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Pressure Prediction by Programme Logic Control Approach on Superplastic Forming in 7075 Al Alloy

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Abstract:

A widespread problem in a superplastic forming process is to obtain a uniform thickness distribution in multiple geometry components. Hence, nowadays, the variable pressure control approach has been implementing in order to obtain uniform thickness variation in complex profiles. This paper observed the outcome of various stages in the superplastic forming process for multistage hemispherical die cavity in a newly developed pressure prediction method. Superplastic behaviour such as forming pressure, forming temperature, forming time and thickness distribution are analysed and optimised all parameters in multi-stage profile by using a new pressure prediction approach. Experimentally and numerically evaluated the superplastic parameters and the values are obtained from finite element methods agrees well with the experimental results.

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INTRODUCTION

The superplastic forming technique is used to form a near-net shape in superplastic materials, with tremendous cost savings and weight reduction potential over conventional forming processes. The superplastic sheet material is usually formed into a fixed die cavity, shaped to the geometry of the desired part; using gaseous pressure in one single step bulge forming setup was designed and fabricated.

The superplastic forming process is an established technique for manufacturing enormous amounts of deformation under low strain rates and flow stresses. Olden days, they have been made in deep drawing, cup drawing and hot rolling [1- 2]. However, presently superplastic forming processes play an important role in industrial and aerospace applications. The superplastic forming characteristics and time duration in multi-shape components [3-7] range from a few minutes to a very few hours due to lower strain rates in the range of 10^{-5} to 10^{-2} s^{-1}.

The superplastic forming of Ti-6Al-4V alloy sheet in stepped rectangular in different conditions has been examined by [8]. They reported that forming pressure requirement was decreased with increasing die entry radius and Optimum pressure requirement decreases with increase in friction coefficient. The superplastic forming characteristic of AA 7075 Alloy is investigated by [9]. They are reported that maximum elongation of 219% obtained at an optimum temperature of 410 °C and strain rate sensitivity index value of 0.48.

Simulation with high-temperature bulge forming of 5083 aluminium sheet at different constant pressure levels by [10]. They have computed a new approach of time-varying pressure profile in order to maintain the maximum strain rate at the bulge dome pole within a specified range. The authors suggest that the constant pressure control process can lead to a smooth profile rather than stepwise variation in the pressure profile. In superplastic forming process are conducted at constant pressure control method to predict the pressure cycle in a 7075 Al alloy.

They evaluate optimum pressure in order to obtain a uniform thickness profile in hemispherical components [11]. The constant pressure control method to predict the pressure cycle by using theoretical and experimentally for the superplastic forming process in a 5083 Al alloy [12]. They determine optimum constant pressure in three-stage hemispherical complex components in order to obtain uniform thickness at different die entry regions.

In this paper, a combined process of superplastic forming and multistage (various die radii) were formed in an experimental process for dome shape. This process has not been cited much in the past literature. Experimental has been done with using constant pressure conditions of 0.4 MPa, 0.5 MPa, 0.6 MPa and variable pressure control method of Programme Logic Control (PLC) process under constant strain rate condition. The FEA simulation process has been made with the same constant pressure conditions, constrained algorithm, logarithmic algorithm and PLC method. The experimental and Finite Element Method (FEM) results have been compared with respect to forming height, pole thickness and thickness distribution.

MATERIAL SELECTION

In a superplastic forming process, currently, AA 7075 alloy material is mostly used in automobile and aerospace applications due to its more strength, excellent corrosion resistance, very low cost and fine - grain structure.

The chemical composition of superplastic forming material AA 7075 alloy as shown in Table **1**.

Table 1: Chemical Composition (Wt%) of AA 7075 Alloy

Fe	Cu	Mg	Mn	Cr	Zn	Al
0.4	1.2	2.1	0.5	0.22	5.1	Balance

The superplastic blow forming equation has been written as

$$\sigma = K\dot{\varepsilon}^{m} \quad (1)$$

Where "σ" is the flow stress, $\dot{\varepsilon}$ is the strain rate, "m" is the strain-rate sensitivity index of the flow stress and "K" is a material constant.

EXPERIMENTAL SETUP

The experimental setup consists of an argon gas, and a split type electric furnace. The forming die consists of the top (male) and bottom (female) parts, and a space is provided in the bottom part to hold the forming sheet. The bottom part of the die is a complex shape. The complex die assembly was placed inside the furnace, and the temperature of 410°C, was maintained by the temperature controller at the forming temperature. Figure **1a** and **b** represents the geometric model of female die and specimen and superplastic forming setup.

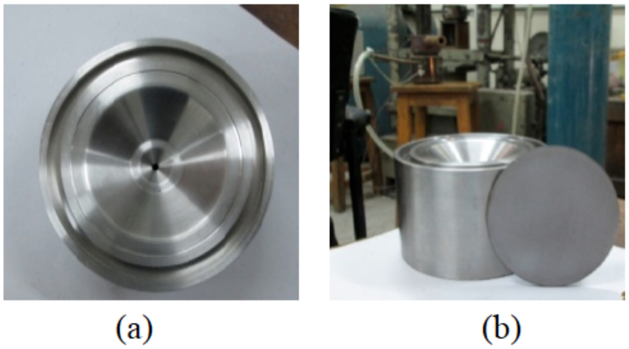

Figure 1: (**a**) & (**b**) Illustration of experimental die and experimental Setup in Superplastic forming process.

EXPERIMENTAL PROCEDURE

The AA 7075 alloy sheet with 32 mm diameter and thickness of 1.5 mm is heated at elevated temperatures in a closed die. The bottom die has two different die radius of 15 mm and 3 mm with a total depth of 18 mm and die entry radius 2 mm in stage one and 1 mm for stage two. Die opening radius is considered as 16 mm. The male and female die fabricated from stainless steel of 304 grades. A compression moulding press with a 200-ton capacity is used for clamping the die assembly in order to prevent the leakage of argon gas. It is well-known that the superplasticity can be induced in a stable ultrafine grain size material at a temperature greater than $0.4T_m$, where T_m is the melting point of the material. A circular band heater of capacity 1500W X 220V was used to heat the specimen to the selected temperature. AK type thermocouple was used to measure the heat of the die and PD type temperature controller was used to maintain the temperature of the die assembly at a set value. Superplastic forming was carried out at 0.4 MPa, 0.5 MPa, 0.6 MPa and a newly developed PLC approach. A pressure control valve was used to maintain constant pressure during forming. A spring-actuated needle was used to measure the pole height. Characteristics of forming time, variable controlled pressure cycle, formability height and instantaneous thickness were recorded. Figure **2** shows that, the final formed components of the two-stage hemispherical dome in the superplastic forming process.

The experimental setup for the SPF process, with PLC processing circuit, is shown in Figure **3**. The setup consists of three major parts, viz., the PLC processing circuit, the forming die and the pressure regulator. In this experimental setup, the PLC circuit consists of Program Interface Circuit (PIC) with a microcontroller. It is simultaneous access of program, highly data memory technology and integrates a number of the component of a microprocessor system on to single-chip of PIC 16F877. It is inbuilt of CPU, memory, peripherals and other devices such as s timer module to allow the microcontroller to perform tasks for certain time periods, a serial I/O port to allow data to flow between the controller and program interface circuit and an analogue/digital inverter to allow the microcontroller to accept analogue input data for processing.

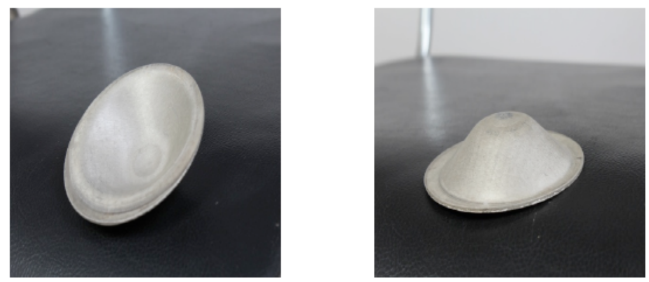

Figure 2: Illustration of formed components of SPF process.

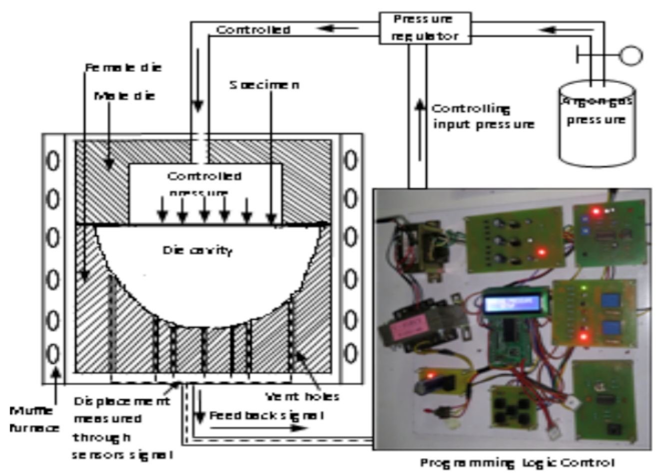

Figure 3: Illustration of Experimental setup for PLC control in SPF process.

The PLC programme starts to function, once the optimum temperature of 510°C was reached. The set temperature (optimum experimental temperature) values are received from the temperature control unit, the PLC programme, start to open the pressure control valve very slowly and controlling pressure passes on the surface of the blank. Now blank start to blow forming, the PLC circuit sensors measure the displacement of blank and send feedback to PLC programme. The PLC sensors are measured for every small positive incremental displacement value at a different place of the die surface. The input pressure values are varying with respect to the movement of the blank into the die cavity. The PLC coding was developed based on the die profile, that is, to release the high quantity of pressure, when the blank move free regions and reduced the pressure values when the blank move towards die corner and other forming regions in order to obtain a smooth profile. The pressure values are determined by the researcher, based on the die dimensions and fed into the input values through the PLC input key before starting the programme. The input values are also changed during the progress because of the slowly filling of blank in the die corner and other forming regions thereby eliminating the defects because of otherwise fast filling.

The experimental process was started with controlling pressure during forming. The pressure was regulated for every incremental displacement (x) of 0.1 mm during forming of the sheet in the die cavity. Each increment step, the movement was sensed by the sensor and send feedback to the program. The x value of 0.1 mm displacement is further reduced to 0.05 mm, if the blank move towards corner regions. The process running until the blank reach all regions. The displacement value of 0.1 mm and 0.05 mm are variable input parameters and change to an appropriate numerical value (with a lower value of decimal point) before starting the program.

FINITE ELEMENT ANALYSIS

The superplastic forming process was analysed by the Finite element modelling software using Abaqus. A few basic assumptions [17] have been made during FEA simulation of the superplastic forming process. The material is assumed to be isotropic and incompressible flow. The diaphragm is rigidly clamped at the periphery of the die. The material does not work-harden and the elastic limit is so low that it may be neglected. The specimen thickness is very small when compared with the die radius, so that bending and shearing effects are negligible. During FEA simulation process, the superplastic materials are to satisfy the relationship between the flow stress and strain rate which is expressed by $\sigma = K\dot{\varepsilon}^{m}$. Cavitation behaviour is not considered for this FEA simulation process. The procedure type was assumed to be visco-elastic type [13-14] and the actual experimental time period was considered for analysis.

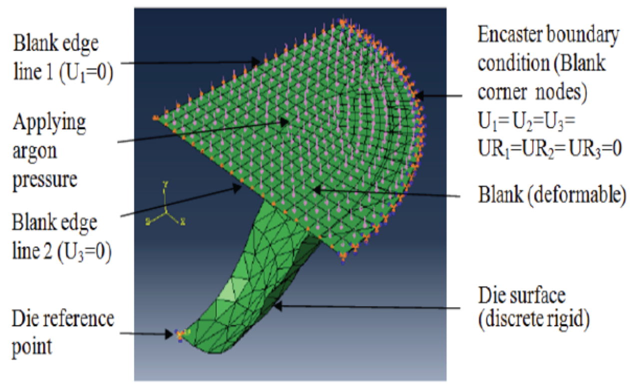

Figure 4: Illustration of Finite element model.

Figure **4** shows the blank and die configuration modelled in ABAQUS 6.10.1 version with the mesh region of the blank. The rigid die and deformable blank were assembled together at the die edge. The blank meshed with S4R element type with the mesh size of 1854 nodes. Similarly, the rigid die was meshed with R3D3 [15] element type with mesh size of 565 nodes. The Rigid die and periphery of the blank were also firmly clamped using boundary conditions. Constant

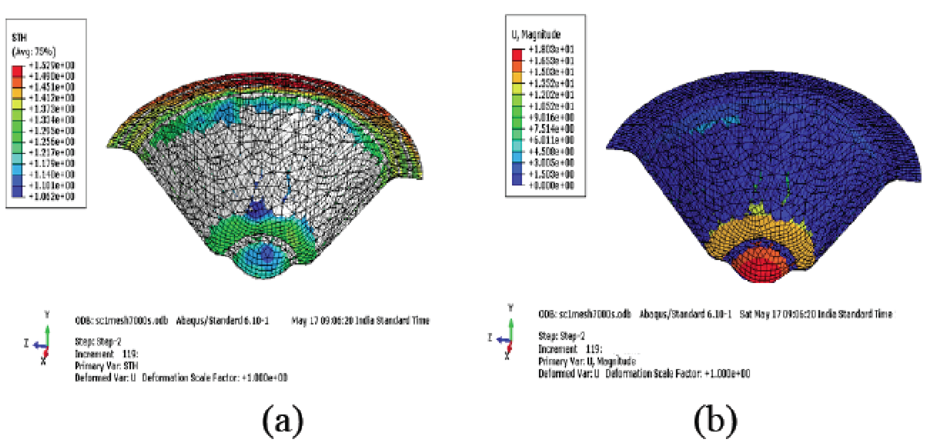

Figure 5: (**a**) & (**b**) Illustration of the final stage of FEA simulation profile.

and variable pressure was applied over the blank surface and evaluated the SP forming characteristics. In the present work, the material constants [9] of k value is 250 MPas^{-m}, Temperature is 410°C, $\dot{\varepsilon}$ is 1.5 x10^{-3}s^{-1} and m value is 0.48 chosen for AA 7075 alloy in numerical simulation analysis. Figure **5a** and **b** represent that, the final FEA simulation profile of thickness distribution and displacement of profile.

RESULTS AND DISCUSSION

Predict the Best Pressure Control Method with a Function of Forming Time and Pressure Cycle for Optimizing Thickness Distribution

The pressure applied during forming has been accurately controlled and monitored in all the experiments. The same code has also been generated using the FEA model to predict the forming pressure at target strain rate conditions.

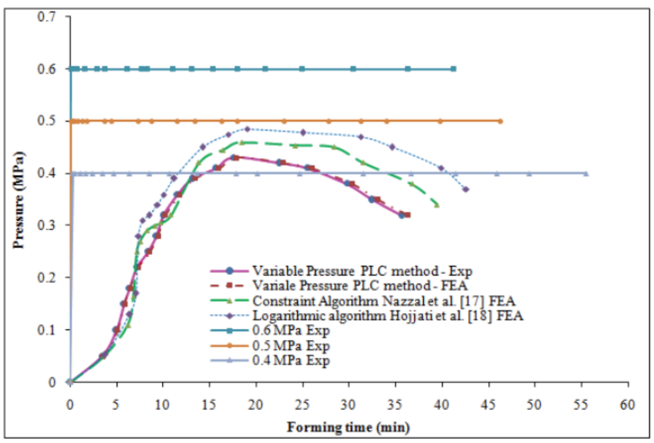

Figure 6: Illustration of forming pressure with respect to time using different pressure control method.

The experiments were carried out at different constant pressure of 0.4 MPa, 0.5 MPa, 0.6 MPa and variable pressure control approach of PLC method. The FEA simulation process was carried out at different constant pressure of 0.4 MPa, 0.5 MPa, 0.6 MPa, and different variable pressure control methods [16] of logarithmic algorithm, constrained algorithm and PLC method. Figure **6** shows that, the comparison of forming pressure as a function of forming time was obtained using different pressure control approaches. The newly developed PLC method, the experimental and FEA simulation results are in close agreement. In FEA simulation process, the constraint algorithm and logarithmic algorithm has been incorporated and the pressure time cycle profile has been evaluated. The applied pressure gradually increasing until the blank reaches the die surface beyond which it gradually decreases to achieve uniform thickness distribution in a multi dome shape in all three pressure control processes.

In constraint algorithm [17] and logarithmic algorithm [18], the applied pressure takes a step by step time increment process reflecting more oscillations in the stress and therefore resulting in a pressure of 0.46 MPa and 0.48 MPa needed to fill die cavity at forming time of 39.45 minutes and 42.58 minutes respectively. In the PLC approach, as can be seen, 0.43 MPa of maximum pressure level is needed to fill the die cavity within 35.7 minutes and the smooth pressure profile has been achieved as evident in Figure **6** and Table **2**. In the PLC method, the forming time is minimum because of very less oscillations and stress during forming at die entry regions.

The PLC-based pressure cycle mechatronics approach will be designed and constructed to change the very small amplitude of displacement during forming with the provision of a high accuracy feedback system. And it's also being more flexible, highly precise to regulate the flow of pressure for slow filling in corner regions, eliminating the oscillations and also accurately maintains the optimum strain rate throughout the process in order to optimize the thinning, and prevents

Table 2: Comparison of Forming Time and Forming Pressure at Maximum Level with Different Pressure Control Methods

S.No	Pressure forming method	Time (min)	Forming pressure (MPa) at maximum level
1	Constant Pressure of 0.4 MPa	55.46	0.4
2	Constant Pressure of 0.5 MPa	46.3	0.5
3	Constant Pressure of 0.6 MPa	41.2	0.6
4	Logarithmic algorithm	42.58	0.48
5	Constraint algorithm	39.45	0.46
6	PLC approach	35.7	0.43

premature fracture and obtains very close to net shape during multi-stage superplastic forming.

Predict the Best Pressure Control Method with a Function of Thinning Factor

In a two-stage hemispherical die forming, the deformed sheet can be divided into different regions. During the first stage of forming, the die entry contact region, sidewall contact region, and second stage of forming the die entry contact region and a bottom contact region. In this complex profile, the thickness variation has been measured and recorded. Figure **7** shows that, thickness distributions are drawn during experimentation along with dome profile by using constant pressure of 0.4 MPa, 0.5 MPa 0.6 MPa and newly developed PLC approach. The (Figure **8**) shows that thickness distributions are drawn during FEA simulation along dome profile by using constant pressure of 0.4 MPa, 0.5 MPa 0.6 MPa and variable pressure of constraint algorithm, logarithmic algorithm and PLC approach.

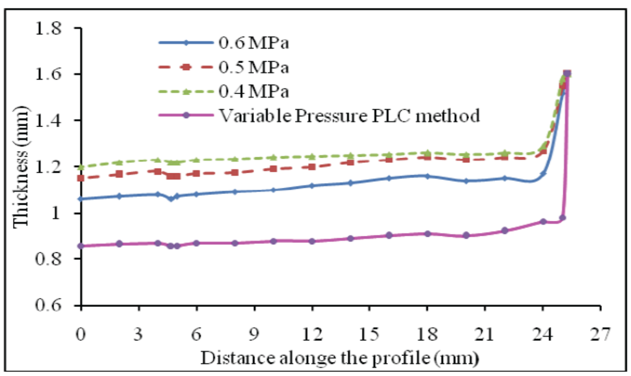

Figure 7: Illustration of thickness distribution along the dome profile in experimental method.

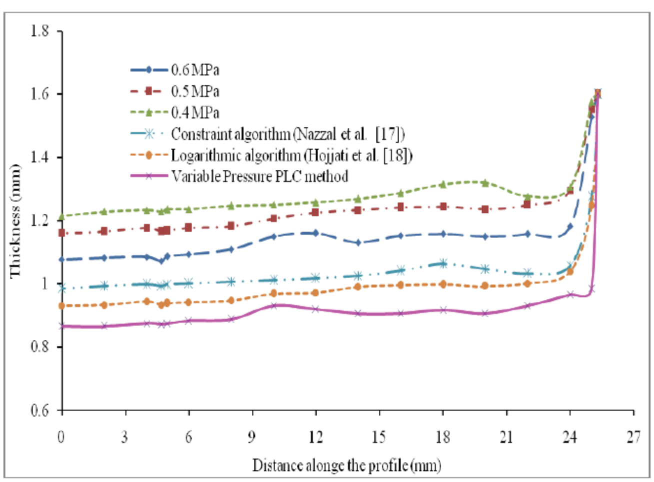

Figure 8: Illustration of thickness distribution along with the dome profile in FEA simulation method.

The pole thickness and thickness at various points were measured at different pressure conditions experimentally and numerically. The average thickness and thinning factor were evaluated at all kinds of pressure approaches. The experimentally and numerically evaluated values of pole thickness, average thickness and thinning factor values of the fully formed final components at different pressures are given in Tables **3** and **4** respectively.

The data in Tables **3** and **4** indicate that though the significance of variation in thinning factor as a function of applied pressure. The thinning factor is defined [18] as the ratio of thickness at the pole to the average sheet thickness that plays a vital role in predicting the uniformity of thickness in the formed profile with the highest value indicating greater uniform thickness in the product.

From Table **3** (experimental data), and Table **4** (FEA simulation data) observed that the PLC approach method has a higher thinning factor of 96.31 % experimentally and 96.64 % numerically when compared with other pressure control methods. The results show that the profile reaches all die entry regions and obtain uniform thickness variation throughout the formed profile in a PLC approach method. Further, it can improve the filling ability of the sheet towards die entry regions in both the stages of the profile with a minimum forming time of 35.7 minutes. Hence, the PLC approach is the best method for optimizing thickness variation in a full two-stage dome profile with minimum pressure and forming time when compared to other pressure control methods.

Change of Pole Thickness with a Function of Pole Height

The superplastic forming process was carried out experimentally at different constant pressure control of 0.4 MPa, 0.5 MPa, 0.6 MPa and microprocessor control based PLC method. Pole thickness with a function of forming height is representing in (Figure **9**). In generally observed that the pole thickness gradually decreases as a function of forming height in most of the single-stage forming operations. But more than two stages of forming have discontinuities [15] are observed in an otherwise gradual reduction of thickness. From (Figure **9**), it is observed that, in the constant pressure method, the reduction in pole thickness is significant changes when compared to the PLC technique. But PLC method has eliminated the discontinuities and obtained a smooth profile.

Table 3: Pole Thickness, Average Thickness and Thinning Factor with Effect of Forming Pressure from Experimental Data

Description	0.4 (MPa)	0.5 (MPa)	0.6 (MPa)	PLC approach
Pole thickness (mm)	1.2	1.15	1.06	0.86
Average thickness (mm)	1.327	1.225	1.142	0.893
Thinning factor (%)	90.43	93.87	92.82	96.31

Table 4: Pole Thickness, average Thickness and Thinning Factor with Effect of Forming Pressure from FEA Simulation Data

Description	0.4 (MPa)	0.5 (MPa)	0.6 (MPa)	Constraint algorithm	Logarithmic algorithm	PLC approach
Pole thickness (mm)	1.216	1.162	1.078	0.984	0.932	0.867
Average thickness (mm)	1.342	1.224	1.158	1.0345	0.9744	0.8971
Thinning factor (%)	90.61	94.93	93.09	95.12	95.65	96.64

The superplastic forming process was carried out experimentally at different constant pressure control of 0.4 MPa, 0.5 MPa, 0.6 MPa and microprocessor control based PLC method. The flow forming time was measured with a function of forming height at different pressure control methods and it is represented in (Figure **10**).

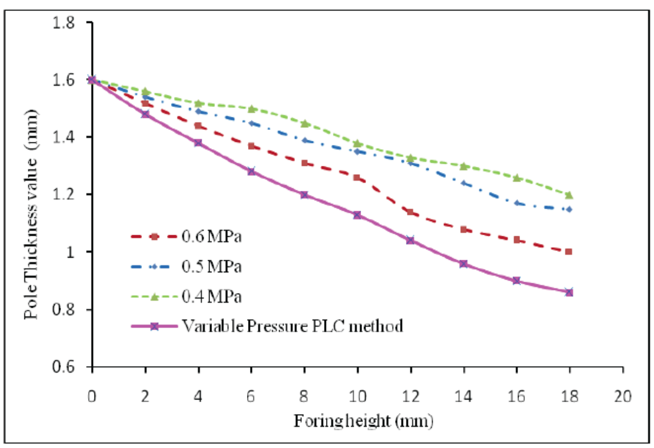

Figure 9: Illustration of Change of pole thickness with a function of pole height.

Forming Time with a Function of Forming Height

From (Figure **10**), it was observed that the forming time linearly increases with respect to pole height up to 60 % due to the free flow forming region in the dome profile. After that gradually increases and further rapidly increases due to sticking of a sheet on the die profile. The PLC approach was better linear variation and achieved a smooth forming profile at an optimum (minimum) forming time of 35.7 minutes and it is evident in (Figure **10**), and Table **5**.

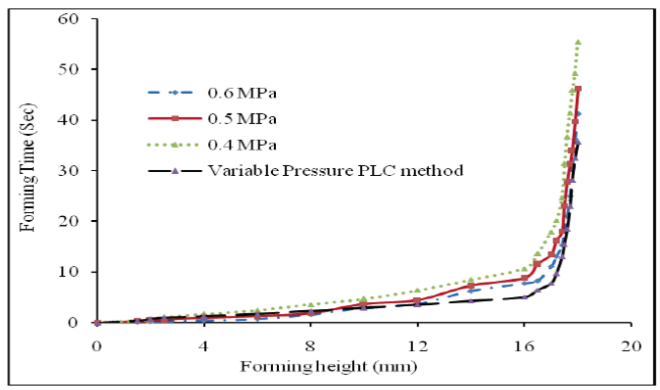

Figure 10: Illustration of forming time with a function of forming height.

Table 5: Forming Time with a Function of Forming Height at Different Pressure Control Method

S.No	Pressure forming method	Time (min)
1	Constant Pressure of 0.4 MPa	55.46
2	Constant Pressure of 0.5 MPa	46.3
3	Constant Pressure of 0.6 MPa	41.2
4	PLC approach	35.7

CONCLUSION

In this paper, experimental and finite element study of multistage superplastic forming behaviour of the 7075 aluminium sheet investigated. The following conclusions were drawn for multistage bulge forming.

The finite element modelling predictions confirm suitable agreement with experimental results. During superplastic forming the blank stuck well to the female die surface and the well placed over the die profile. At lower constant pressure leads to the lower interfacial friction force between the blank and the die surface, thus causing the variation in sheet thickness over the die surface.

In the PLC method, the forming pressure has been reduced by more than 6.52 % compared to other pressure control methods.

The SPF forming duration has been minimized 9.51 % when compared to other pressure control methods.

Thickness distribution can be found to be highly uniform in all the regions indicating the advantages of pressure control using PLC approach for the multidimensional dome profile.

The developed PLC system is found to effectively control the strain rate of superplastic forming of the AA7075 alloy sheet. Hence thickness distribution in the die entry and corner regions was uniform for a complex multi-dimensional profile.

The PLC method has to achieve wrinkle-free superplastic formed multi-dimensional components.

REFERENCES

[1] Cebeli Ö, Engin Ü. Optimization and modeling of angular deep drawing process for square cups. Journal of Materials and Manufacturing Process 2011; 26: 1117-1125. https://doi.org/10.1080/10426914.2010.532526

[2] Wang LR, Zhao YQ, Zhou L. Effect of hot rolling on the structure of TC21 alloy with acicular alpha. Journal of Materials and Manufacturing Process 2012; 27: 154-159. https://doi.org/10.1080/10426914.2011.566662

[3] Balasubramanian M, Anand Chairman C, Pritima D, Dhinakaran V, Stalin B, Ravichandran M. Re-entrant formation on superplastic forming process by mechatronics approach in 5083 Al Alloy. Materials Science and Engineering 2020; 988: 012098.

[4] Balasubramanian M, Stalin B, Ramanathan K, Ravichandran M. Hot tensile test for determining the material constant on superplastic 5083Al alloy sheet. International Journal of Materials Today: Proceeding 2020; 21(1): 324-328. https://doi.org/10.1016/j.matpr.2019.05.453

[5] Balasubramanian M, Ramanathan K. Numerical simulation and analysis of superplastic forming in Ti-6Al-4V alloy. International Journal of Applied Engineering Research 2015; 10(55): 3746-3750.

[6] Balasubramanian M, Ramanathan K, Ganesh P, Senthilkumar VS. Numerical analysis and simulation of the superplastic forming in 5083 aluminium alloy sheets. International Journal of Applied Engineering Research, Special issue 2014; 9(26): 9098-9102.

[7] Pradeep P, Ayyanar S, Balasubramanian M, Ramanathan K, Senthilkumar VS. Advanced finite element analysis and simulation in superplastic forming process of stepped semispherical die. Journal of Applied Science 2012; 12(10): 1048-1052. https://doi.org/10.3923/jas.2012.1048.1052

[8] Balasubramanian M, Ramanathan K, Senthilkumar VS. Mathematical modeling and finite element analysis of superplastic forming of Ti-6Al-4V alloy in a stepped rectangular die. Procedia Engineering 2013; 64: 1209-1218. https://doi.org/10.1016/j.proeng.2013.09.200

[9] Balasubramanian M, Anand Chairman C, Marichamy S, Dhinakaran V, Stalin B, Ravichandran M. Investigation and optimization of superplastic forming parameter in aluminium alloy. Materials Science and Engineering 2020; 988: 012097.

[10] Jarrar FS, Abu-Farha FK, Hector Jr, LG, Khraisheh MK. Simulation of high temperature AA 5083 bulge forming with hardening/softening material model. Journal of Material Engineering Performance 2009; 18(7): 863-870. https://doi.org/10.1007/s11665-008-9322-5

[11] Balasubramanian M, Ramanathan K. Simulation and experimental investigation on superplastic forming of 7075 Aluminum alloy. International Journal of Applied Engineering Research 2015; 10(49): 429-433.

[12] Balasubramanian M, Sathish Kumar MK, Stalin B, Ravichandran M. Theoretical predictions and experimental investigation on three stage hemispherical dome in superplastic forming process. Materials Today: Proceedings 2020; 24: 1424-1433.

[13] Senthil Kumar VS, Viswanathan D, Natarajan S. Theoretical prediction and FEM analysis of superplastic forming of AA7475 aluminum alloy in a hemispherical die. Journal of Material Processing Technology 2006; 173: 247-251. https://doi.org/10.1016/j.jmatprotec.2005.04.112

[14] Balasubramanian M, Ramanathan K, Senthil Kumar VS. Finite element modeling and numerical simulation of superplastic forming of 8090 Al-Li alloy in a rectangular die. International Journal of Advanced Material Research 2012; 487: 116-121. https://doi.org/10.4028/www.scientific.net/AMR.487.116

[15] Balasubramanian M, Ganesh P, Ramanathan K, Senthilkumar VS. Superplastic forming of a three stage hemispherical 5083 aluminium profile. Strojniški vestnik. Journal of Mechanical Engineering 2015; 61(6): 365-373. https://doi.org/10.5545/sv-jme.2014.2178

[16] Balasubramanian M, Ganesh P, Ramanathan K, Senthilkumar VS. An Experimental investigation and numerical simulation in SPF of AA 5083 Alloy using programming logic control approach. Strojniški vestnik. Journal of Mechanical Engineering 2017; 63(4): 255-264. https://doi.org/10.5545/sv-jme.2016.3721

[17] Nazzal MA, Khraisheh MK, Darras BM. Finite element modeling and optimization of superplastic forming using variable strain rate approach. Journal of Materials Engineering and Performance 2004; 13: 691-699. https://doi.org/10.1361/10599490421321

[18] Hojjati MH, Zoorabadi M, Hosseinipour SJ. Optimization of superplastic hydro forming process of Aluminium alloy 5083. Journal of Materials Processing Technology 2008; 205: 482-488. https://doi.org/10.1016/j.jmatprotec.2007.11.208