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Investigation of Optimum Process Parameters on the Sheet Hydroforming of Titanium / Aluminum Clad Metal for Battery Housing

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Abstract: This research presents an optimization implement to improve the clad metal formability and design cycle efficiency in sheet hydroforming process (SHF). An integration of finite element FE code (ABAQUS) and optimization code (SmartDO) has been presented for SHF with the consideration of response smoothing technology which can solve the optimum process parameters and avoid the local minimum by surmounting the numerical noise. In addition, a virtual film technique was proposed to realistically simulate the hydraulic loading for metal sheet during SHF. The forming of a 3C product (battery housing) has been carried out both numerically and experimentally, to verity the usefulness of this analysis module.

Keywords: Clad metal, Sheet hydroforming, Virtual film, Finite element, Optimization

1. INTRODUCTION

Recently, the electronics industries are working on reducing the weight of 3C products by using light-weight metals. However, since the formability of light-weight metals such as titanium alloy or magnesium alloy are poor in room temperature, various materials such as clad metal and new forming techniques such as SHF have been developed.

The applications of the clad metal have become progressively popular in recent years. Generally, clad metals not only can preserve the original characteristics of the base metals but also can create additional functional properties. However, most clad metals are produced at room temperature; the residual strain generated in the rolling process cannot be released by the traditional annealing process because the melting temperatures of the individual layer sheets are often different from each other. Therefore, the effect of residual strain on the secondary forming of the clad metal is significant.

SHF is the process that metal sheets were formed by deep drawing punch with a hydraulic counter pressure. The counter pressure was controlled by a relief valve and an additional safety relief valve avoids bursting of the counter pressure. Nowadays, SHF have been widely accepted by industries for the production of components characterized by fine quality, precise dimension, high drawing ratio and complex shape. The application of SHF on clad metal can combine the advantages of both process and material, and thus become promising in producing 3C products.

Finite element analysis (FEA) has become an established tool for predicting the formability of sheet metals. It has enabled significant reduction in the cost and time for design, and facilitation in improving the quality of products. FEA has also been integrated with optimization procedure to efficiently obtain the most suitable process parameters for many forming process including SHF.

Kim et al. compared an implicit and an explicit FE method for the hydroforming simulation of an automobile lower arm. The influences of time scaling and mass scaling were investigated [1]. Kim et al. proposed a multi-stage SHF, which have increased the formability of a structural parts with complex shape [2~3]. Palumbo et al. adopted a moveable inferior plate to enhance the SHF [4~5]. Thiruvarudchelvan et al. provides a technique that uses a hydraulic pressure to apply peripheral push on the flange, which apply counter pressure in the die cavity to provide frictional support at the cup wall and also provide excellent lubrication at the die radius [6]. Lang et al. presented an optimization of the blank shape and studied the effect of the pressure in the die cavity on the formed parts by using a typical aluminum alloy for aircraft manufacturing [7]. Oliveira et al. presented a blank shape optimization procedure that used three numerical tools to determine an optimum blank shape for a formed part [8~9].

2. SIMULATION AND VERIFICATION OF SHF ON CLAD METAL

In this research, an explicit FE code (ABAQUS) was used to simulate the SHF of a battery housing made of Ti / Al clad metal. Fig. 1 shows the CAD model of the battery housing. The influence of important process parameters on the hydroforming was analyzed first. The investigated SHF has been modeled using ABAQUS/CAE. In simulation, a 1/4 symmetric model was utilized. The Ti / Al clad metal was regarded as an equivalent anisotropic material, with material properties determined from tensile tests. The bonded thickness of Ti / Al clad metal sheets is 0.45 mm. The blank was meshed with quadrilateral shell elements while the die, punch, and holder were considered to be discrete rigid bodies. During the forming process, the operative area of blank was modified. Here a virtual film was created that will become the loading surface of pressure. A contact pair was defined between blank and this virtual film, the Coulomb coefficient of friction was set to 0. The thickness of virtual film is set to 0.01 mm, which is an order smaller than the sheet thickness.

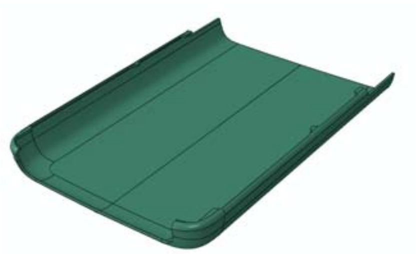

Figure 1 The CAD model of battery housing

A FE model was thus constructed as shown in Fig. 2 (a). For boundary conditions, the punch was specified to move in the z direction and a blank holding force (BHF) was applied on the blank through the holder. Three contact pairs (punch-blank, holder-blank, and blank-die) were defined in this study. The Coulomb coefficient of friction was set to 0.1 for interface between punch-blank and holder-blank, and set to 0.05 for blank-die with oil lubrication. The boundary conditions were shown in Fig. 2 (b). Fig. 3 shows the verification of the above FE model by comparing the thickness distribution with experiment at critical points. This verified model was adopted to be integrated with an optimization code.

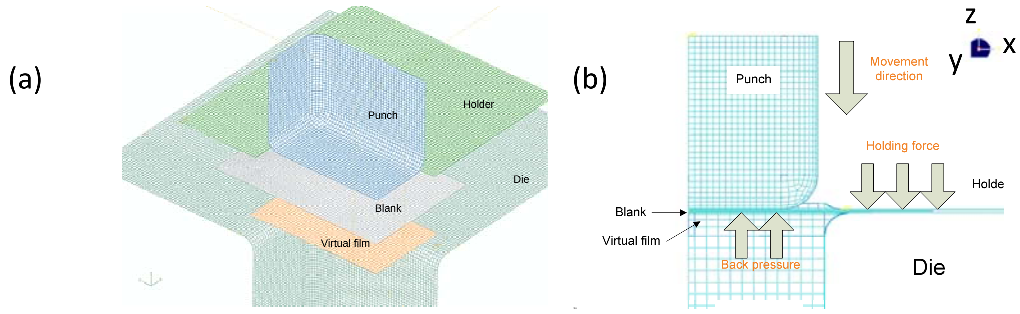

Figure 2 (a) FE model with virtual film, (b) Boundary condition for hydroforming

Figure 3 The verification of FE model with thickness distribution

3. FORMULATION OF THE OPTIMIZATION PROBLEM

Optimization is the action of obtaining the preferable results during the part design. In the CAE-based application of optimization, several situations can cause the numerical noise. When the numerical noise exists in the design analysis loop, it will create many artificial local minimums [10]. Generally, the problems of nonlinear programming can be formulated as eq. (1).

Find a vector $\mathbf{x} = \{x_1, x_2, \ldots\ldots x_n\}$ of design variables to minimize a cost function.

$$f(x_1, x_2, \ldots\ldots x_n) \tag{1}$$

Subject to the p inequality constraints

$$G_i(\mathbf{x}) = \frac{g_i(\mathbf{x})}{g_i^0} - 1 \leq 0 \qquad i = 1, \ldots\ldots, p \tag{2}$$

In addition, simple bounds on design variables such as $x_k^L \leq x_k \leq x_k^U$, $k = 1$ to n, can be specified to provide more feasible design in optimization cycle. Here x_k^L and x_k^U are lower and upper bound. Most of the gradient-based solution algorithms require eq. (1) to be smooth, and can only solve for local optimum. Here, the response smoothing technology in SmartDO code was adopted that will be helpful in searching better solution. In order to achieve this goal, eq. (1) is modified as eq. (3)

To minimize

$$w \cdot f(x_1, x_2, \ldots\ldots x_n) + \mathbf{\Phi} \tag{3}$$

Subjected to the p inequality constraints

$$G_i^*(\mathbf{x}) = \frac{g_i(\mathbf{x})}{g_i^0} - 1 - \phi_i \leq 0 \qquad i = 1, \ldots\ldots, p \tag{4}$$

Here w, $\mathbf{\Phi}$ and ϕ are proprietary formulations which take the values of cost function and constrains into account from the design history. The purpose of these additional functions is to assist the design point out of the local minimum, and modify the search path in the design history.

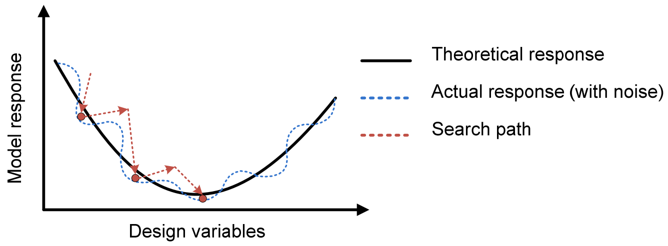

Figure 4 The schematics of the response smoothing technology [10]

4. INTEGRATING ABAQUS AND SmartDO

First of all, the minimization of local thinning condition in the SHF of clad metal battery housing was tested. With the consideration of total element numbers and corner region of battery housing, a cost function of the optimization system was chosen to minimize the thinning ratio of 2% thinnest element.

i.e. Cost function: $f(\mathbf{x}) = -(\frac{t_1 - t_0}{t_0} \cdot 100\%)$ (5)

Where t_0 : the initial thickness, t_1 : the final thickness

The BHF is a significant design variable for formability of blank during hydroforming process, and the constraints of BHF were defined in eq. (6).

0.25 ton $\leqq x_{\text{holding force}} \leqq$ 5 ton (6)

The optimum shape of blank will improve the quality of part, resulting in a more uniform deformation and reduced the restraining force. The two fillet widths of blank were considered to be design variables. In this research, the length and width of blank were invariably defined to be 120mm and 80mm. To avoid unreasonable blank shape, the fillet width were limited and shown in Fig. 5 (a). Point C is intersection point of corner edge of die. Also, a suitable tooling gap will increase the lubrication efficiency between blank and die as shown in Fig. 5 (b). Hence the tooling gap was also chosen as a design variable, and the constraint of tooling gap was defined in eq. (7).

0.4 mm $\leqq x_{\text{tooling gap}} \leqq$ 1.0mm (7)

For hydroforming process, the severe wrinkling condition as shown in Fig. 6 might cause oil leakage and pressure drop, and the resulting counter pressure might be insufficient to support the forming. Hence the upward z-displacement of holder was also chosen as a design variable, and the constraint of upward z-displacement of holder was defined in eq. (8).

0.5 mm $\geqq x_{\text{displacement}}$ (8)

In this research, the hydraulic pressure was defined to be a fixed loading curve with maximum pressure 10MPa in simulation. After inputting the above cost function, design variables, and constraints into SmartDO; a linking program was also built. During the optimization process, whenever the design variables were changed, the linking program will calculate value of the cost function by calling ABAQUS as the analysis solver.

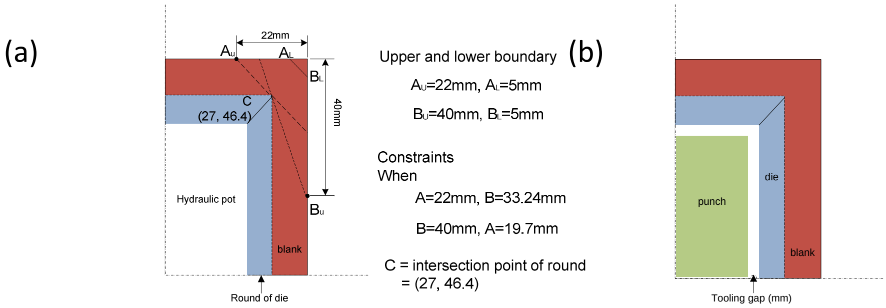

Figure 5 (a) The limitations of fillet width of blank, (b) The tooling gap

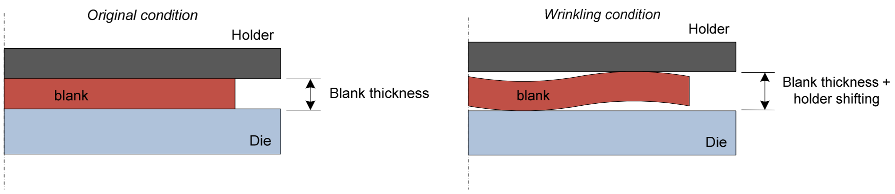

Figure 6 The wrinkling condition of blank in the forming process

Result of optimization

This research integrated the FE code with the optimization code for simulation of SHF of battery housing with Ti / Al clad metal, and successfully decreased the cost function (thinning ratio) from 21.43% to 19.66%. Fig. 7 (a) shows the iteration trend. Fig. 7 (b) shows the optimum thickness distribution of blank. For results of other optimum parameters, the BHF is 3 ton, the tooling gap is 0.453 mm, and fillet widths are 21.4 mm and 37.5 mm, respectively. Fig. 8 compares the initial and optimum blank shape.

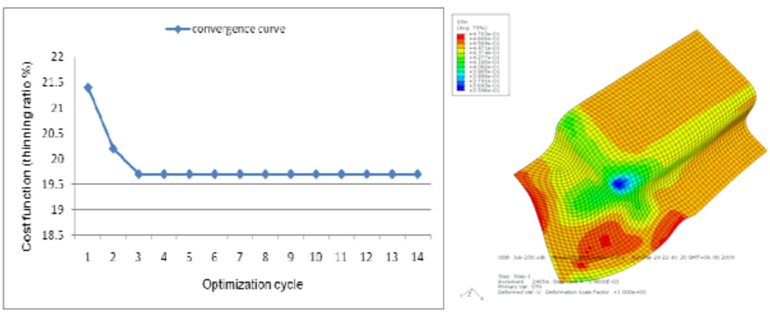

Figure 7 (a) Convergence curve, (b) The thickness distribution of optimum solution

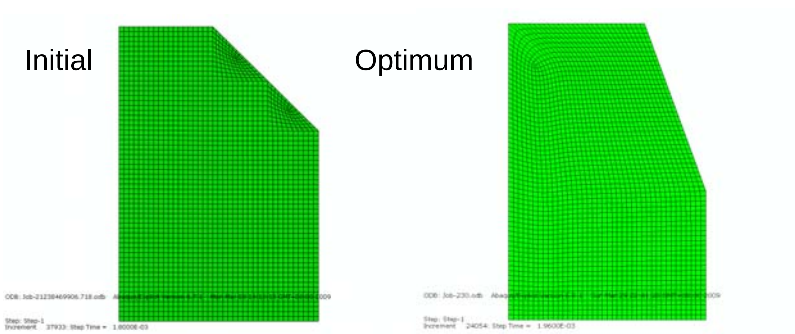

Figure 8 The comparison of initial and optimum blank shape

5. SUMMARY

In this research, a virtual film for applying counter pressure during simulation of SHF was presented. FEA with this technique on the SHF of a Ti / Al clad metal battery housing was verified by experiment. The integration of ABAQUS and SmartDO was tested on clad metal SHF and successfully solved the optimum problem, and avoid the local minimum by surmounting the numerical noise. The optimum process parameters determined were BHF, tooling gap, and fillet width of blank. The cost function (thinning ratio of blank) was improved by 8.2%.

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Submission Information

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