FEM study of process parameters in a novel superplastic forming of titanium alloy Ti-6Al-4V

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Abstract. A novel hybrid forming process involving the use of hot drawing along with superplastic forming (SPF) is studied here. The hot drawing stage helps in enhancing the formability and in fast deforming the sheet metal into a hollow shape with desired amount of material draw-in. During the subsequent SPF stage, gas pressure was applied onto the pre-formed part to complete the forming process at a targeted strain rate. With the hybrid process, titanium alloy Ti-6Al-4V sheets have been successfully formed in lab-scaled conditions at 800°C in 16 min. In this paper, finite element modelling (FEM) was used to demonstrate the effects of each stage (hot drawing and SPF) during the process. A plasticity model based on tensile test data was adopted as a material model for simulation. The pressure cycle which was predicted from the simulation has been used in the process to maintain the sheet forming at an average strain rate (e.g. 10^{-3} and 5×10^{-4} s^{-1}). Material draw-in and thickness distribution were used to compare and optimise the process parameters. The simulations have shown the capability of the model to be used for the hybrid superplastic forming process. The influences of varying process parameters, such as punch geometry, blank size, blank-holder force, friction coefficient and pressure cycle, were investigated by the simulations. It was found that the punch geometry and blank size played significant roles on the thickness uniformity of the final part, from which an optimised hot-drawing system that could lead to minimum thinning has been designed by FEM method.

Introduction

Titanium Ti-6Al-4V is a well-known lightweight alloy that exhibits characteristics, such as high strength-to-weight ratios and good superplastic behaviour for aerospace applications [1]. Superplasticity in titanium alloys has been known for over 50 years [2]. Superplastic forming (SPF) [3] is used by the relevant industry to form large and complex components in one operation at the targeted temperature and strain rate. The superplastic behaviour of Ti-6Al-4V alloy is achieved at high temperatures (typically above 900ºC) and at low strain rates (usually lower than 10^{-3} s^{-1}) [4].

The formed product has excellent precision and a good surface finish. It also does not suffer from springback or residual stress. The benefits of SPF are its high formability, complex (and intricate) shape possibilities, lower tooling cost, labour and material saving through elimination of

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parts joining and secondary machining. However, the disadvantages of SPF are mainly the slow forming rate, high forming temperature and poor thickness control. In order to address those limitations, a hybrid SPF process which combines hot mechanical drawing and blowing has been developed to address the problems aforementioned [5].

Finite element modelling (FEM) is a numerical method commonly used to investigate the process feasibility and facilitate the SPF process design. Prediction of the process variables, e.g. pressure cycles, strain rate control, thickness evolution and tooling design, can be derived from these analyses. Most of the experiments and the SPF simulations are carried out by using commercial FEM codes, such as ABAQUS, ANSYS, MSC.MARC and PAM-STAMP. In superplastic forming, the ability of the simulation code to predict the deformation behaviour of the material is a key factor in developing optimum gas pressure cycles that can form the part in the least time and obtain the best results [6].

In this paper, a validated power-law material model has been implemented in PAM-STAMP to study the process feasibility and predict the process parameters. The influence of process parameters has been studied, including the level of material draw-in and thickness distribution. An optimised forming process window has been proposed by designing the tooling.

Material data

The flow stress behaviour at strain rates ranging from 10^{-4} to 10^{-1} s^{-1} during tensile testing can be characterised by the power law model as seen below:

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

where σ is the flow stress, $\dot{\varepsilon}$ is the strain rate, ε is the plastic strain, K is the stress index, m is the strain rate sensitivity index, and n is the strain hardening index. High-temperature tensile tests following ASTM E2448 [7] have been carried out to determine the superplastic behaviour (elongation, flow stress and strain rate sensitivity) at the targeted conditions. It is noted that the mechanism of strain hardening in superplastic flow is essentially due to grain growth, and therefore the n value is determined as a function of strain due to grain growth during tension. In this study, the strain rate sensitivity and strain hardening index were calibrated to be 0.505 and 0.05 at 900°C, respectively. The Young's modulus of 20 GPa was estimated for the material. The Poison's ratio of 0.3 was used in the simulation.

Simulation model

The model used for simulation is shown in Fig. 1(a). It comprises of the die, punch, blank holder, and blank. The tools (i.e. die, punch, and blank holder) were modelled using rigid elements and the blank was defined as standard deformable elements in PAM-STAMP. The simulation follows the experimental sequence and is divided into two stages. Firstly, the punch, which is modelled as a rigid tool, moves towards to the blank at a constant speed (16 mm/s) until it reaches a pre-defined displacement, as illustrated in Fig. 1(b). This phase is also called hot drawing or mechanical pre-forming. For the second phase of the process (Fig. 1(c)), the punch is inactive, and the sheet is deformed due to the applied pressure only. This phase is also called superplastic forming or blowing.

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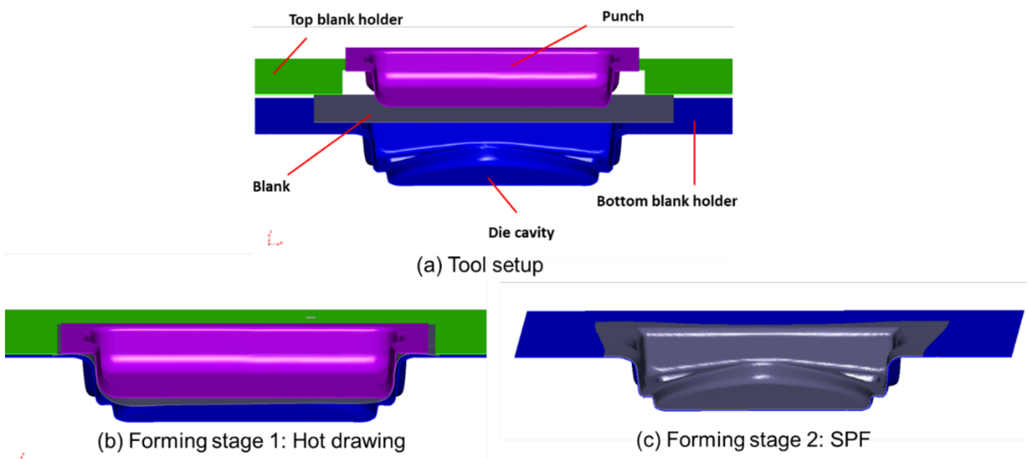

Fig. 1. Cross-sectional view of the simulation model.

Results and discussion

Material draw-in. The material draw-in length was obtained from the variation in width between the undeformed and the deformed sheets, as illustrated in Fig. 2. It can be seen that the maximum material draw-in level for the deformed sheet is found in the middle of each side, while the minimum draw-in is located at the blank corners. In this study, thickness distribution at the end of hot drawing and blowing stages will be compared to understand the effects of different parameters.

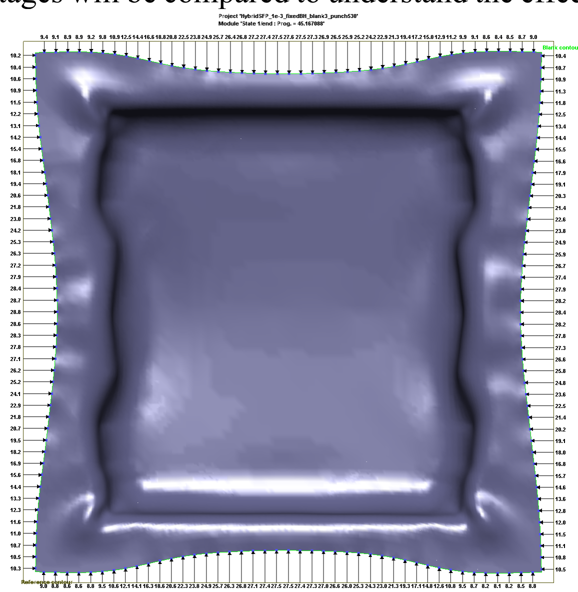

Fig. 2. Illustration of the material draw-in for a pre-deformed (hot-drawn) blank.

Effect of punch geometry.

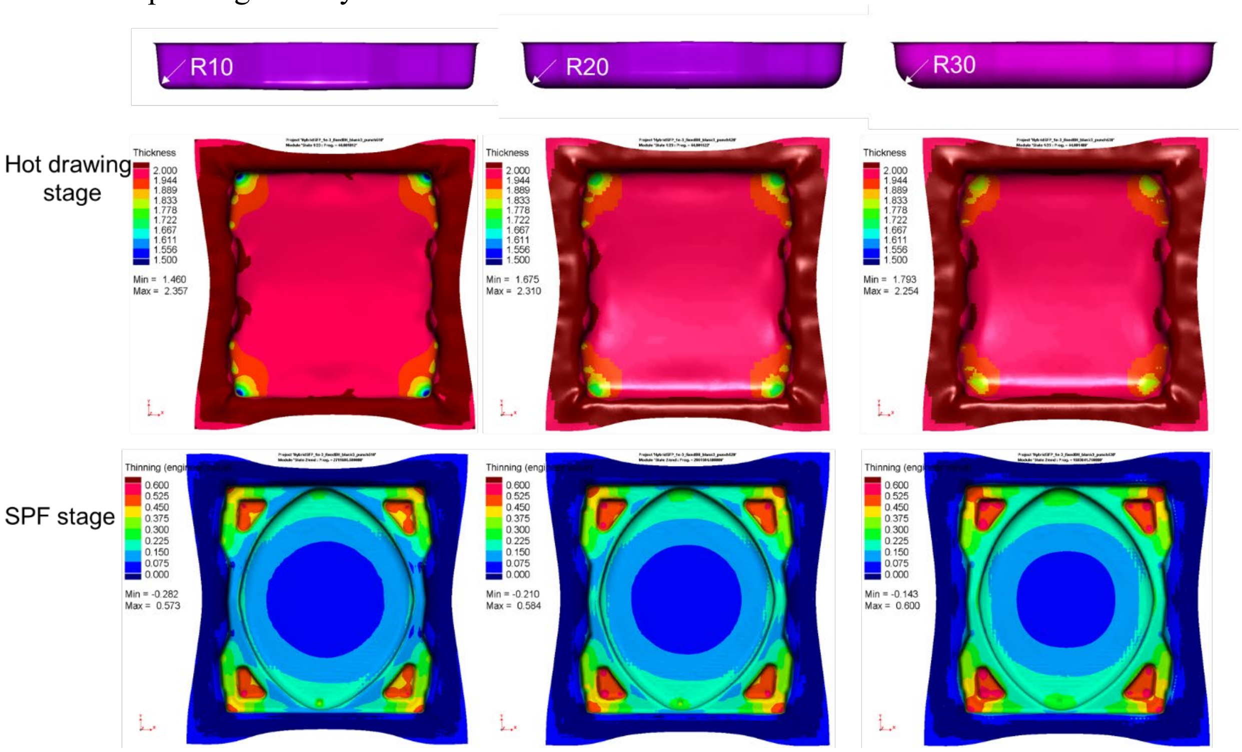

Fig. 3. Material thinning at hot-drawing and SPF stages with different punch radius (thickness unit: mm).

In the mechanical pre-forming (hot drawing) phase, punch is used to deform the material into the die cavity and control the material flow on the blank flanges. The effect of punch geometry has been studied. As shown in Fig. 3, a series of punch shapes with different radius (R10, R20 and R30) are compared.

According to the simulation results, with increase of the punch radius, there is a decrease of material draw-in. The predicted material thinning values after hot drawing (pre-forming) and superplastic forming (blowing) are also compared in Table 1. The formed parts show less material thinning with the punch radii of R10, as a result of more material draw-in at the pre-forming stage. Thus, a more uniform thickness can be achieved after SPF as more material is pre-deformed into the die cavity during the hot-drawing phase.

Table 1.The effect of punch radius on simulation results.

Punch radii	R10	R20	R30
Max material draw-in length at hot drawing stage	36.9 mm	31.9 mm	27.2 mm
Max material thinning at hot-drawing stage	0.270	0.176	0.103
Max material thinning at SPF stage	0.573	0.581	0.600

Effect of blank size. The FE simulation is used to optimise the blank size with which an optimal forming results are achieved. In the case, the punch radii of R20 is selected in simulation to study the effects of blank size/shape.

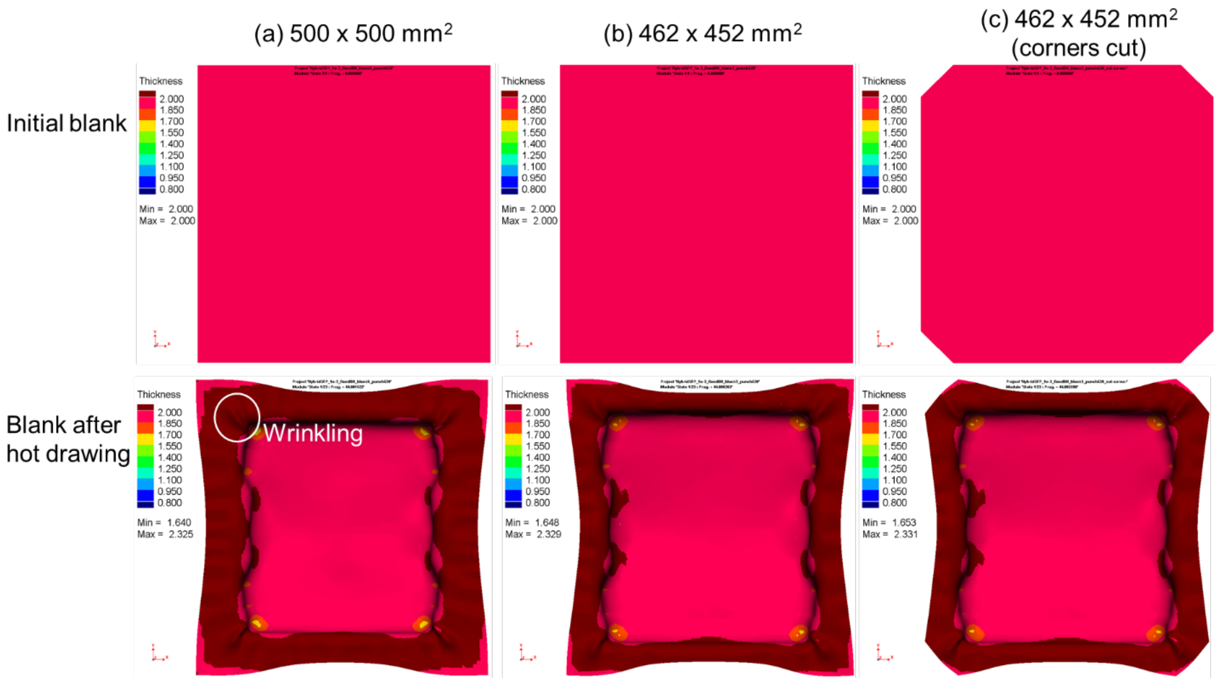

Fig. 4. The effect of blank size on the thickness distribution at the end of hot drawing (legend unit: mm).

Table 2. The effect of blank size on simulation results.

Blank size/shape	**500x500 mm^2**	**462x452 mm^2**	**462x452 mm^2 (corners cut)**
Max material draw-in length at hot drawing stage	28.2 mm	31.9 mm	32.3 mm
Max material thinning at hot-drawing stage	0.181	0.176	0.174
Max material thinning at SPF stage	0.582	0.581	0.575

As shown in Fig. 4, three blanks with different shapes are compared, in terms of the material draw-in and the thickness distribution. With decrease of the blank size, there is an increase of material draw-in, which leads to a more even thickness distribution with less material thinning on the formed part. It is also noted that the larger blank is more prone to wrinkling. As seen in Fig. 4(a), wrinkling is easily found on the corners of the hot-drawn parts as the blank holder is not designed in the region. Simulation results also indicate that more material draw-in can be available when the blank corners are trimmed off before hot drawing, as shown in Fig. 4(c), which will lead to a more even thickness distribution in the final part (Table 2).

Effect of blank-holder force during hot drawing. During hot drawing, blank holder force should be optimised to avoid wrinkling (as seen in Fig. 5) on the blank and minimise the frictional force between the blank and tool. The effect of blank holder force has been studied by comparing different levels of blank holder force, as shown in Table 3. With the increase of blank holder force, there is a decrease of material draw-in, which will eventually affect the thickness distribution on the formed part. Simulation has confirmed that an optimal blank holder force of 20 kN for the material deformed at the hybrid SPF condition.

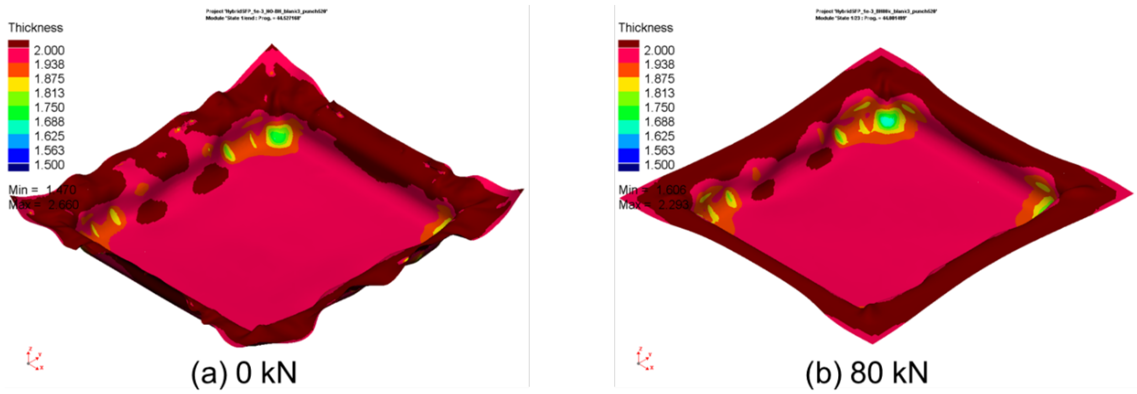

Fig. 5. Thickness distribution at end of hot drawing under different blank holder forces (legend unit: mm).

Table 3. The effect of blank holder force on simulation results.

Blank holder force (kN)	**0**	**20**	**40**	**80**
Max draw-in length	N/A (wrinkling)	31.9 mm	30.7 mm	28.7 mm
Max material thinning at hot-drawing stage	N/A (wrinkling)	0.176	0.187	0.197

Effect of friction. As in the superplastic forming process, it has been reported that material can be locked against the tool by friction and forming pressure, once the material contacts the surface of the die [5]. The friction effect was investigated in the simulation so as to develop the process, as shown in Table 4.

In comparison with different levels of friction, three friction coefficients were used to simulate the hybrid SPF process. It is observed that the material draw-in is affected significantly, showing less material draw-in under higher friction. In the superplastic forming stage, the thickness is affected by friction, as shown in Fig. 6, when comparing the cavity area of the formed parts. The maximum thinning occurred in the four ‘pocket’ regions. Ideally, a lower friction can deliver a more even thickness distribution in the formed part. However, it is well accepted that the friction coefficient is assumed to be 0.3 in real forming conditions.

Table 4.The effect of friction on simulation results.

Coefficient of friction	**μ = 0.1**	**μ = 0.3**	**μ = 0.5**
Max material draw-in length	33.0 mm	31.9 mm	30 mm
Max material thinning at hot drawing	0.177	0.176	0.177
Max material thinning at SPF	0.533	0.581	0.595

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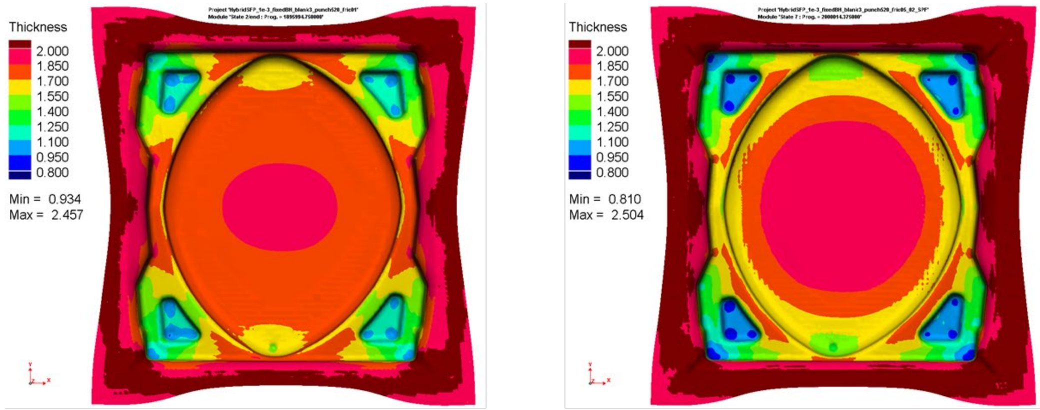

(a) μ = 0.1 (b) μ = 0.5

Fig. 6. Thickness distribution under different friction levels (legend unit: mm).

Effect of pressure cycle during blow forming. The material exhibits superplastic behaviour at a specified temperature and strain rate. In this study, the forming temperature is 900°C. The optimal strain rate during the superplastic forming stage is set to be between 5×10^{-4} and 10^{-3} s^{-1}.

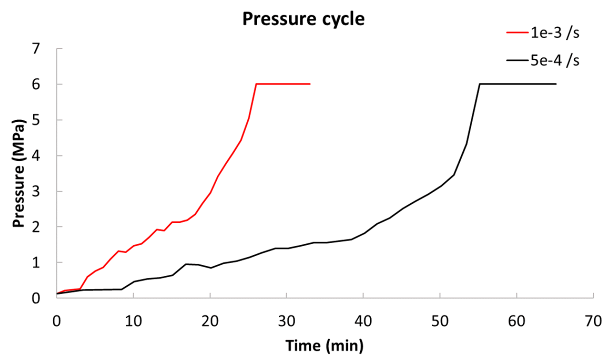

Fig. 7. Pressure cycles predicted by FE simulation at the targeting strain rates.

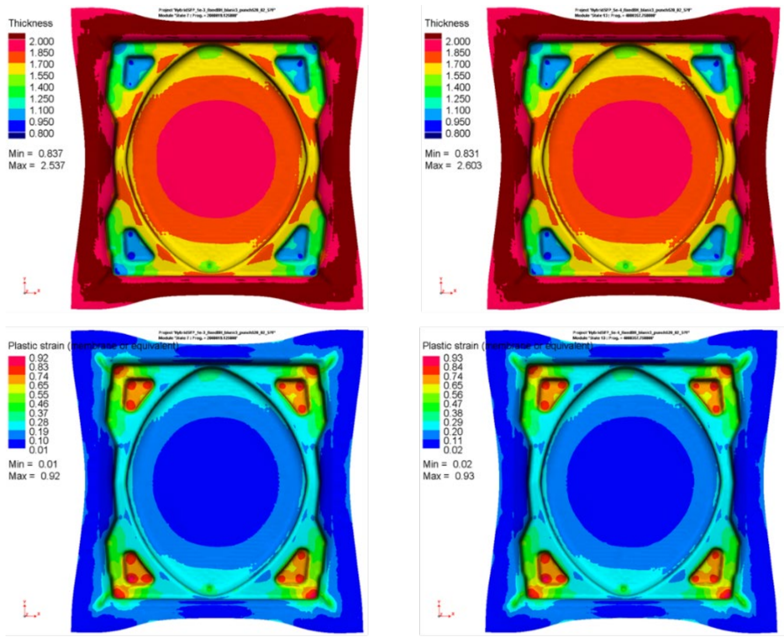

Fig. 8. Distribution of thickness and equivalent strain at different forming strain rates (thickness unit: mm).

Accordingly, the pressure cycles were predicted by FE simulation, as plotted in Fig. 7. It is predicted that the superplastic forming process is completed within 65 min and 33 min at a targeting strain rate of 5×10^{-4} and 10^{-3} s^{-1}, respectively. The thickness distribution at the corresponding strain rate is also shown in Fig. 8. Little difference in the distribution of thickness and equivalent strain is found between the two strain rates.

Conclusions

Finite element modelling was used to simulate the superplastic forming combined with a mechanical pre-forming process. Simulations showed the material localised thinning area, where the punch is in contact with the blank during hot drawing. The material draw-in and thickness distribution were predicted by introducing a power law material model based on the tensile test results at 900ºC into PAM-STAMP. The influence of punch geometry, blank size, blank holder force, friction and strain rate was investigated in the simulations. It was observed that the level of material draw-in decreased, as the blank holder force or friction increased. In the comparison of the thickness distributions, a more uniform formed part can be achieved with the optimised tooling design (punch geometry and blank holder force) and process parameters (blank size and strain rate).

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