Optimal Metal Mold Design Using MSC.AutoForge and Statistical Design Support Software DesignDirector

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Abstract

This paper is a brief introduction of DesignDirector and an example of optimization of metal mold design collaborated with MSC.AutoForge. Our goal is to optimize metal mold design using MSC.AutoForge and DesignDirector. We use DesignDirector to make decisions about optimized metal mold design. DesignDirector is an optimization software that employs the Design of Experiment and the Mathematical Programming to achieve the optimal calculation of nonlinear problems.

The Design of Experiment, combined with a series of finite element analyses (FEA), is used to generate approximate evaluation functions for controlling behaviors depending on the changes in design variables. The Mathematical Programming is employed to solve the optimal calculation of the approximate evaluation functions of the behavior.

These methods realize the optimization of nonlinear problems, like metal mold design, with a small number of FEA.

Introduction

One of the most practical methods for optimization of nonlinear problems was proposed by Dr. M. Shiratori at Yokohama National Univ. in Japan[1]. This method employs the Design of Experiment (DOE) [2], so it is called the Statistical Design Support System (SDSS).

Though a variety of methods for the optimal design are proposed, most of them are complicated and their efficiencies are low. The reason for their low efficiency is that these methods incorporate structural analyses and sensitivity analyses in their loops for optimization calculations. SDSS uses response surface equations , predicting the outcome of structural analyses, in their loops for optimum calculations, instead of structural analyses and sensitivity analyses. The response surface equation is generated by DOE, and it is possible to describe the nonlinear phenomena. Thus the SDSS method enables us to do an optimization calculation for a nonlinear problem efficiently.

We developed an optimization software DesignDirector[3] based on SDSS, and we are trying to apply it to the metal mold design. This paper shows the ability of optimal metal mold design with DesignDirector collaborated with MSC.AutoForge.

Theory of DesignDirector

DesignDirector is an optimization software based on the SDSS method, which employs two major mathematical methods. The first one is the Design of Experiment (DOE). DOE combined with a series of finite element analyses (FEA) generates the response surface equation depending on changes in design variables of an object structure. The response surface equations are expressed by a orthogonal polynomial of equation[2] and predict the characteristic behavior of a design structure.

The other method is successive quadratic programming (SQP), a kind of mathematical program, which is one of the most efficient methods against nonlinear optimization under constraints. DesignDirector uses SQP to solve the optimization problem expressed by the response surface equations generated by DOE. As a result, DesignDirector optimizes the nonlinear problem efficiently.

Besides the optimization, DesignDirector has the following functions estimating the characteristic behaviors : the effectiveness analysis, the reanalysis, and the evaluation of dispersion.

It has been confirmed that DesignDirector can be used for almost all kinds of nonlinear problems, including the forge process, and that they can be solved in a much smaller number of FEA than other existing methods.

Optimization with MSC.AutoForge

We are trying to apply DesignDirectorfor the optimization of a forge metal mold design with MSC.AutoForge. The forge process behavior involves large deformation and material nonlinearity, so we use MSC.AutoForge to simulate the forge process and to get the response values that measure the characteristic behaviors of forge process. The flowchart of metal mold optimization is illustrated below.

***Figure 1**. The collaboration between DesignDirector and MSC.AutoForge*

The first thing the operator has to do is to choose important design factors that affect the responses and to decide the range of the design factor variables. This information is input to DesignDirector, and a series of combinations of design factor values will be produced. A series of FEA simulations based on the each combination of design factor values will be carried out by MSC.AutoForge to get the response values of the forge process. During this trial, an interface-software which produces the procedure files to operate MSC.AutoForge was developed. A series of FEA calculations of MSC.AutoForge was conducted by this procedure file automatically.

After conducting a series of FEA calculations, the response values are input to DesignDirector and response surface equations of each character are generated automatically. These response surface equations are used for the optimization, the reanalysis, the sensitive analysis, and the evaluation of dispersion.

This collaboration between DesignDirector and MSC.AutoForge will generate response surface equations of the characters of the forge process and result in the optimal design of the forge process.

Application for Metal Mold Design

We tried to optimize a simple example to confirm the ability of the optimization of metal mold design by DesignDirector and MSC.AutoForge. The example was to optimize the die and the punch, which compresses a plate between them at the upsetting process. The purpose of optimization is to determine the punch and die shape, which keeps the surface of the workpiece flat.

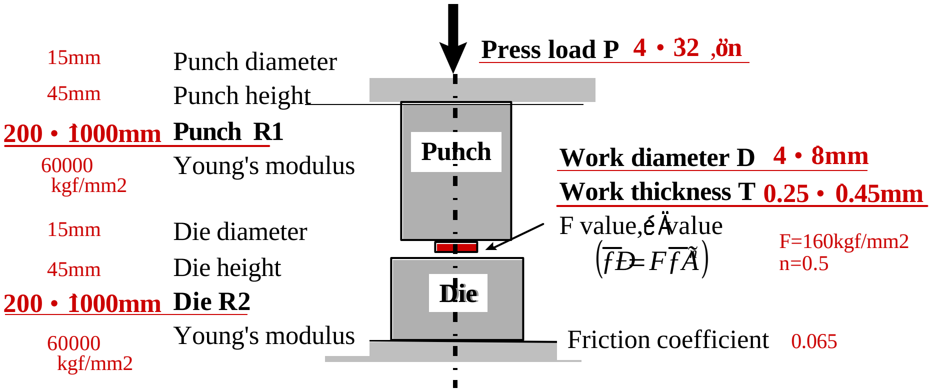


***Figure 2.** The punch and the die*

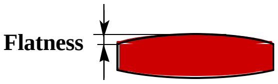


***Figure 3.** The definition of workpiece flatness*

This process is a compression of an axisymmetric plate between the deformable die and the deformable punch (Figure 2). The punch and die are deformed by a presser, so that the punch and die have a round shaped surface to keep the workpiece flat after it is released from the punch and the die. In the above example, the round shape of the die and the punch was determined by the workpiece shape and the press load P, under the constraint that the stress at the die and punch was kept under the desirable value.

The flatness of the workpiece (objective function in the example) was defined as the space in Figure 3. The design factors and response variables are written below and the others are constant.

Analysis

Design of Experiments

To get the response surface equations of the characters, we ran a series of FEA calculations based on the different design factor values. DesignDirector generates a series of combinations of design factor values based on an orthogonal array, so that the times of FEA analysis are reduced. In this case, five design factors were chosen and DesignDirector showed us 81 combinations of design factor values (Table1). After that, 81 FEA models were produced and run by MSC.AutoForge automatically by the procedure file to get the response values of characteristic behavior.

The design factors:

- Radius of the punch surface R1
- Radius of the die surface R2
- Workpiece diameter D
- Workpiece thickness T
- Press load P

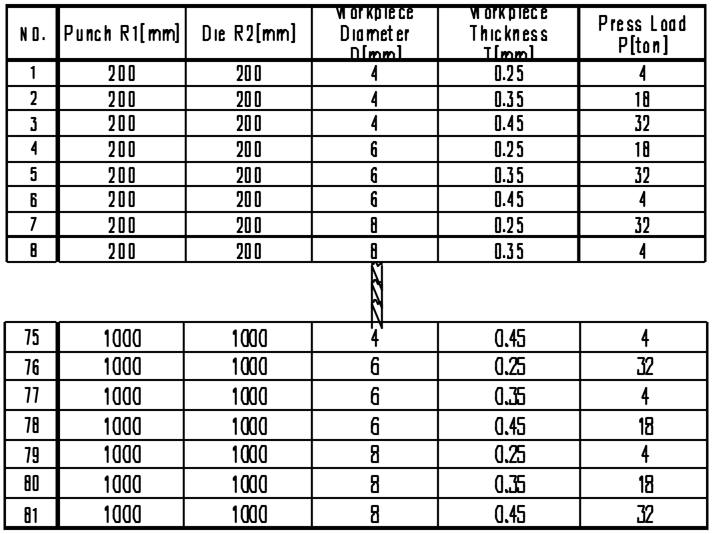
The response variables:

- Flatness
- Punch stress
- Die stress

Table 1. *The combinations of the design factor values*

Factors

81 Cases



NO.	Punch R1[mm]	Die R2[mm]	Workpiece Diameter D[mm]	Workpiece Thickness T[mm]	Press Load P[ton]
1	200	200	4	0.25	4
2	200	200	4	0.35	18
3	200	200	4	0.45	32
4	200	200	6	0.25	18
5	200	200	6	0.35	32
6	200	200	6	0.45	4
7	200	200	8	0.25	32
8	200	200	8	0.35	4
75	1000	1000	4	0.45	4
76	1000	1000	6	0.25	32
77	1000	1000	6	0.35	4
78	1000	1000	6	0.45	18
79	1000	1000	8	0.25	4
80	1000	1000	8	0.35	18
81	1000	1000	8	0.45	32

Finite Element Analysis

Because of the axisymmetric nature of the geometry, this process can be idealized to an axisymmetric model. The die and the punch are modeled as a deformable body in order to assume the deformation of the die and the punch. The contact between the die, the punch, and the workpiece is assumed to have friction. Here it is assumed that the upsetting process takes place at room temperature. An example of the FEA model is shown in Figure 4.

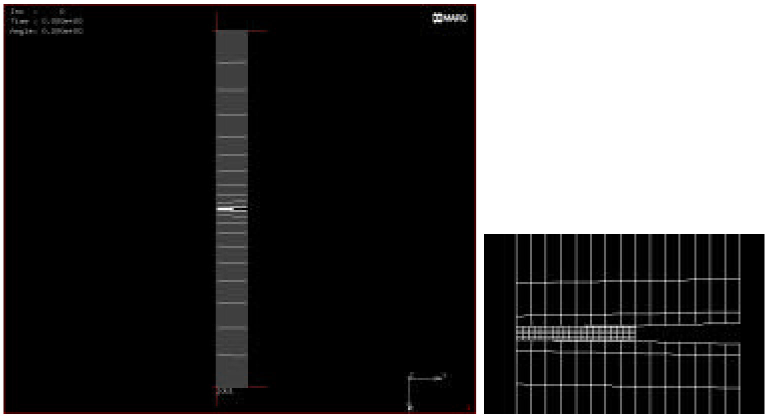


Figure 4. *An example of the FEA model for simulating the upsetting process*

Results

Estimation Expression

The response surface equations for the upsetting process were generated in terms of the design factors((1),(2),(3)), which were regarded as significant by the variance analysis (Criterion used 5% risk rate in F-Table). The variables R1 , R2 , D , T, and P in the equations represent the design factors.

Flatness F(R1 , R2 , D , T , P)=
1.808942E-02-7.196936E-05*R1+2.959266E-08*R1^2+1.522639E-06*R2-6.650702E-03*D+6.994992E-
03*T+4.170708E-03*P-6.842709E-05*P^2+2.186639E-05*R1*D-1.231727E-08*R1^2*D-7.102083E-
07*R2*D-2.537245E-03*T*P+7.047902E-05*T*P^2+4.271042E-05*R1*T-3.969293E-04*D*P+7.26311E-
06*D*P^2-7.009584E-03*D*T+2.354977E-06*R1*P-2.025758E-08*R1*P^2-8.805431E-10*R1^2*P
(1)

Punch stress G(R1 , R2 , D , T , P)=
2019.212-.5594194*R1+4.537251E-04*R1^2-.5591987*R2+4.536466E-04*R2^2-
560.104*D+45.48388*D^2-3379.048*T+140.0511*P-2.267204*P^2+1.852836E-03*R1*R2-1.54403E-
06*R1^2*R2-1.54403E-06*R1*R2^2+1.286692E-09*R1^2*R2^2-9.083118*T*P+.8119346*T*P^2-
9.57942*D*P+.1797035*D*P^2+1001.106*D*T-83.42547*D^2*T-1.232962E-02*R2*P+7.627038E-
06*R2^2*P-.0123809*R1*P+7.665888E-06*R1^2*P (2)

Die stress H(R1 , R2 , D , T , P)=
2019.21-.5591845*R1+4.536353E-04*R1^2-.5594288*R2+4.537325E-04*R2^2-
560.1034*D+45.48383*D^2-3379.042*T+140.051*P-2.267203*P^2+1.85283E-03*R1*R2-1.544025E-
06*R1^2*R2-1.544025E-06*R1*R2^2+1.286687E-09*R1^2*R2^2-9.083235*T*P+.8119396*T*P^2-
9.579407*D*P+.1797032*D*P^2+1001.104*D*T-83.42529*D^2*T-1.238065E-02*R2*P+7.665678E-
06*R2^2*P-1.232991E-02*R1*P+7.627274E-06*R1^2*P (3)

Optimization Calculation

To minimize the flatness (this is, to minimize the space in Figure 3), the optimization calculation was done by the SQP method using the response surface equations (1),(2),(3). As the constraint conditions, the maximum level of stress was assigned to prevent the damage of the punch and the die by a load pressure. In this calculation, all the design factors were assumed to be continuous variables.

The result of the optimization calculation is written bellow.

(1) Design factors: R1 , R2 , D , T , P
(2) Objective function: Flatness of plate [F(R1 , R2 , D , T , P)] -> Minimize
(3) Constraints:
  Max. punch stress [G(R1 , R2 , D , T , P)] 650Kgf/mm2
  Max. Die stress [H(R1 , R2 , D , T , P)] 650Kgf/mm2
  $200\ mm\ \ R1,R2\ \ 1000\ mm \qquad 4\ mm\ \ D\ \ 8\ mm$
  $4\ ton\ \ P\ \ 32\ ton\ \ 0.25\ \ T\ \ 0.45$
(4) Results of Optimization
  Objective value: 0.1e-6 mm
  Variable: $R1 = 290\ mm, R2 = 290\ mm\ \ (At\ D = 6.1\ mm\quad T = 0.25\ mm\quad P = 9.5\ Ton\rangle$

Conclusion

In conclusion, the characteristics of the collaboration of DesignDirector and MSC.AutoForg are described below:

(1) DesignDirector is applicable to nonlinear problems.
(2) DesignDirector is very practical because it is possible to make use of existing programs for a structural analysis.
(3) The collaboration of DesignDirector and MSC.AutoForge have resulted in the optimization of the metal mold design for the upsetting process and are capable of optimizing more complicated forge processes.

References

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