 and 38.1 mm), to measure the amount draw-in that occurred during forming.

TABLE 2. Input parameters used to conduct warm SHF-P test at elevated temperature of about 150°C (experimental test with maximum cycle time = 20 sec)

Sample #	Pot Pressure (psi)	BHF (kip)	Punch Stroke (inch)
21	500	1	0.56
27	1000	1	0.56
28	2000	1	0.56
29	2000	1	0.70
30	2000	1	1.00
33	2000	1	1.50

EXPERIMENTAL RESULTS

Table 3 compares input (entered at the control panel) and output values (BHF and pot pressure measured from sensors inside the press machine) and the measured draw depth, D_d, of the formed part. Since the output values of BHF fluctuated throughout the punch stroke, an average value of BHF was calculated. Measured flange perimeter, F_f, draw depth, D_d, and the bulge height, h, are presented in Table 3.

TABLE 3. Comparison of experimental input to the output readings and measurements at room temperature (initial flange perimeter, f_i= 53.41 in)

EXPERIMENTAL INPUT				EXPERIMENTAL OUTPUT				
Sample #	BHF (kip)	Pot Pressure (psi)	Punch stroke (in)	BHF (kip)	Pot Pressure (psi)	Flange Perimeter, F_f (in)	Draw Depth, D_d (in)	Bulge Height, h (in)
5	5.6	300	1.35	6.78	304.7	49.1	1.349	0.353
6	5.6	300	1.13	6.81	307.5	50.1	1.083	0.333

Table 4 compares the input and output values (BHF and forming pressure) and the measured draw depths, D_d, of the samples formed at elevated temperature. The steady BHF output obtained from the experimental results is higher than the experimental input value. This may be because the BHF (clamp load) was very small relative to the press capacity. Also, this load was measured using pressure transducers, which are placed on either side of the actuator's piston and the cross sectional areas of the piston areas are then considered to calculate the load. Thus, it gave only approximation for measurement of a very small load. The comparison of output values of pot pressure for samples 21, 27, and 28 indicates that a maximum of 842.5 psi (5.8 MPa) was needed to draw this part to a depth of 0.56 in (14 mm). In order to draw the part to a depth of 1.5 in (38 mm), the required pot pressure increased to 1494 psi (10.3 MPa), keeping the BHF to the same value of 2.2 kip (9.8 kN).

TABLE 4. Comparison of experimental input and output readings and profile measurements, for SHF-P experiments at elevated temperature (Initial flange perimeter, Fi = 53.41 in)

EXPERIMENTAL INPUT				EXPERIMENTAL OUTPUT			
Sample #	BHF (kips)	Pot Pressure (psi)	Punch Stroke (inch)	BHF (kips)	Pot Pressure (psi)	Flange Perimeter, F_f (in)	Draw Depth, D_d (in)
21	1	500	0.56	2.19	595.3	52.3	0.578
27	1	1000	0.56	2.21	834.6	51.9	0.570
28	1	2000	0.56	2.21	842.5	52.1	0.573
29	1	2000	0.70	2.23	977.5	51.8	0.715
30	1	2000	1.00	2.19	1140.1	50.2	1.025
33	1	2000	1.50	2.22	1494.4	47.9	1.514

The temperature of the tooling (die, blank holder and punch) was controlled by two dual channel Watlow F4 temperature controllers using resistance heaters. The fourth Watlow channel was used to monitor the oil temperature with a thermocouple positioned inside the lower die. Thermal data was collected for each component of the tooling using thermocouples that were embedded in the tooling. Due to the constraints of the machine, it was very difficult to obtain isothermal conditions within a 10°C range. Results indicate that the temperatures of the blank holder, die and oil ranged from 127 to 140°C, while the punch temperature was measured to be 157°C.

NUMERICAL ANALYSIS

The part geometry was designed at General Motors as representative of a challenging feature to form with aluminum by conventional stamping. The AA5754-O sheet blank was 0.039 in (1 mm) in thickness *(t_i)* and 17 in (432 mm) in diameter (d_i). The FE model was created using PAMSTAMP 2G, Ver. 2009, which enabled input of the material model as a function of temperature and strain rate simultaneously. Only one quarter of the geometry was modeled since the tooling and part geometries were axisymmetric.

For all temperatures, the process was modeled using the Aquadraw Module in PAMPSTAMP 2G, which allows efficient control of pressure input in the tool cavity, based on compressed fluid volume and maximum pressure limit to be applied on the blank. To create a simplified model and replicate the elevated temperature deformation, an 'isothermal condition' was assumed. By approximation, the FE model was set up at 150°C (whereas temperature readings of tools and fluid ranged from 127 to 157°C).

The input parameters used during the simulation are summarized in Table 5. The major difference between simulation of this process at room and elevated temperature conditions is the input of material properties. As the material at elevated temperature is strain rate sensitive, the deformation speed at different regions of the blank in the simulation should take into account the influence of strain rate.

Abedrabbo et al. (2007) conducted tensile tests and applied the Fields and Backofen's material model (power law equation) to describe the stress-strain behavior of AA5754-O as show in Equation (1). Flow stress data was input as a function of strain, strain rate and temperature, in tabular format in PAMSTAMP 2G.

$$\overline{\sigma} = K\overline{\varepsilon}^{n}\dot{\overline{\varepsilon}}^{m} \qquad (1)$$

Where:

K = 503.7-0.592*T (for T = 25-93°C) and 641.3-1.829*T (for T = 93-260°C)
n = 0.3304 -0.000529*T (for T = 25-93°C) and 0.4048-0.001192*T (for T = 93-260°C)
m = 0.00118*exp(0.0161*T) (for T = 25-260°C)

TABLE 5. Input parameters for FE simulations of SHF-P.

Mechanical Properties	
Blank material	AA5754-O
Flow stress (obtained by tensile test)	(Abedrabbo et al. 2007)
Young's Modulus (E)	69 GPa
Poisson's ratio (ν)	0.3
R_0, R_{45}, R_{90}	1 (material assumed isotropic)
Interface Condition	
Friction coefficient μ (blank/ tools)	0.12
Mesh	
Element type	Shell (Belytschko-Tsay)
Object type	
Blank	Elastic, Plastic
Tools	Rigid
Sheet Hydroforming with Punch (SHF-P)	
Aquadraw	Activate
Bulk Modulus, K	50 GPa

Pot Pressure	Variable
BHF	Variable
Punch stroke	Variable
Punch Velocity	0.074 in/sec

COMPARISON OF FE PREDICTIONS WITH EXPERIMENTAL RESULTS

The results from room temperature FE simulations have been summarized below for Sample #5 (BHF = 6.8 kip, pot pressure = 304.7 psi and punch stroke = 1.35 in). The results compared in **FIGURE 3** indicate that the flange perimeter measurements, F_f from the experimental and FE predictions match very well. **FIGURE 4** presents the thickness distribution along the curvilinear length of the part. Note that the maximum thinning location occurred near the punch corner region (location #4) for the part formed at room temperature.

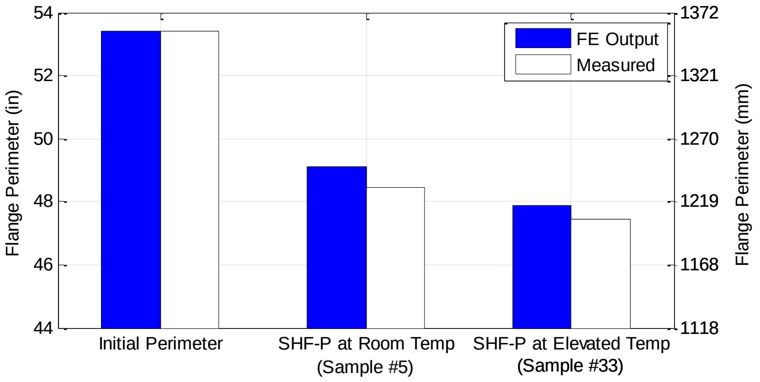


FIGURE 3. Comparison of flange perimeter measurement and prediction between initial blank and final part after SHF-P at room and elevated temperatures.

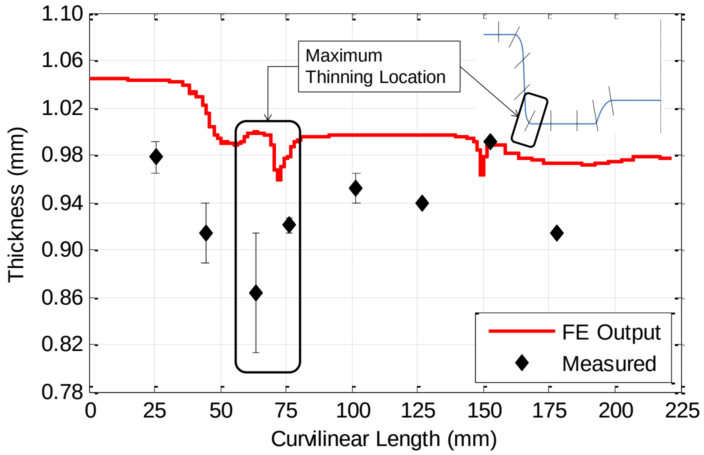


FIGURE 4. Thickness distribution along the curvilinear length for the part formed at room temperature (BHF = 6.81 kip, pot pressure = 304.7 psi)

Sample #33 (BHF= 1 kip (4.45 kN), pot pressure = 2000 psi (13.8 MPa) and punch stroke=1.5 in (38 mm)) was selected for FE analysis at elevated temperature. The results of SHF-P at the elevated temperature of 150°C are presented in Table 4. There was only a small difference (0.5%) in the values of the final flange perimeter determined by FE simulation and experimental measurement. The BHF prediction of the FE simulation for Sample #33 indicates some fluctuation, but the average value remains close to the experimental output. The FEA input of BHF force did not work in PAMSTAMP because forming pressure is balanced by blank holder only, but in reality the punch force adds to BHF to balance the forming pressure. So in simulation, the forming pressure caused the blank holder to open up. Therefore, input clamp/blank holder stroke (instead of BHF) that was recorded in ITC data file. In putting clamp stroke provided simulation that matched experiments.

Another set of tests were simulated to determine the effect of pot pressure on the formed part geometry. The formed samples are # 23, 27 and 28, for BHF ~2.2 kip (9.8 kN), cycle time = 20 sec, 0.56 in (14 mm) punch stroke and variable pressure limits of 500, 1000 and 2000 psi (3.4, 6.9 and 13.8 MPa). From Table 6, it can be inferred that with an increase in the input pot pressure limit, the maximum thinning along the part would increase. However, there is not a significant experimental difference in percent thinning between 1000 and 2000 psi (6.9 and 13.8 MPa), because the physical output for the maximum pressure only attained about 840 psi (5.8 MPa), regardless of the value input at the control panel. In order to form a part at elevated temperature (ET) for a draw depth (D_d) of 0.56 in (14 mm) and 2.2 kip (9.8 kN) BHF, a maximum of 592.5 psi (4.1 MPa) pot pressure should be used to achieve the least thinning percentage ~ 6.5%.

TABLE 6. Percent thinning affected by the applied pot pressure while keeping the other process parameters constant (BHF ≈ 2.2 kiPs, punch stroke = 0.56 in, cycle time = 20 sec, average temperature = 150°C)

Sample #	Set pot pressure (psi)	Max. thinning (%)	Max. thinning location	Max. output pot pressure (psi)
23	500	6.54	Reverse bulge region	592.5
27	1000	8.51	Reverse bulge region	834.6
28	2000	8.56	Reverse bulge region	842.5

FIGURE 5 is a comparison of the part profile measurement using the CMM and the FE results of SHF-P for sample #33. For the CMM measurement of the experimental sample, a significant bend in the reverse bulge region of the part was observed. This bend in the part may be due to springback and distortion from thermal contraction after part was removed from the press and cooled to room temperature.

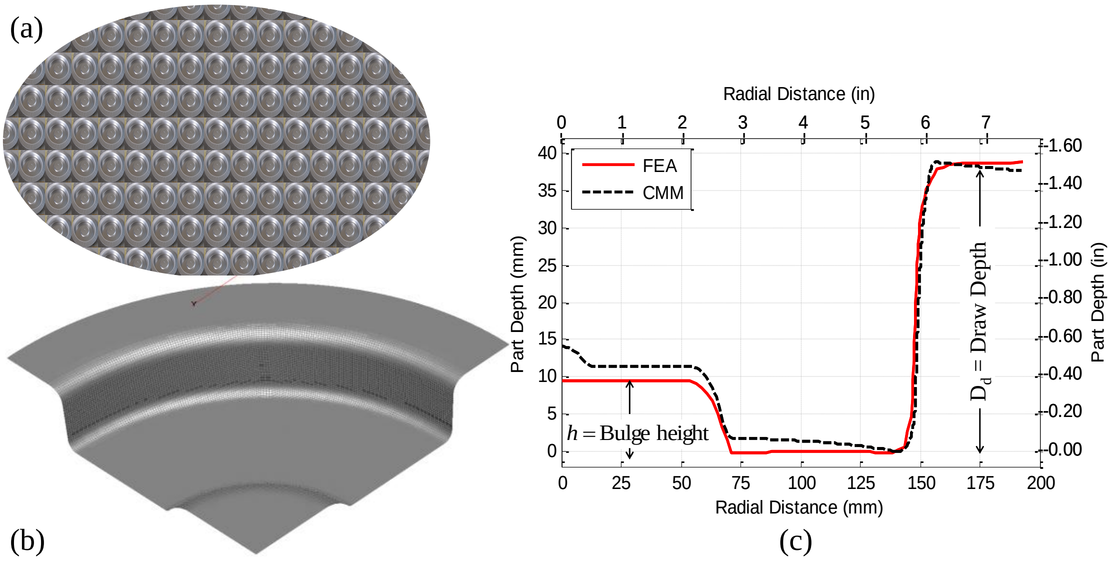


FIGURE 5. (a) experimental workpiece, (b) Pam-Stamp result of quarter model, (c) comparison part profile from FEM and experiment, for the SHF-P of Sample #33 (punch stroke = 1.50 in, average temperature = 150°C, pot pressure = 840 psi)

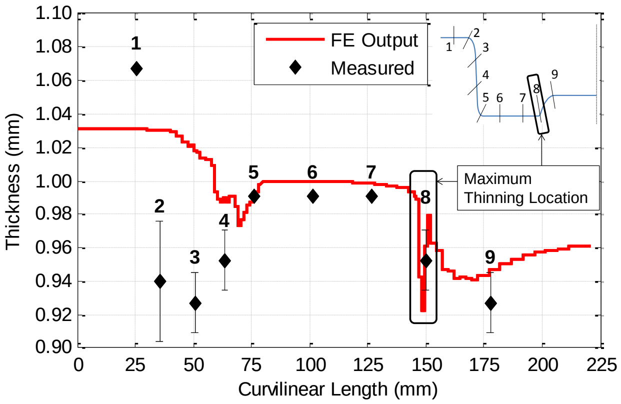


FIGURE 6. Thickness profile along the curvilinear length measured by the mechanical indicator and compared with FE results for Sample #33 (punch stroke = 1.50 in, average temperature = 150°C, pot pressure = 840 psi)

For comparison of the thickness profile generated from the FE simulations, the mechanical indicator (Mitutoyo) was used to measure thickness along the curvilinear length of the formed sample. **FIGURE 6** presents the comparison of the thickness profile of Sample #33 formed at elevated temperature. The thickness profile for the FE simulation matches fairly well with the measurements. FE results predict that maximum thinning occurred near the reverse bulge region (position 8) along the curvilinear length.

CONCLUSIONS

FE modeling of the SHF-P process at room and elevated temperatures with the assumption of isothermal conditions was completed using PAMSTAMP 2G Ver. 2009. Simulation results compared favorably with experimental measurements. The experimental values of the process parameters (i.e. fluid pressure) were input into the FE model to emulate similar conditions. The final flange perimeter (F_f) predictions for both room and elevated temperature were within ± 0.5% of the experimental results. For room temperature, the part profile prediction matched the experimental measurement, whereas for the elevated temperature case, there was some difference in the part profile in the reverse bulge region. This difference could be caused by artifacts of springback and thermal distortion as the part cooled to room temperature or by thermal gradients within the part during the forming process. The maximum thinning for the room temperature drawn part was predicted to occur near the punch corner region. For elevated temperature, however, the maximum thinning location occurred within the reverse bulge region of the part. Simulation of thickness strain or thinning distribution across a curvilinear length of the part matched reasonably well with the experimental measurements. This study also shows that the SHF-P at elevated temperature can form a cup with larger cup height and better reverse bulge profile than SHF-P at room temperature.

Since the tooling (blank holder, lower die, punch and fluid) temperatures during the actual forming process were not isothermal, ranging from 127 to 157°C, elevated temperature FE simulation was attempted using a non-isothermal model that considered heat transfer. In this non-isothermal model, the initial temperature conditions and the heat transfer coefficients were the required inputs of the FE model, but this exceeded the capability of the FE code. The current software used for this study did not allow modeling of the hydroforming process (using the Aquadraw module) and heat transfer simultaneously. There was also difficulty to define the heat transfer condition between the fluid and the blank under non-isothermal conditions. ESI Group (USA) is improving the capability of the PAMSTAMP code in order to model the warm SHF-P process.

Future research in the continuation of this study would include additional experimentation and FE analysis at higher forming temperatures (250°C) and warm forming of other materials (e.g. Mg alloys) using solid dies. Furthermore, non-isothermal conditions will be modeled to study the benefit of using a punch that is cooler than the remaining tooling environment to enhance warm forming of metal sheet.

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