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IMPROVEMENT OF PRODUCT THICKNESS DISTRIBUTION IN GAS PRESSURE FORMING OF A HEMISPHERICAL PART

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Abstract. Hot gas pressure forming is one of the sheet metal forming processes. One of the drawbacks of this method is non-uniform thickness distribution in final parts. In this paper a new method is proposed to control thickness distribution in this process by dividing the process's die into two segments. Due to lead's considerable strain rate dependency in ambient temperature, pure lead is selected to investigate whether the method is feasible or not. At first, tensile tests at various strain rates are performed on the material to find required mechanical properties. Then the common gas pressure forming process is simulated and the required pressure to obtain the optimum strain rate is calculated. Experimental and predicted results are compared to verify the simulation. Since the proposed new method have several parameters, python scripting in conjunction with neural network and genetic algorithm are used to optimize these parameters. Producing a part by the new method shows improvement of thickness distribution comparing with the common process. Minimum of thicknesses is increased about 20 percent that causes improvement of product performance and decreasing probability of part failure in forming.

Key words: gas pressure forming, product thickness distribution, finite element modeling, neural network, genetic algorithm.

1. INTRODUCTION

Hot gas pressure forming is one of the important methods among sheet metal forming processes. Especially superplastic blow forming is widely used in the aerospace industry to form the shapes requiring high strength-weight ratios parts [1]. Superplasticity is a viscous behavior shown by small grain size alloys and recognized by elongations more than 200 percent. Titanium, aluminum and magnesium alloys are common superplastic materials. Superplastic materials exhibit high elongations and low strengths in superplastic conditions [2, 3]. Superplasticity occurs at a temperature over half of the melting point and a limited strain rate range [4, 5].

Lack of uniform thickness distribution in final product of hot or superplastic gas pressure forming, decrease its performance and increase probability of failure during forming. For example, Ghosh and Hamilton [4] reported excessive thinning over the die entry radius of a long rectangular box section of Ti–6Al–4V.

A vast of researches was done to improve thickness distribution in gas pressure forming especially in superplastic forming (SPF).The most studied method of product thickness improvement in SPF is applying a pressure-time diagram in such a way that maximum strain rate does not exceed the target value [6]. Different equations and pressure algorithms for controlling strain rate are presented [7–10]. Hambli *et al*. [6] presented a pressure-cycle control algorithm which keeps track of the maximum strain rate sensitivity, and adapts the pressure law applied in order to approach as nearly as possible the optimal pressure time history law. Guo and Ridley [9] developed an analytical function for applied pressure in the gas pressure forming of domes. A pressure algorithm consistent with finite element modeling has been suggested by Carrino *et al*. [8]. Jarrar *et al.* [10] suggested a more precise pressure algorithm and implemented it in the finite element software Abaqus.

More complex tools have also been developed for SPF. These tools promote the strategic thinning of certain regions of a part during forming to improve the final thickness distribution in more critical regions. Reverse gas forming is a widely used two-stage technique applied in industry, in which a blank is pre-formed into a cavity and then reversed into the final shape by gas pressure [11–13]. A simple and efficient preform design method is proposed by Xing *et al*. [13] based on a rigid–viscoplastic finite element program and applied to the design of pre-form mold for manufacturing parts with uniform wall thickness. However, the ability of this method to improve strain distribution and help protect critical areas from excessive thinning is limited.

Die systems that couple mechanical forming with SPF have also been developed for example by Luo *et al.* [12]. This method is relegated to simple geometries due to a lack of a blankholder to control the material feed into the die as is performed by Jiang *et al*. [14] and Zhang *et al*. [15].

Optimal blank shape is also suggested to produce a uniform product. Kim *et al.* [16] proposed a systematic method to find the optimal blank shape. Lee *et al*. [17] used rotary forging to change thickness distribution of initial blank. They obtained a fairly uniform thickness distribution but their methods require more time (and material) to manufacture the initial blank.

In the present study, a new method is presented to produce a part with fairly uniform thickness distribution. In this method a die that have a movable segment is used. By moving this segment during the process, part is formed during two stages and final thickness distribution is controlled. Comparing with the previous methods, this method has the following advantages:

- part is formed only in one direction therefore:
  - material do not experience cyclic loading
  - in some cases the process can be carried out with applying pressure only on one side
  - total process time is less than making a preform by reverse forming
- a relatively small force is required to move the die segment comparing with the method that use mechanical preforming, consequently a smaller press is required

In the reminder of the paper finite element (FE) simulations of the common and the new presented process are carried out and compared with experimental data and finally it is shown that the presented process can improve product thickness distribution.

2. MECHANICAL PROPERTIES OF THE MATERIAL

To investigate the new proposed method, common experiments are done on pure lead. This material shows a considerable strain rate dependency in ambient temperature as will be shown in this section. The material is considered to be isotropic with a Young modulus of 16GPa and Poisson's ratio of 0.44.To derive material constants that are needed in simulations, tensile tests at the strain rates of 0.0001, 0.001, 0.01 and 0.1 (1/s) were carried out on the material. Figure 1 shows measured stresses at various strains and strain rates. Figure 2 shows elongations of the final specimens at various strain rates. It can be concluded from these two figures that this material can bear a larger value of strain at strain rates less than 0.001 (1/s) therefore gas pressure forming should be done in strain rates less than 0.001 (1/s). Strain rate sensitivity, 'm-value' is a measure of deformability rather than material elongation and can be calculated as:

$$m = \frac{dLn(\sigma)}{dLn(\varepsilon)}. \tag{1}$$

Figure 3 shows calculated logarithm of stresses vs. logarithm of strain rates for pure lead. The slope of the illustrated curve represents m-value and is about 0.1 for this material. The value is higher for strain rates less than 0.001 (1/s) as it can be seen.

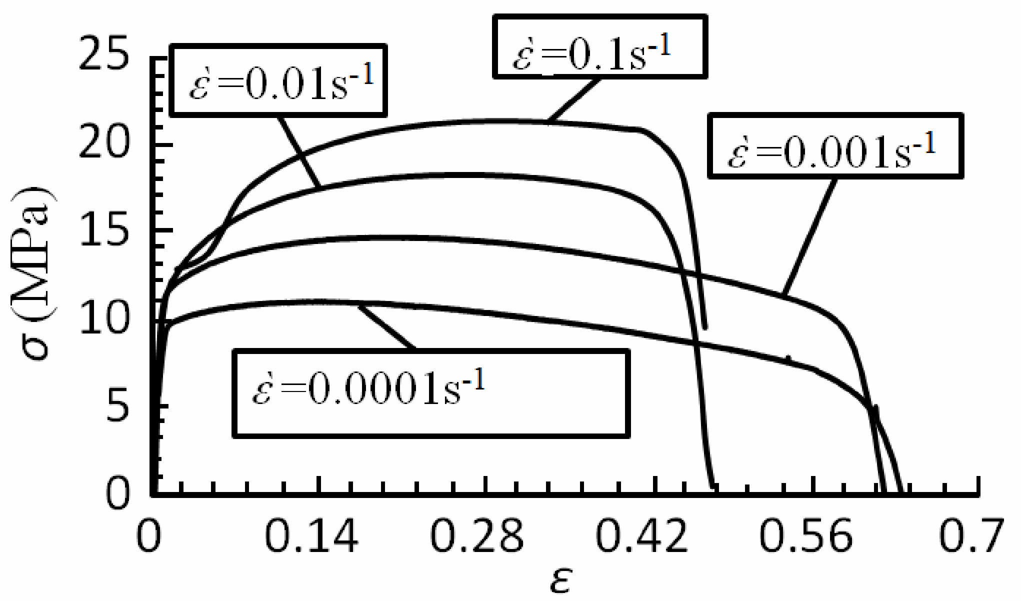

Fig. 1 – Stress-stain curves of pure lead as determined by tensile tests for different initial strain rates at room temperature.

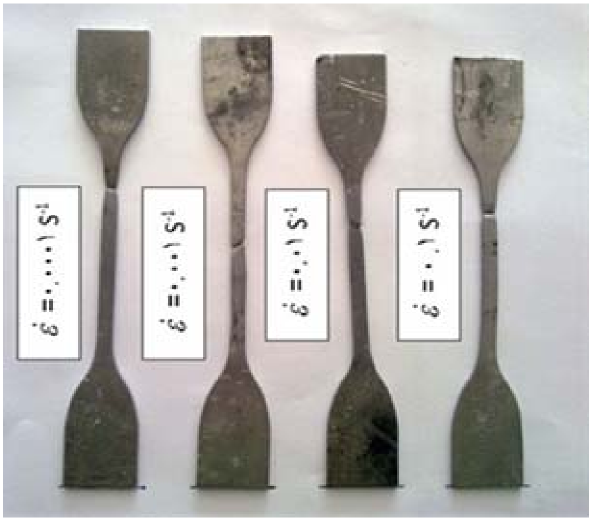

Fig. 2 – Elongations of the specimens at various strain rates.

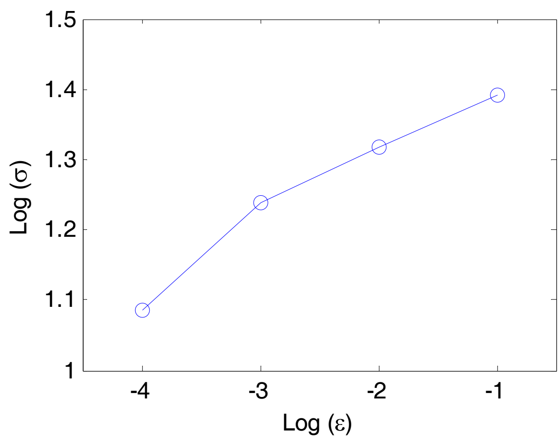

Fig. 3 – Calculated logarithm of stress vs. logarithm of strain rate for pure lead at the strain of 0.2.

3. MODELING OF THE COMMON GAS PRESSURE FORMING PROCESS

To reduce the cost and time due to experiments, FE modeling was used to model and optimize the process. At first common process of manufacturing a hemispherical part is modeled and results are compared with experimental data. Then after optimization of the new process' parameters, predicted and experimental results of the new process are compared with common process.

In common process as it is illustrated in Fig. 4, the die is fixed and the lead blank edge is also fixed on the die. The die consists of a simple cylinder with a hemispherical hole of diameter 190 mm and an entrance fillet with radius of 25 mm. The lower die only serves a path for applying gas pressure on the blank. The initial blank is a 230 × 230mm square with a thickness of 1.7 mm.

The sheet was constructed using axisymmetric shell elements and the die is modeled as analytical rigid surface. Coulomb friction law with coefficient of 0.1 is used to model friction between sheet and tool contact surface. The sheet is clamped at the outer boundary.

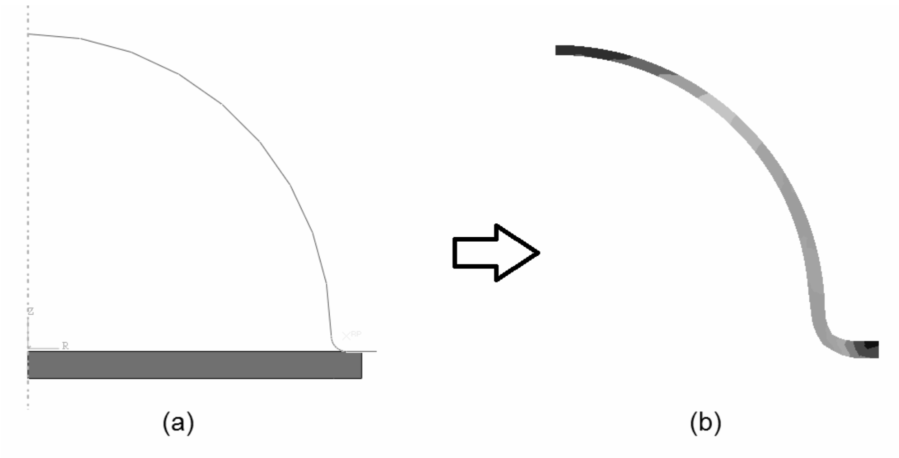

Fig. 4 – Common gas blow forming process of a hemispherical part:
a) the initial bank and the die; b) final part.

Isotropic elastic constants of lead and stress-strain curves of Fig. 1 are used to represent material properties for all the simulations. The gas pressure, required for sheet forming, should be calculated in a way that the maximum strain rate induced in the part be less than 0.001 (1/s) as it is mentioned in section 2. Maximum strain rates were calculated for several pressures and it was seen that maximum strain rate is near the target value in the most of the process time by a pressure of 5.5 bars. In the current work a constant pressure is applied to entire of the process but all of the simulations and experiments can be done by a specific pressure-time diagram to improve results.

In Fig. 5, predicted thicknesses of the product are illustrated based on the distance from center. The final thickness difference between the center and edge of the part is about 70 percent of the minimum thickness that is a considerable value.

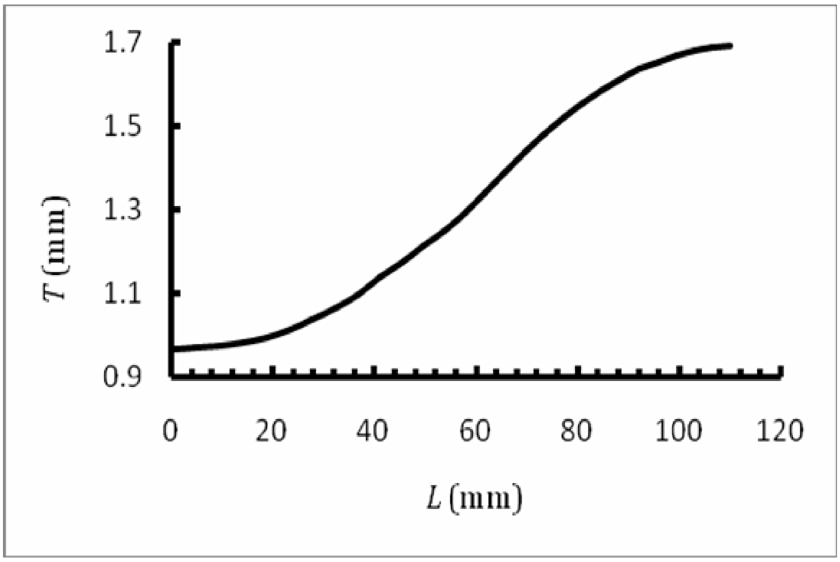

Fig. 5 – Predicted thicknesses of the product based on the distance from center.

Since FE simulations play the main role in design of the new process, at first FE results are compared with the same experiment to investigate reliability of the FE simulations. Thicknesses of the experimentally formed part are measured in a diagonal path by the use of a coordinate measuring machine. Figure 6 compares predicted thicknesses of the sheet and experimental measurements. It can be concluded from this figure that FE simulations results are in an acceptable agreement with the experimental data and we can use FE simulations to optimize the new process.

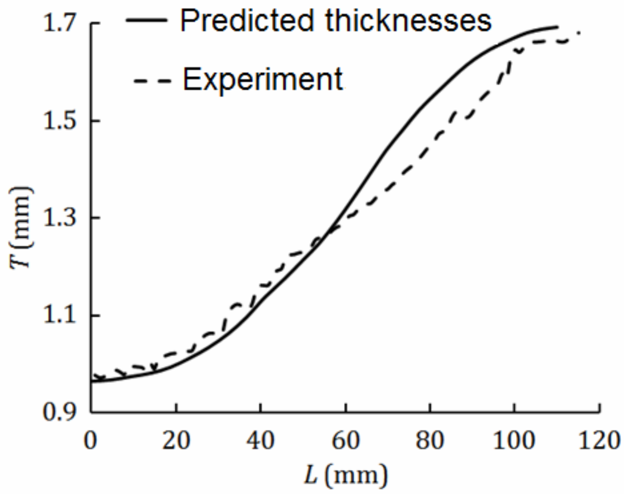

Fig. 6 – Comparison of the predicted thicknesses of the sheet and the experimental measurements.

4. THE NEW PROCESS

Figure 5 suggests that in the final product, maximum of part thinning occurs in the center of the blank and it reduces by moving to the blank edges that have no thickness changes. The main idea of this study is to reduce thicknesses of the zone between the center and edge of the product and consequently improve thinning of the center. This can happen by forming the sheet in the opposite side or manufacturing a pre-form before gas pressure forming as was mentioned in the introduction. In the current study we will use a die that have a movable and a fixed segment. The movable segment is called “internal die” and the fixed segment is called “main die” during this paper. Figure 7 shows the stages of forming in this method. At first internal die is located near the blank and gas pressure forms the blank to the shape shown in Fig. 7b. Then the internal die is moved and joins the main die and makes the final shape of the product illustrated in Fig. 7c. After that gas pressure forms the blank to the final shape. This process is also simulated the same as the common process.

4.1. Process optimization

The objective function of the optimization is to produce a part with uniform thickness. However as it can be seen in Fig. 5, in gas pressure forming, thickness of the part edge is the same as the initial blank and during the process thicknesses reduce in other zones Therefore it can be concluded that if the minimum value of the thickness across the product is increased, a part with more uniform thickness was produced.

The new process has several variables that should be determined in the optimization process including:

- internal die diameter (*r*)
- initial position of the internal die (*H*)
- gas pressure in the first stage of the forming
- time of the first stage of the forming
- gas pressure in the second stage of the forming.

Values of the above mentioned variables are calculated by the genetic algorithm (GA) to maximize the minimum thickness of the final product. GA needs a function that calculates objective (minimum thickness) from the arguments (mentioned variables). In this case the function is not available explicitly and the objective should be compute by FE simulations based on the variables. One method is to directly connect FE calculations and GA to optimize the process. In this method for each set of variables suggested by GA, a FE run should be performed and the calculated minimum thickness returned to the GA.

In this paper a different approach is used. At first, sufficient numbers of FE runs are carried out by the use of python scripting in Abaqus software and then these results are used to train and test the neural network. The neural network is trained to play the role of the GA function and interpolate the objective for new variables. To check the validity of the GA result, after predicting optimized variables by the GA, a FE model by this variable is constructed and predicted thicknesses are compared with the result of common process simulations as it is shown in Fig. 8. Predicted variables are listed in Table 1.

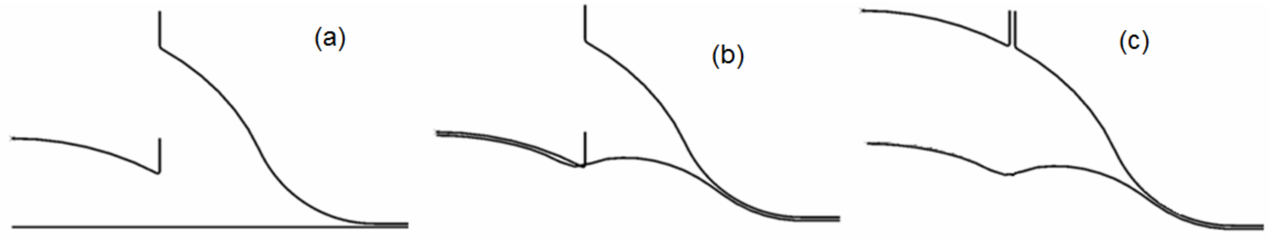

Fig. 7 – The suggested method for two stage gas pressure forming:
a) initial positions of the dies and blank; b) stage one of the forming; c) forming of the blank to its final shape.

Table 1

Optimized process's parameters

variable	value
Internal die diameter (r)	35mm
Initial position of internal die (H)	29.8mm
Gas pressure in the first stage of the forming	2.5bar
Time of the first stage of the forming	15s
Gas pressure in the second stage of the forming	7bar

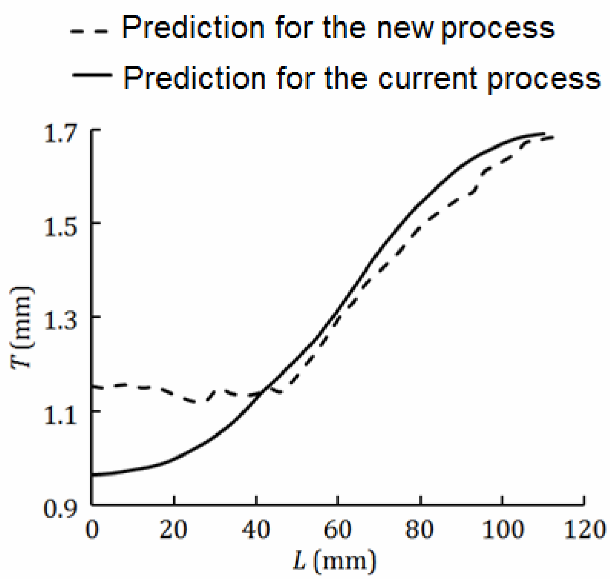

Fig. 8 – Optimized thickness distribution and thickness distribution
of the part produced by common process.

4.2. Experimental investigation

At the final step, dies for the optimized process are designed and manufactured. After producing a part with optimized variables, thicknesses are measured. Figure 9 shows the designed dies. A view of the experiment under a semi-automatic press is also shown in Fig. 10.

Figure 11 depicts the produced hemisphere and the path of thickness measurement. Measured thicknesses in comparison with the measurement on the common process's product are shown in Fig. 12. As it can be seen in this figure, minimum of thickness is increased significantly (about 20 percent). By this increase not only the final product has a more uniform thickness that causes its better performance but also the probability of the material failure during forming is reduced.

As it is mentioned before, the main idea is to reduce thickness of the zone between the center and edge of the part. Figure 13 illustrates predicted thickness after stage one of the process (Fig. 7b). At this time, thickness in this zone is less than others. At the next stage thicknesses will became uniform since the central zone deform more than others.

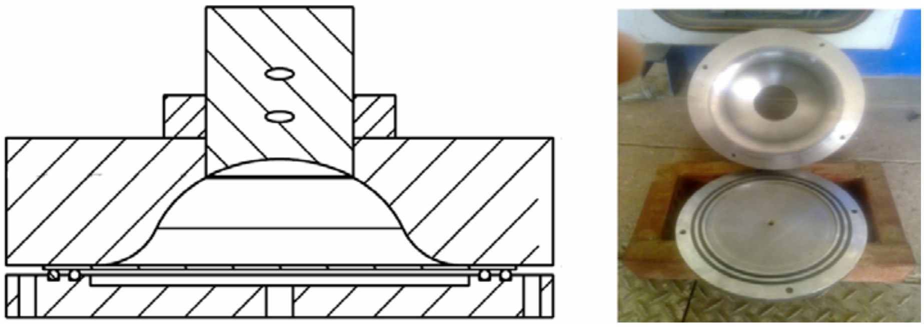

Fig. 9 – The designed dies with optimized variables.

Fig. 10 – Performing the experiment with the use of a semi-automatic press.

Fig. 11 – The produced hemisphere and the path of the thickness measurement.

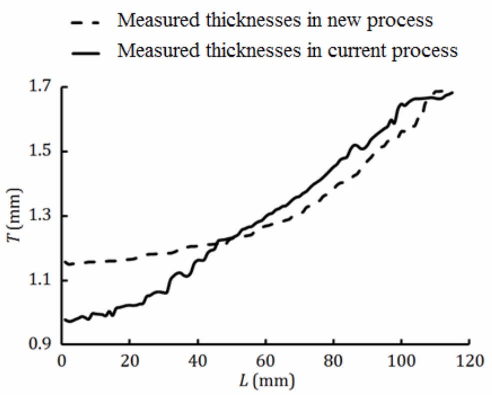

Fig. 12 – Measured thicknesses in both of the common process and the new one.

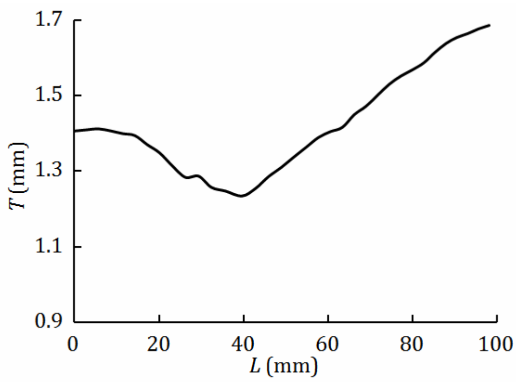

Fig. 13 – Predicted thickness after stage one of the new process (Fig. 7b).

Although Fig. 12 shows a considerable progress in the uniformity of thickness, several works can be done to even improve the resulted distribution including:

- pressure-time diagrams can be applied in each stage
- internal die movement can be gradually and a function of time or in several steps
- this method can be used simultaneously with previous methods mentioned in the introduction.

5. CONCLUSIONS

In this paper a new method was proposed to control thickness distribution in gas pressure forming process and produce a final part with uniform thickness by dividing the die of the process into two segments. Python scripting in conjunction with neural network and genetic algorithm were used to optimize the proposed process. Producing a part by the new method showed improvement of thickness distribution comparing with the common process. Minimum of thickness was increased about 20 percent that causes:

- improvement of product performance
- decreasing probability of part failure in forming.

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