Simulation-based Prediction Model of the Draw-bead Restraining Force and Its Application to Sheet Metal Forming Process

G. H. Bae¹⁾, J. H. Song¹⁾, H. Huh^{1)†}, S. H. Kim²⁾ and S. H. Park³⁾

¹⁾ Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology,
Science Town, Daejeon, 305-701 Korea

²⁾ School of Automotive, Industrial and Mechanical Engineering, Daegu University,
15 Naeri, Jillyang, Gyeongsan, Gyeongbuk, 712-714 Korea

³⁾ Automotive Steel Research Center, POSCO, Gwangyang, Jeonnam, 545-090, Korea

Abstract

Draw-bead is applied to control the material flow in a stamping process and improve the product quality by controlling the draw-bead restraining force (DBRF). Actual die design depends mostly on the trial-and-error method without calculating the optimum DBRF. Die design with the predicted value of DBRF can be utilized at the tryout stage effectively reducing the cost of the product development. For the prediction of DBRF, a simulation-based prediction model of the circular draw-bead is developed using the Box-Behnken design with selected shape parameters such as the bead height, the shoulder radius and the sheet thickness. The value of DBRF obtained from each design case by analysis is approximated by a second order regression equation. This equation can be utilized to the calculation of the restraining force and the determination of the draw-bead shape as a prediction model. For the evaluation of the prediction model, the optimum design of DBRF in sheet metal forming is carried out using response surface methodology. The suitable type of the draw-bead is suggested based on the optimum values of DBRF. The prediction model of the circular draw-bead proposes the design method of the draw-bead shape. The present procedure provides a guideline in the tool design stage for sheet metal forming to reduce the cost of the product development.

Keywords: prediction model, draw-bead restraining force, Box-Behnken design, tool design

1. Introduction

Sheet metal forming processes have taken an important role in industries because of its various advantages. Product quality of sheet metal parts was effected by many process parameters such as the tool and die geometry, the draw-bead restraining force (DBRF), the blank shape, the friction and so on. The draw-bead has to provide the sufficient drawing force in order to control the material flow into the die cavity. DBRF directly depends on the shape of the draw-bead. The shape of the draw-bead, however, has been determined with expert engineer's experiences or trial-and-error procedures. A systematic tool design scheme incorporated with the accurate estimation of DBRF is necessary prior to the tryout stage of press working in order to reduce the development cost and time of a product efficiently.

The mechanism of DBRF and its application to forming simulation have been the subject of extensive studies in the past several decades[1-4]. Recent researches have been focused on the optimum die design incorporated with prediction of DBRF. Liu *et al.*[5] carried out the optimum design of the draw-bead in drawing tools of an auto-body

cover panel with an improved hybrid optimization algorithm. An analytical model considering anisotropy is adopted to determine the draw-bead dimensions. Jansson *et al.*[6] optimize DBRF adopting response surface methodology and a space mapping scheme in order to control the draw-in displacement of an automotive sheet metal part. Naceur *et al.*[7] combined an inverse approach with a mathematical programming algorithm to optimize the restraining forces and design draw-beads. Song *et al.*[8] carried out the optimum design of DBRF to minimize the amount of

Figure 1. Cross-section of circular draw-bead and flow chart of design procedure

springback in a stamping process of a front side member of an auto-body.

In this paper, a simulation-based prediction model of DBRF is constructed with the Box-Behnken design and applied to the tool design for auto-body members. In order to construct the prediction model, shape parameters such as the bead height, the shoulder radius and the sheet thickness are selected as design variables and draw-bead analyses are carried out in each design case. The DBRF obtained from each design case by analysis are approximated with a second order regression equation. Then, the prediction model is applied to the shape design process of the draw-bead in an auto-body member by considering the formability of a product. The optimization of DBRF is carried out with response surface methodology in order to prevent wrinkling and tearing of a product. The converged optimum design is obtained with the iterative searching algorithm. The suitable type of the draw-bead is suggested based on the optimum values of DBRF. The prediction model of the circular draw-bead proposes the design method of the draw-bead shape.

2. Simulation-based prediction model of DBRF with the Box-Behnken design

DBRF, which is defined as the sum of the bending and friction force, is the main parameter to control the formability of a product. Since the value of DBRF depends on the shape parameters of the draw-bead such as the bead height, the shoulder radius and the sheet thickness, prediction of DBRF considering shape parameters can be utilized effectively at the initial stage of the tool design. In this paper, a new scheme is suggested to predict DBRF of the circular draw-bead with finite element analysis in the design space. The Box-Behnken design is adopted for the approximation of the DBRF obtained from design cases by analysis with a second order regression equation. This equation can be applied practically not only to prediction of DBRF but also to determination of the draw-bead shape when DBRF and stamping conditions are known.

2.1 Circular draw-bead and design variables

The circular draw-bead is generally used in a stamping process of auto-body members since it is suitable to a large amount of the material flow. By reason of its general usage in sheet metal forming processes, the circular draw-bead is selected as an object to develop a prediction model of DBRF. Since DBRF is greatly influenced by the shape of the draw-bead, three design variables such as the bead height, the shoulder radius and the sheet thickness are selected to construct a prediction model. Figure 1 explains the shape of the circular draw-bead and the design procedure.

2.2 Box-Behnken design

The Box-Behnken design is utilized for a reliable approximation of DBRF. The value of DBRF obtained from the analysis is interpolated with a second order regression model. This design scheme has a precious advantage such that the design case constructed with the combination of the maximum or minimum values of the design variable can be avoided. Table 1 shows the range of design variables, which are determined from actual stamping processes. The factorial design technique with three levels is adopted for the selection of design cases.

Table 1. Range of design variables

Design parameter	Bead height (h)	Shoulder radius (R_s)	Sheet thickness (t)
Range (mm)	2~6	3~5	0.6~1.2

Figure 2. Schematics of equivalent draw-bead analysis

Figure 3. Variation of the restraining force during the drawing process

Table 2. Results of DBRF with respect to design variables using Box-Behnken design

Design	h (mm)	R_s (mm)	t (mm)	DBRF (N/mm)	Design	h (mm)	R_s (mm)	t (mm)	DBRF (N/mm)
1	4.0	3.0	0.6	103.81	8	6.0	4.0	1.2	281.64
2	4.0	5.0	0.6	75.28	9	2.0	3.0	0.9	155.61
3	4.0	3.0	1.2	303.92	10	6.0	3.0	0.9	208.13
4	4.0	5.0	1.2	239.53	11	2.0	5.0	0.9	126.62
5	2.0	4.0	0.6	76.16	12	6.0	5.0	0.9	154.00
6	6.0	4.0	0.6	88.21	13	4.0	4.0	0.9	168.72
7	2.0	4.0	1.2	212.58					

2.3 Construction of a prediction model

Finite element analysis is carried out in each design case to construct a prediction model of DBRF. A commercial implicit finite element code, ABAQUS/Standard[9], is employed in the simulation. The material used for the blank is high strength steel of SAPH38. The material properties and the process variables are as follows: the hardening curve of $\bar{\sigma} = 765.8(0.0232 + \bar{\epsilon})^{0.283}$ MPa; the Lankford values of 1.78; and the coefficient of Coulomb friction of 0.15. A blank is discretized with plane-strain elements and the die is modeled with the analytic rigid surface. Considering the accuracy of the numerical simulation, fine meshes are imposed on the blank inside of the die. The analysis is carried out with two step simulations: bead formation; and drawing process as described in Figure 2. The restraining force shown in Figure 3 increases to its ultimate value at the early stage and drops to a stationary value with the moderate drawing distance because the bending force and frictional force of the blank become in equilibrium with the external drawing force. In this case, the drawing distance is 40 mm and DBRF is measured with the averaged value of drawing forces in the steady-state region. Measured results in each design case are also illustrated in Table 2 and the prediction model of DBRF can be constructed as follow:

$$DBRF (N/mm) = -26.93 + 24.87h - 15.98R_s + 159.09t - 3.14hR_s + 23.75ht - 29.89R_s t - 2.95h^2 + 4.18R_s^2 + 85.95t^2 \quad (1)$$

This regression equation interpolates the measured results accurately with the correlation coefficient of 0.9977. This equation can be applied not only to the prediction of DBRF but also to the determination of the draw-bead shape.

Figure 4. Initial tooling system and configuration of draw-beads

Figure 5. Distribution of the thickness and the principal strain on the forming limit diagram (initial design)

3. Application of the prediction model to sheet metal forming processes

The draw-bead plays an important role to enhance the product quality by controlling the material flow into the die cavity. The shape design of draw-beads based on the predicted value of DBRF can enhance the formability effectively at the initial stage of the die design and reduce the development cost of a product. The prediction model can be utilized in the shape design of the draw-bead for auto-body members by considering the formability and quality of a product.

A reinforcement part of a front side member is selected as an example of the optimization. Figure 4 shows the initial tooling system of the reinforcement part for the stamping analysis. A commercial explicit finite element code, LS-DYNA3D[10], is employed in the forming simulation. The material used for the blank is high strength steel of SAPH38 whose material properties were represented in the previous section. The punch speed is fixed to 2 m/s and the blank holding force is assigned as 200 kN. Simulation is carried out until the blank is fully drawn out from the binder. Initial guess of design variables is assumed as 200 N/mm. Figure 5 shows the simulation result with the initial design. The result explains that both wrinkling and tearing is likely to occur with the constant draw-bead force. The optimization region is established to prevent wrinkling and tearing tendency considering the forming limit diagram. DBRF is optimized by considering the formability and quality of the part and then a suitable circular draw-bead is sought with the prediction model in the present tool design.

3.1 Formulation of optimization condition

In sheet metal forming processes, the indicator of fracture is the distribution of the principal strains on the forming limit diagram. If it is possible to control the distribution of the strains on the forming limit diagram, stamping or deep drawing can be safely achieved without fracture and wrinkling. In order to enhance the formability in the optimization region, the distribution of the principal strains is assumed to be a linear curve on the forming limit diagram as shown in Figure 5. The target line is also assumed that the slope has the value increased by the ratio of 20 % from that of the initial distribution line. The objective function is constructed with the least square form so as to minimize discrepancy between the target and the distribution of the principal strains on the forming limit diagram as follows[11]:

$$\text{minimize} \quad \Phi = \frac{\int_{\Omega_{\text{opt}}} (E_1 - \tilde{E}_1)^2 d\Omega}{N} \quad (2)$$

$$\text{subject to} \quad E_1 < \tilde{E}_c \quad (3)$$

where E_1 , $\tilde{E}_1$ and $\tilde{E}_c$ are the major principal strain, the desired major principal strain and the limit strain on the forming limit diagram, respectively. N denotes the number of candidates to be optimized below the target line in the optimization region. It normalizes the objective function value in each iteration step. The constraint condition is assigned so that the principal strains should be located under the forming limit line for prevention of the failure. The minimization procedure of the objective function with response surface methodology provides the optimum restraining force of the draw-bead.

3.2 Optimization of DBRF

Optimization of DBRF is carried out using response surface methodology for enhancement of the product quality in a stamping process. There are 4 design variables assigned because draw-beads located on the opposite side have the same dimension to each other. The Box-Behnken design is also adopted during the optimization procedure for fitting a second order response model. For the optimum searching, the initial perturbation size is assigned as 200 N/mm and the perturbation size is reduced sequentially with the ratio of 50 % after 2 iteration steps. The response surface is approximated into a second order regression model to improve the accuracy of the optimum searching. Procedure for the optimization of the draw-bead force can be summarized as shown in Figure 6. Firstly, the finite element analysis is performed with input data in each design case. Secondly, the objective function and constraint conditions are calculated from these results. Finally, the optimum design is sought by response surface methodology when the change of the objective function becomes sufficiently small. Construction of the response surface of the objective function for optimization is carried out with the help of HyperStudy[12]. Figure 6 depicts the variation of the objective function and design variables during the optimization process. As the optimization step proceeds, DBRF has a steady value in order not to violate the constraint condition. The converged optimum design is obtained after four times of iterative calculations. The simulation result with the optimum design satisfies the constraint line on the forming limit diagram and principal strain is located near the target line as shown in Figure 7. The figure represents that the stamping process could be performed without fracture and local thickening when the optimum value of DBRF is imposed in the simulation.

The optimum value of DBRF is reexamined to check if the circular draw-bead determined is suitable to a real process. When the material of the blank sheet is SAPH38 and its thickness is 0.9 mm, the prediction model shown in Eq. (1) indicates that circular draw-beads

Figure 6. Optimization procedure with RSM and change of variables during the optimization

Figure 7. Distribution of thickness and principal strain on the forming limit diagram (optimum design)

Table. 3 Optimum values of DBRF

Design variable	Bead1	Bead2	Bead3	Bead4
DBRF (N/mm)	163.67	391.96	600.00	69.77

provide DBRF ranged from 128 N/mm to 212 N/mm in the suitable design space. The model can be utilized to decide a type of the draw-bead. The prediction model expects that the circular draw-bead is just applicable to Bead1. There are two other kinds of commonly used draw-beads for sheet metal processes in automotive industries: the step draw-bead; and the rectangular draw-bead. Comparing with the circular draw-bead, the step draw-bead provides the small amount of the restraining force, and the square draw-bead restrains the material flow severely and supplies the large amount of the restraining force in result. Based on the optimum values of DBRF, the step draw-bead is recommended to Bead4 and the rectangular draw-bead is appropriate to Bead2 and Bead3. Shape parameters of Bead1 can be determined mathematically with the prediction model in various types considering the known values such as the sheet thickness and the DBRF.

4. Conclusion

This paper is concerned with a simulation-based prediction model constructed using the Box-Behnken design for sheet metal forming processes to design the draw-bead. The shape parameters such as the bead height, the shoulder radius and the sheet thickness are selected as the design variables and equivalent draw-bead analyses are carried out with respect to each design case constructed with the combination of the design factors. The prediction model is obtained by approximating the analysis result with a second order regression equation for application to the design of the draw-bead in sheet metal forming of auto-body members. Optimization of DBRF is carried out by considering the formability such as wrinkling and tearing of the product. The suitable type of the draw-bead is suggested based on the optimum values of DBRF. The prediction model of the circular draw-bead proposes the design method of the draw-bead shape. The results show that the prediction model and the draw-bead design procedure can be effectively utilized to the initial stage of the die design in sheet metal forming process.

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