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Numerical simulation-driven optimization of sheet metal drawing part shape①

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Abstract: Numerical simulation and perturbation method were coupled into the iteration process for optimizing the sheet metal part stamping quality, by minimizing the risk of rupture, wrinkle and unstretched area. The optimization of the sheet metal drawing part surface was realized by adjusting the FEM node/element perturbation vector directions and values. The sweeping simplex algorithm was modified to better control the optimization process, and one-step simulation code was used to verify the new design formability. Finally, an autoauto fender drawing part shape optimization testified the proposed methods successfully.

Key words: sheet metal drawing; surface optimization; numerical simulation; modified sweeping simplex; fender

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1 INTRODUCTION

During auto product development process, many structure components/parts and body panels are sheet metal parts that are fabricated through stamping processes. The effective stamping tool and die development can certainly speed up the vehicle product development process and shorten the time to market. While among the stamping techniques, the drawing process is the most important process that shapes most of the geometric features excluding the holes and flanges. During the sheet metal part drawing process design, it's critical to select/determine the feasible process parameters that have potential effect in manufacturing the trouble-free sheet metal parts. These parameters can be categorized into three main classes: 1) operating conditions (including punch load and velocity, blank-holder force, friction); 2) geometry of the blank and the tool and die geometry (including the die work face, addendum and binder-wrap surface); and 3) material properties (including elastic properties, hardening pattern, and anisotropy etc). Unreasonable determination of the process parameters will probably result in the forming defects, such as rupture, wrinkle, unstretchness and springback. The goal of the drawing process design is to optimize the process parameters so that the sheet metal parts could be precisely fabricated[1, 2] in the workshop.

Meanwhile, the FEM-based numerical simulation has been widely used to predict the formability and the forming defects during the stamping process[3, 4]. As a result, this will greatly shorten the die development cycle time, and decrease the die tryout iterations. The numerical simulation method also serves as the tool to check the optimized die and process design[5-7]. The geometric shape optimization has been successfully realized in the field of structural engineering problems[8]. In this paper, a novel method is investigated to integrate the one-step simulation method and perturbation method in optimizing the non-parametric surface of the drawing part to assure the better formability.

2 MATHEMATIC MODEL OF AUTO PANEL DRAWING PROCESS

The optimal mathematical model should be able to precisely describe the specific engineering problems. According to the specific features of the sheet metal drawing parts, three optimal items are illustrated as follows.

2.1 Design variables

In order to precisely grasp the key features of the drawing part, and to flexibly modify the features, two kinds of variables are used to describe the shape of the interested surface area and the effect on the formability.

2.1.1 Drawhead height, H

The determination of H mainly focuses on con-

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sidering the effect of drawhead resisting force, thus the drawhead resisting force model is used in the FEM model rather than generating many small size meshes in the drawhead area. This will save much computation time.

2.1.2 Perturbation vectors

During the sheet metal drawing process simulation, in order to quickly fix the problems resulting in the forming defects, the method is frequently used to move the nodes so that the FEM model and drawing part shape will be changed accordingly. Usually, the number of the nodes is very large, so it's not feasible to define so many node coordinates as the design variables. Based on the Meridian method[9] and the design element[10], the authors first analyzes the initial simulation result, and then defines the domain on the sheet metal part surface that needs shape optimization. Each node in this domain will move along the perturbation vector $\boldsymbol{V}_i$, and $\boldsymbol{V}_i$ is usually the normal direction at that position. Define $\boldsymbol{V}_{\text{cen}}$ as the element basic perturbation vector $\boldsymbol{V}_{\text{basic}}$, and $\boldsymbol{V}_{\text{basic}}$ is represented as follows, as shown in Fig. 1:

$$\boldsymbol{V}_{\text{basic}} = \boldsymbol{V}_{\text{cen}} = \sum_{i=1}^{n} (\boldsymbol{N}_i \cdot \boldsymbol{V}_i) \tag{1}$$

where $\boldsymbol{N}_i$ is the shape function, n is the total number of the interested nodes.

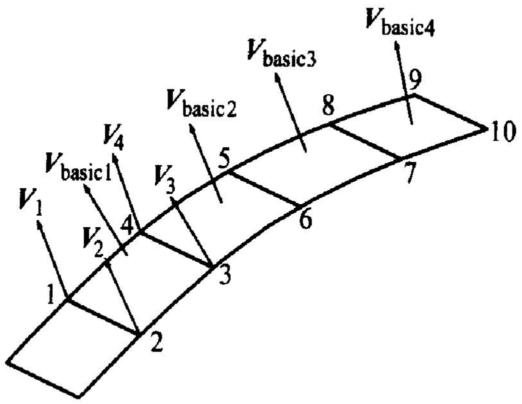

Fig. 1 Domain elements and perturbation vectors

If the angle between $\boldsymbol{V}_{\text{basic1}}$ and $\boldsymbol{V}_{\text{basic2}}$ is less than 8°, the two elements will move in the same direction that is the bisector direction between the above two vectors. All of the moving scales of $\boldsymbol{V}_{\text{basic}}$ are defined as the optimal design variables, and the adjusting value of each node is defined as

$$d_i = \boldsymbol{V}_i \cdot |\boldsymbol{V}_{\text{basic}}| \tag{2}$$

If a domain node (such as node 5 or node 6 in Fig. 1) is located on the edge between the two adjacent elements, the nodal movement value is

$$d_i = \boldsymbol{V}_i \cdot |\boldsymbol{V}_{\text{basic1}} \otimes \boldsymbol{V}_{\text{basic2}}| \tag{3}$$

All design variables are based on the FEM mesh model rather than the CAD model. After the value of each perturbation vector is calculated, it is very convenient to adjust the FEM nodes.

2.2 Boundary conditions

To assure the continuity of the geometric model and to keep the connection between two elements, the boundary nodes are prevented from moving during optimization; while H will be allowed to change within the scope from 2 to 8 mm, and the maximum strain should be larger than 3%.

2.3 Objective function

The goal of the process optimization is to avoid the forming defects, such as fracture and wrinkle. After the numerical simulation is completed, a quantitative criterion should be calculated to check the formability. In this paper, the fracture criterion and the wrinkle criterion are used to generate an integrated criterion. The two fundamental criteria are elaborated as follows.

2.3.1 Fracture criterion

$$f_r = \varepsilon_t / \varepsilon_{t,\text{cri}} \tag{4}$$

where ε_r is the thickness strain, $\varepsilon_{t,\text{cri}}$ is the critical thickness strain.

$\varepsilon_{t,\text{cri}}$ is calculated from the Forming Limit Diagram (FLD)[3]. The higher the f_r, the more likely the fracture appears. Because the comprehensive effect of thinning and thickening prevents getting the exact information about the dangerous area of fracture, ten elements with the highest f_r are selected to calculate the final fracture criterion:

$$f_r = \sqrt{\left(\sum_{i=1}^{10} f_{r,i}\right)/10} \tag{5}$$

2.3.2 Wrinkle criterion

$$f_w = |\varepsilon_{\min} / \varepsilon_{\text{maj}}| \tag{6}$$

where $\varepsilon_{\min}$ and ε_{maj} are the minor strain and the major strain of an element, respectively. The higher the f_w, the more likely the wrinkle appears, too. Similar to the final formulation of f_r, the ten elements with the highest f_w are selected to calculate the final wrinkle criterion:

$$f_w = \sqrt{\left(\sum_{i=1}^{10} f_{w,i}\right)/10} \tag{7}$$

2.3.3 Objective function

The final objective function f can be represented as

$$f = h_r \cdot f_r + h_w \cdot f_w \tag{8}$$

where h_r is the weight factor of f_r, h_w is the weight factor of f_w.

Here $h_r = h_w = 1$ which means the control of fracture has the same weight in the control of wrinkle. The goal of optimization is to minimize the value of the objective function f.

3 PROCEDURES OF SHEET METAL DRAWING PART SURFACE DESIGN OPTIMIZATION

The sheet metal drawing part surface design optimization can be performed following the listed steps as shown in Fig. 2. The one-step simulation method is used to quickly predict the distribution of the strain. Compared with the incremental FEM simulation for loading process, one-step simulation method is very effective in saving computation time with adaptive meshing to calculate the strain distribution, and can be performed even though the die and process have not been fully designed.

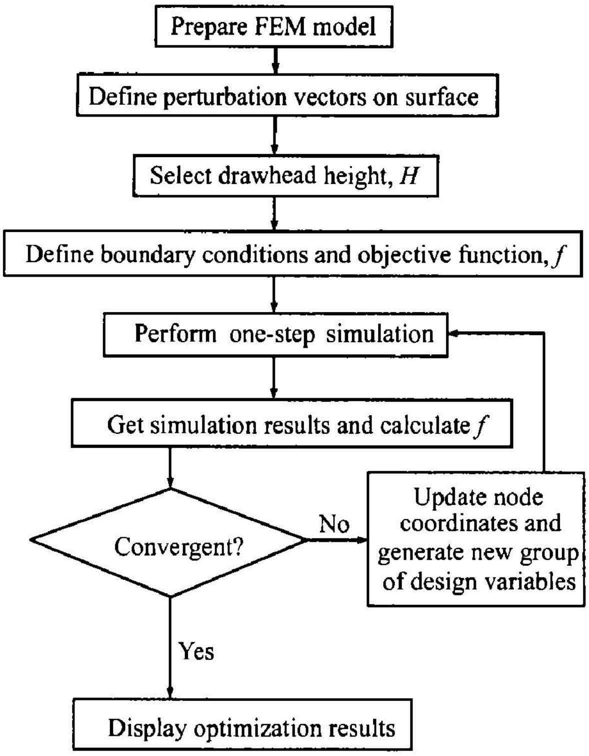

Fig. 2 Flowchart of optimization procedures

In the optimal model, it's difficult to set up the direct relation between the objective function and the design variables. Their indirect relation has to be determined through the numerical simulation. In order to make the optimization process effective and efficient, it needs to select an effective optimal algorithm with fast convergent speed and no specific requirement to the objective function is required. The sweeping simplex (SS) algorithm[11] is selected for controlling the optimization iteration. In order to avoid jumping over the global best solution in the neighboring area during the simplex updating, this paper makes two modifications about SS. Firstly, the algorithm will only perform the operations of "reflection" and of "contraction", and not perform the operation of "extension". Secondly, during each iteration step, the solutions to the design variables will be mapped into the domain space, and this mapping method does not affect the convergence[12]. In this paper, the perturbation value is within [− 10 mm, 10 mm].

4 CASE STUDY

An industrial case of an auto fender is selected to verify the proposed method. For the corresponding drawing part design, the addendum and the binder-wrap surface are designed at first based on the experience. The process parameters and material properties are listed in Table 1, and the initial simulation result for one-step simulation is shown in Fig. 3.

Table 1 Process parameters and material properties

Material	n	σ_b/MPa	m
ST1405	0.21	309	0.15
Anisotropic coefficient	σ_s/MPa	t/mm	Binder holding pressure/MPa
1.6	165	0.8	2

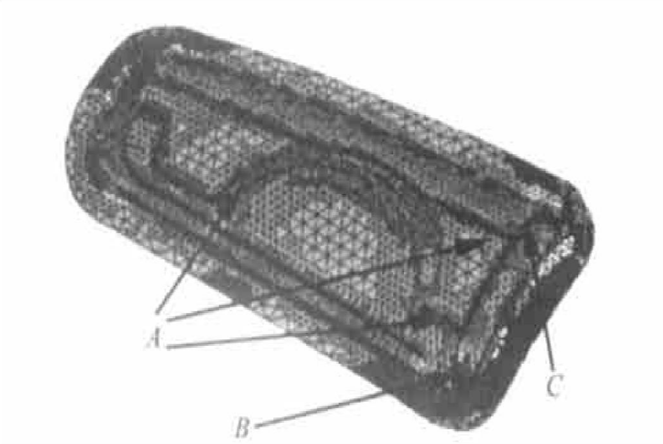

Fig. 3 Simulation result for initial die design

From the analyses of the simulation results, it is found that area A within the trim line has severe thinning which is prone to fracture, while area B within the trim line has severe thickening prone to wrinkle. From the tryout experiment, it's concluded that the shape of area C and the design of the drawhead in the binder-wrap surface near area C have direct effect on the above possible defects. Based on the simulation result, the initial value of the objective function f is calculated, $f = 1.23$. Before the optimization process is initiated, five design variables are defined, among which four variables are the element perturbation vectors as shown in Fig. 4(c) and the remaining is the drawhead height H.

Fig. 4 shows the interesting domain shape that is already discretized by the corresponding elements to be optimized; while the remaining domain on the part surface is not discretized by the mesh. The quadrilateral shell elements of the domain in Fig. 4 are not directly used for one-step simulation, but serves as the base to adjust the shape in this domain. After the domain elements are adjusted, the drawing part surface will be changed accordingly based on the adjusted nod-

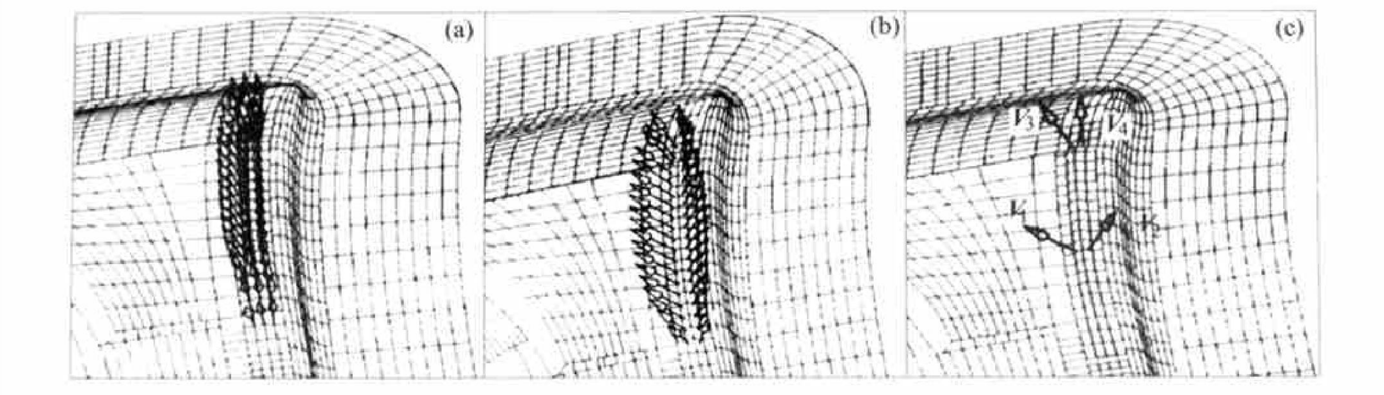

Fig. 4 Shape optimization in domain elements
(a) —Nodal perturbation vectors; (b) —Element basic perturbation vectors; (c) —Design variables

es, and the mesh (triangular shell elements) will be generated for next step simulation and calculation of objective function.

Through iterations, the optimized drawing part design in the formation of FEM mesh is received, and at this time $f = 0.98$. The simulation result for the final iteration step is shown in Fig. 5 where better formability is realized within the trim line.

Fig. 5 Simulation result for final iteration step

5 CONCLUSIONS

The numerical simulation method and perturbation method are integrated in optimizing the shape and drawhead of the auto panel drawing part. The sweeping simplex algorithm is also modified to effectively support optimization. Finally, an auto fender is selected to verify the proposed method. Through eight iterations, the formability is greatly improved to avoid the forming defects. After the optimized sheet metal drawing part shape is determined, the corresponding die design can be easily realized with the feasible input of the drawing part. The proposed method can greatly help the die engineers to find the feasible die design.

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