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Process Variables Optimization Matching Based on the Stamping Forming Quality Index

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Abstract: The study proposes that stamping forming quality index should include defect quality index and thickness variation uniformity quality index and different types of stamping parts focus on different defect quality index .Moreover, the fracture and wrinkle quality index can be demonstrated by the distance between the major strain of the simulation unit and the critical curve of the fracture and wrinkle trend in FLD, while thickness variation uniformity quality index can be expressed by variance of sheet metal thinning rate. It takes the automobile back plate reinforcement as the example, select stamping quality index as optimization objectives and constraint conditions based on numerical simulation technology, then apply the technical means that contain with orthogonal test design, neural network and genetic algorithm to optimize the process variables. The result indicates that the method of this study is feasible and effective and has application value in engineering.

Key words: Stamping forming, quality index, process variables, optimization matching, numerical simulation

INTRODUCTION

Due to high production efficiency, low processing costs and stability of product dimensional accuracy, the stamping process for sheet metal has been extensively applied in the field of automobile manufacturing. Sheet metal stamping is a large deformation, large displacement and large rotation elastic-plastic mechanical process which has the nonlinearity of the material, contact friction boundary and geometry, while the forming quality defects such as fracture, wrinkle, etc. are often happened during stamping process because of its forming rule has not been fully grasped. The stamping forming quality is generally influenced by various factors such as the forming properties of sheet metal, the shape and size of sheet metal, mold type surface geometry, process conditions, etc, which influence and restrict with each other. That how to match these influencing factors to get ideal stamping forming quality and reduce forming defects is hot issues in production enterprises (Xu et al., 2009; Zhou et al., 2009; Zhao et al., 2007).

With the development of computer technology, the numerical simulation has become an important tool in the current stamping process design and mold design (Li et al., 2011; Kayabasi and Ekici, 2007; Wei et al., 2008) In recent years, there are much research about the prediction of forming quality defects and the replacement of actual experiment by the numerical simulation of sheet metal stamping process which is based on the theory of finite element. There are also much research focused on design methods that combine FE-simulation and optimization methods, such as the design of experiments, genetic algorithms and Artificial Neural Networks (ANN). Xu et al. (2009) studied the spring back control of a car plate based on the intelligent optimization. Li et al. (2011) studied numerical simulation and optimization of a car = s front carling based on Dynaform. Wei et al. (2008) proposed a method to optimize process variables and to predict performance with regard to tolerance in the stamping of deck-lid outer panels. Kayabasi and Ekici (2007) proposed an optimization method to improve the formability of automotive side panels. The optimal values of process variables were calculated by the method. A Pareto-based multi-objective genetic algorithm was proposed by Liu and Yang (2008). Their proposed algorithm was applied for the optimization of process variables, such as the blank holding force and the draw bead restraining force. However, most of the optimal design procedures mentioned above may require repeated FE-analysis with different combinations of process variables again. It is also a little difficult and complicated for engineers in the enterprises to determine optimal process variables. Moreover, it is not clear what is the stamping forming quality index.

The objective of this study is to propose a method of optimizing stamping forming process variables. Firstly this study determine the stamping forming quality index of high quality automobile panel. To optimize the process

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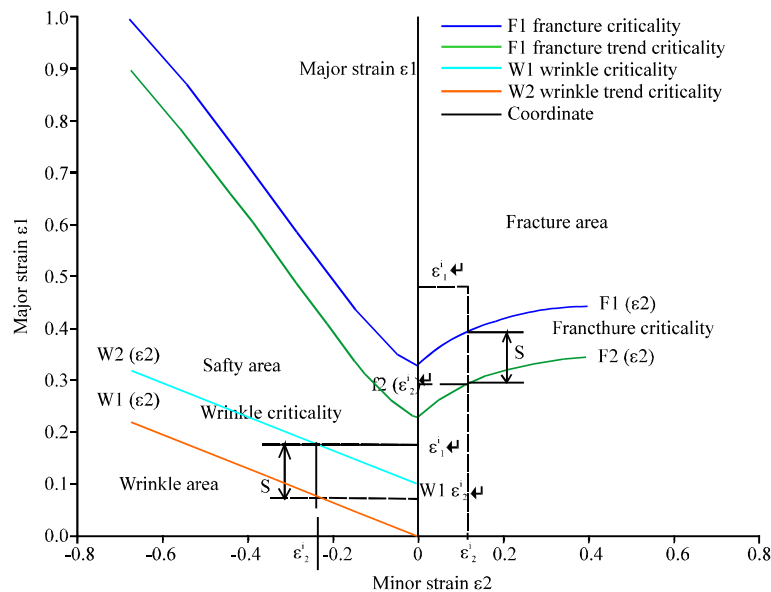
Fig. 1: Critical curve of shape

variables, it takes the blank hold force, the punching speed, the friction coefficient and the sheet size as the design variables and takes the fulfillment of fracture and wrinkle defects quality index as constraint condition and takes the quality index of the thickness variation uniformity as optimization target based on the technology of FE-simulation. Subsequently, to obtain the approximate model of sheet metal stamping forming, the program of numerical simulation is established by orthogonal experiment method, train the simulation result by BP neural network, set up the relationship between process variables and analysis results. Finally the approximate model is optimized by genetic algorithms to obtain the optimal match of process variables.

This study takes automobile back plate reinforcement as an example and combines with the actual needs of enterprise, optimize the process variables using the method mentioned above. The results from optimization are compared with the experimental results.

DETERMINATION OF STAMPING FORMING QUALITY INDEX AND ESTABLISHMENT OF MATHEMATICAL MODEL FOR OPTIMIZATION DESIGN

Automobile panel means the automobile parts that are constitute with automobile body or cab, cover the surface of chassis or engine or interior. According to function and position, automobile panel can be divided into external covering parts, internal covering parts and skeleton covering parts. According to actual stamping deformation characteristics, it also can be divided into deep drawing forming, shallow drawing forming,

expansion deep drawing forming, bending forming, flanging forming and compound forming. As the stamping forming is one complex elastic-plastic mechanics process, the different kinds of quality defect problem are often occurred (Liu and Yang, 2008; An, 2009). How to evaluate stamping forming quality?

The high quality automobile panel products shall have no stamping forming quality defects such as fracture, wrinkle, spring back and surface defect and the material flow of product shall be uniform during the forming process and after forming the thickness changes also shall be uniform. Therefore, this article proposes that stamping forming quality index shall include defect quality index and thickness variation uniformity quality index. As different types of automobile panel contain different materials and have different quality problem, the defect quality index of different panel it focus on will also be different. The automobile = s back plate reinforcement researched in this essay is compound forming internal cover parts, its material is CR2 and thickness is 0.7 mm, its main forming defect is fracture and wrinkle, so the defect quality index it focus on shall include fracture and wrinkle quality index.

Fracture and wrinkle quality index: The determination of fracture and wrinkle quality index in this article is based on Forming Limit Diagrams (FLD). FLD is a graph which describes the ultimate strain of sheet metal in various strain state and it can reflect the relationship between the sheet = s local instability limit strain ε1 and ε2 (real strain) in different strain paths (Ko *et al.*, 2010). The FLD is shown in Fig. 1.

In the research of stamping process based on numerical simulation technology, when the simulation unit = s major strain is locate at fracture critical curve f1 ($\varepsilon 2$) or above fracture trend critical curve f2 ($\varepsilon 2$), the fracture defect may appear in some areas of the parts and the more deviation distance is, the more obvious the fracture trend is; when the simulation unit=s major strain is locate at wrinkle critical curve w1 ($\varepsilon 2$) or under wrinkle trend critical curve w2 ($\varepsilon 2$), the more deviation distance is, the more obvious the wrinkle trend is; When the simulation unit = s major strain is locate between curve f2 ($\varepsilon 2$) and curve w2 ($\varepsilon 2$), it belongs to safety area and this means sheet metal forming quality is good. Figure 1 means the width of wrinkle trend area and fracture trend and it is usually set up according to enterprise requirement. In this article s is 0.1.

In order to quantify the defect quality index, the index f and w that means the distance from the major strain of the simulation unit to critical curve of the fracture and wrinkle trend separately are selected:

$$f = \left(\frac{\sum_1^n \Delta f^i}{n} \right)^{\frac{1}{2}} \quad \Delta f^i = \begin{cases} \left(\varepsilon_1^i - f2(\varepsilon_2^i) \right)^2, & \varepsilon_1^i > f2(\varepsilon_2^i) \\ 0, & \varepsilon_1^i \le f2(\varepsilon_2^i) \end{cases}$$

$$w = \left(\frac{\sum_1^n \Delta w^i}{n} \right)^{\frac{1}{2}} \quad \Delta w^i = \begin{cases} \left(\varepsilon_1^i - w2(\varepsilon_2^i) \right)^2, & \varepsilon_1^i < w2(\varepsilon_2^i) \\ 0, & \varepsilon_1^i \ge w2(\varepsilon_2^i) \end{cases}$$

Where n is the number of calculated units. Obviously the smaller the value of f and w is, the better the quality of the sheet metal forming would be. It is noticed that the calculated unit is the unit of final product.

Quality index of thickness variation uniformity: In statistics, variance can preferably characterize the discrete degree of deviation between each data and average value, while in numerical simulation of sheet metal stamping the thinning rate of sheet (t) is an important index of forming quality. In order to quantify the uniformity degree of the thickness variation after stamping, the variance of thinning rate (t) is used as the quality index in this study. The smaller the value of variance is, the more uniformity and higher forming quality it would be. Its mathematical expression is:

$$S = \frac{1}{n} \sum_1^n \left(t^i - \bar{t} \right)^2$$

Establishment of optimize design mathematical model: In order to optimize technological variables matching, it takes the blank hold force F, the punching speed V, the

Fig. 2: Finite element model of numerical simulation

friction coefficient μ and the sheet size L as the design variables and takes the fulfillment of fracture and wrinkle defects quality index as constraint condition and takes the quality index of the thickness variation uniformity as optimization target based on the technology of finite element numerical simulation. The fracture and wrinkle defects quality index should be less than the allowable value, which is determined by the requirement of part design and the fracture index of allowable value c1 is 0.01 and the wrinkle index of allowable value c2 is 0.05 in this study. The optimization of stamping process variables in sheet metal forming can be abstracted by mathematical model as follows:

$$X = [x_1, x_2, x_3, x_4]^T = [F, V, F, L]^T$$
$$\min. s\,(x) = s\,(x_1, x_2, x_3, x_4)\ X \in R^n$$
$$\text{s.t. } f\,(x) = c_1$$
$$w\,(x) = c$$

ESTABLISHMENT AND VALIDATION OF FINITE ELEMENT MODEL

According to technical requirements of three-dimensional model for automobile back plate reinforcement and manufacturer stamping processes, firstly the three-dimensional model is built with craft supplement in UG, which meets the numerical simulation requirements and accord with stamping processes.

Then it is transmitted into Dynaform software and meshed with quadrilateral element using the adaptive grid technology to achieve grid back-check and repair and the three-dimensional model of punch and die are achieved by using the copy command. According to the actual situation, the stamping direction is adjusted, then the blank sheet, blank holder and the die gap are set up completely to fix position, finally the finite element model of stamping numerical simulation is showed as Fig. 2.

The comparison between the average value in order to verify the accuracy of the finite element model, the thickness measurement for nine regions of forming part shown as Figure 3 is carried out using TM1D Ultrasonic Thickness Gauge.

In measure region and the result of numerical simulation in the same process conditions is made, then

Table 1: Comparison between actual measurement and CAE result

Region			1	2	3	4	5	6	7	8	9
Region 1	Thickness	CAE	0.73	0.65	0.66	0.71	0.72	0.64	0.75	0.63	0.62
		Actual measurement	0.71	0.67	0.67	0.70	0.69	0.66	0.72	0.66	0.65
		Relative error(%)	-2.82	2.99	1.49	-1.43	-4.35	3.03	-4.17	4.55	4.62
Region 4	Thickness	CAE	0.66	0.60	0.61	0.66	0.65	0.59	0.64	0.6	0.57
		Actual measurement	0.69	0.63	0.64	0.68	0.67	0.62	0.66	0.63	0.60
		Relative error(%)	4.35	4.76	4.69	2.94	2.99	4.84	3.03	4.76	5.00
Region 6	Thickness	CAE	0.72	0.66	0.66	0.70	0.68	0.65	0.69	0.66	0.64
		Actual measurement	0.71	0.67	0.65	0.69	0.69	0.67	0.71	0.67	0.66
		Relative error(%)	-1.41	1.49	-1.54	-1.45	1.45	2.99	2.82	1.49	3.03
Region7	Thickness	CAE	0.73	0.65	0.66	0.69	0.68	0.66	0.70	0.61	0.60
		Actual measurement	0.72	0.68	0.67	0.70	0.67	0.68	0.71	0.64	0.63
		Relative error,"%,8	-1.39	4.41	1.49	1.43	-1.49	2.94	1.41	4.69	4.76
Region 9	Thickness	CAE	0.69	0.64	0.64	0.66	0.67	0.63	0.66	0.63	0.62
		Actual measurement	0.67	0.66	0.67	0.67	0.68	0.65	0.69	0.66	0.65
		Relative error,"%,8	-2.99	3.03	4.48	1.49	1.47	3.08	4.35	4.55	4.62

Table 2: The level of each factors in orthogonal experiment method

Level	A/BHF (T)	B/friction coefficient	C/punching speed (mm sec^{-1})	D/size of the sheet (mm)
1	15	0.100	3500	0.0
2	20	0.125	4000	2.5
3	25	0.150	4500	5.0
4	30	0.175	5000	7.5
5	35	0.200	5500	10.0

Fig. 3: Measure region of TM1D

the maximum value of relative error is less than 5%, which indicates the good agreement between CAE and actual result. Some results of comparison are shown in Table 1.

OPTIMIZATION OF PROCESS VARIABLES MATCHING

It is the complex nonlinear relationship between process variables and forming quality index in forming process. In order to optimize the process variables, the program of numerical simulation is established by orthogonal experiment method in this study, it perform the finite element numerical simulation in Dynaform software, train the simulation result by BP neural network, set up the mapping relationship between design variables and analysis results and obtain the approximate model of sheet metal stamping,

finally the approximate model is optimized by genetic algorithms to obtain the optimal match of process variables.

In order to obtain the training sample data in BP neural network, the five levels of the four factors which are BHF, friction coefficient, punching speed and size of the sheet are selected and shown in Table 2 according to the actual production situation and computing requirement in Dynaform. It is noticed that the size of the sheet means offset value which outwardly extended on the basis of the initial sheet size (the initial sheet size is the limit blank size which is obtained by expanding the parts using the BSE module in Dynafrom).

According to test factor and number of test levels, the orthogonal table test program $L_{25}(5^4)$ is selected (Table 3) and the quality index of thickness changing uniformity s is obtained under the condition of meeting fracture and wrinkle quality index.

Theoretical analysis shows that any complex nonlinear model can be expressed by three-layer BP network which consists of input layer, hidden layer and output layer and it can solve the uncertain fuzzy problem in modeling effectively (Chen *et al.*, 2011). The input of the network is the design variables which are blank holder force, friction coefficient, punching speed and sheet metal extension size, the quality index of thickness variation uniformity s is used as the output of the network. As the physical meanings of inputs in network are different and the differences of input value are great, the normalization for each input is processed. According to empirical formula, it is determined that the number of hidden layer nodes is 9, the transfer function of the input layer and the hidden layer is tansig, the transfer function of the output layer is purelin, then the establishment of the network is: net=newff(minmax(P),[91],{'tansig','purelin'},'traingdm', 'learngdm','mse').

Table 3: Orthogonal table

Test	A	B	C	D	s	test	A	B	C	D	s
1	1	1	1	1	0.0189	14	3	4	1	3	0.0162
2	1	2	2	2	0.0161	15	3	5	2	4	0.044
3	1	3	3	3	0.0183	16	4	1	4	2	0.0155
4	1	4	4	4	0.0248	17	4	2	5	3	0.0225
5	1	5	5	5	0.0229	18	4	3	1	4	0.0462
6	2	1	2	3	0.0274	19	4	4	2	5	0.052
7	2	2	3	4	0.0211	20	4	5	3	1	0.0357
8	2	3	4	5	0.0263	21	5	1	5	4	0.0361
9	2	4	5	1	0.019	22	5	2	1	5	0.0511
10	2	5	1	2	0.0285	23	5	3	2	1	0.0234
11	3	1	3	5	0.0276	24	5	4	3	2	0.0137
12	3	2	4	1	0.0183	25	5	5	4	3	0.0633
13	3	3	5	2	0.0244						

Table 4: Error between numerical simulation and neural network training

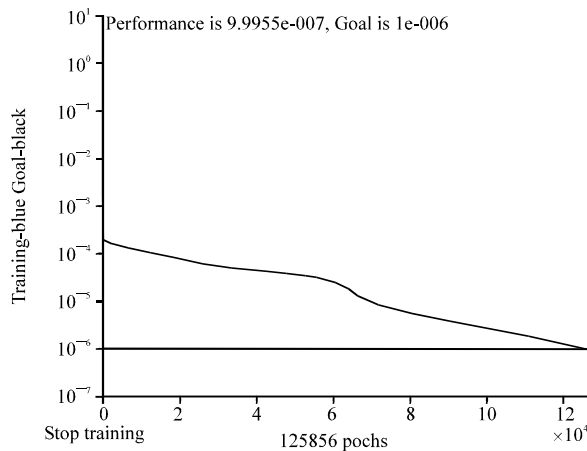| BHF(T)	Friction coefficient	Punching speed (mm)	Sheet metal extension size	Value of s by numerical simulation	Value of s by network forecast	Relative error (%)
15	0.100	4500	2.5	0.0283	0.0272	3.77
30	0.125	5000	0.0	0.0275	0.0277	0.78
25	0.150	5000	5.0	0.0531	0.0554	4.26

Fig. 4: Training error curve

Fig. 5: Mean of population's objective

The 25 groups of orthogonal test data are taken as the neural network training sample data and another 3 groups of numerical simulation data are used as test sample data. After 125,856 iterations, the system error reach 1.0×10^{-6} and the training error curve of neural network is shown in Fig. 4. The three groups of numerical simulation data are used for checking and the error between numerical simulation and network training is less than 5% shown in Table 4, which approve the reliability of the established network model of neural network function and the variation of optimal solution the genetic algorithm is an iterative adaptive global optimization probability search algorithm based on the ideas of biological evolution which has the feature of simple universal and great robustness. The range of the design variables is between the minimum and maximum values of the
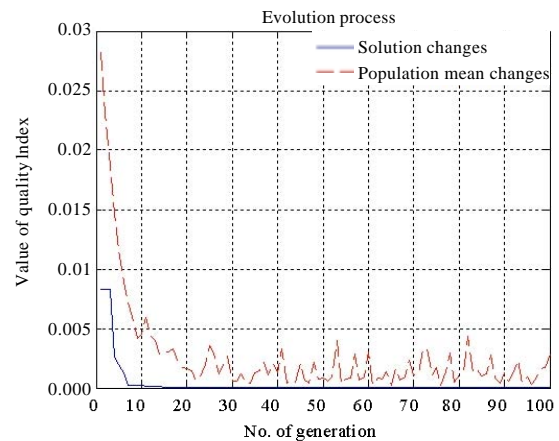
variables' level in orthogonal design in this study and the quality index of the thickness variation uniformity was selected as optimization objectives. Initial population is generated randomly with the scale of 50 using binary encoded form and each variable corresponds to a 20-bit binary code string. The probability of crossover is 0.7, the probability of mutation is 0.01 and the maximum number of iterations is 100. The target value which is predicted by BP neural network is selected as fitness function in order to control the variance of sheet thinning rate. After 100 iterations, the mean of population's objective function and the variation of the optimal solution are shown in Fig. 5. The matching program of optimal process variables is gotten: the BHF is 26T, the friction coefficient is 0.17, punching speed is 4886 mm sec^{-1}, sheet metal extension size is 8 mm.
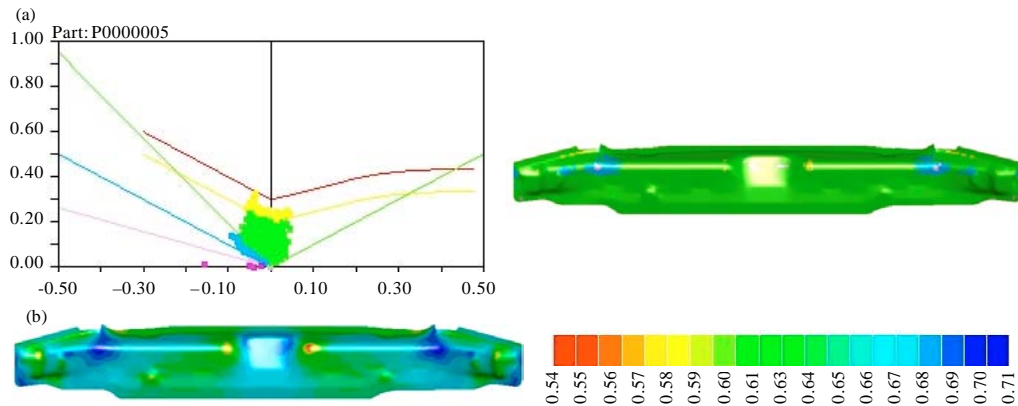
Fig. 6(a-b): Result of numerical simulation after optimization, (a) Forming limit diagrams and (b) Cloud map of thickness

Fig. 7: Practicality stamping test result

Fig. 8: Point cloud of the stamping part using laser scanner

COMPARISON BETWEEN TEST RESULTS AND NUMERICAL SIMULATION AFTER OPTIMIZATION

According to the optimization results, the forming process variables are set up in Dynaform, then the numerical simulation result is shown in Fig. 6 and the value of quality index s which describes the thickness variation uniformity is 0.027. It can be seen from the figure that the quality of back plate reinforcement is good without fracture and wrinkle and the variation of thickness is uniform. The stamping part which is gotten by practicality stamping is shown in Fig. 7, the point cloud of the stamping part is obtained in Fig. 8 using laser scanner. The thickness of the part is achieved by measuring the distance between the front and rear section line which spilt the stamping part. The quality index of the thickness variation uniformity s is 0.0304 by measurement and the relative error between it and numerical simulation result is 11.18%, which demonstrates the great fit between numerical simulation and test. It shows that the technical means combined with numerical simulation, orthogonal experimental design, neural networks and genetic algorithms is feasible and effective to optimize the stamping process variables.

CONCLUSION

- The high quality automobile cover parts products should have forming variation uniformity features without stamping forming quality defect. This article put forward an idea that stamping forming quality index should include defect quality index and thickness variation uniformity quality index. Different types of stamping parts focus on different defect quality index and the fracture and wrinkle quality index can be demonstrated by the distance between the major strain of the simulation unit and the critical curve of the fracture and wrinkle trend in FLD, while the thickness variation uniformity quality index can be expressed by the variance of sheet metal's thinning rate
- It take the automobile back plate reinforcement as the example, select tamping quality index as optimization objectives and constraint conditions using numerical simulation technology, then apply the technical means that contain with orthogonal test design, neural network and genetic algorithm to optimize and match the process variables, finally the result show that this method is feasible and effective and has application value in engineering

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