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Investigation of Simulated Annealing Method and Its Application to Optimal Design of Die Mold for Orientation of Magnetic Powder

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***Abstract* - Factors affecting the results obtained by the optimal design method using the finite element and simulated annealing are investigated systematically, and the optimal parameters for simulated annealing method are obtained. The optimal shape of the die mold for orientation of magnetic powder is obtained using the finite element and simulated annealing. The experimental verification is also carried out.**

I. INTRODUCTION

In order to obtain the optimal shape (global minimum of objective function) of an electric machine, the simulated annealing method [1-2] should be combined with the finite element method. Although it is pointed out that the parameters, such as temperature parameter, used in the simulated annealing affect the convergence characteristics and results obtained, the systematic investigation for the optimal parameter is not investigated in detail.

In this paper, the factors affecting the convergence characteristics and the obtained results using the simulated annealing are investigated systematically. The combined method using the finite element and the simulated annealing is applied to the optimal design of the mold of die press with electromagnet for orientation of magnetic powder (nonlinear magnetostatic problem). A die press models which correspond to the initial and optimal shapes are produced and the flux distributions are measured .

II. SIMULATED ANNEALING METHOD AND ANALYZED MODEL

Fig.1 shows the flowchart of the simulated annealing method. The maximum numbers Ns and Nt of iterations, the reduction factor rt and the coefficient k related to the initial value of the temperature parameter affect the convergence characteristics and the results obtained.

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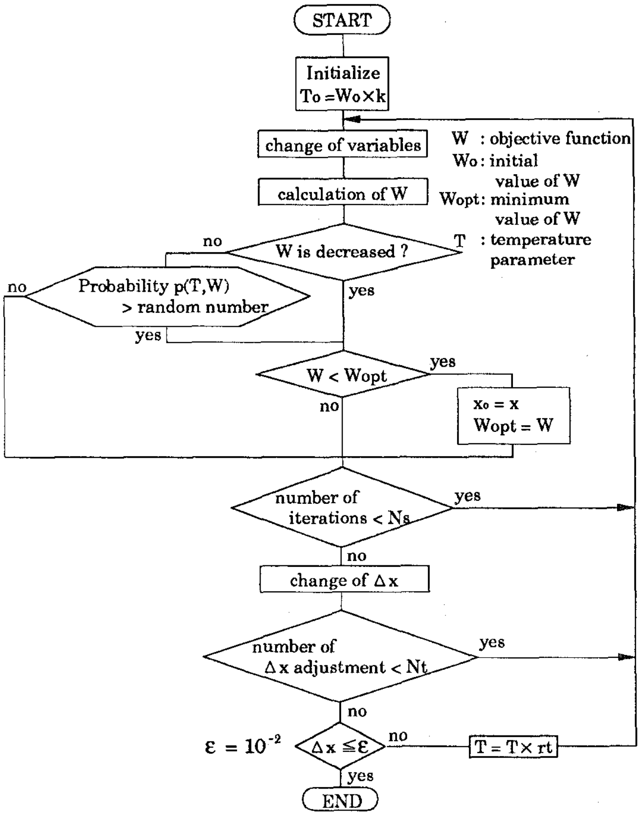
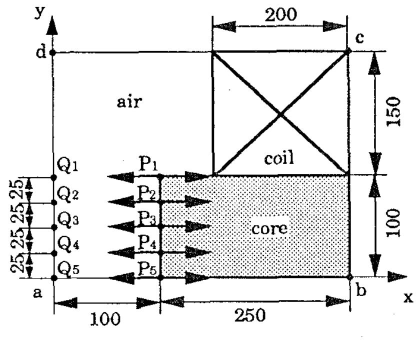


Fig.1 Flowchart.



a - b : Dirichlet boundary
a - d - c - b : Neumann boundary

Fig.2 Analyzed model.

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Fig. 2 shows the model investigated. The ampere-turns of the coil are 45kAT. The coordinates of points Pi(i=1~5) of pole piece are chosen as design variables. x- and y- components Bxi, Byi at the points Qi (i=1~5) are specified as Bxio=1, Byio=0T, respectively. The optimal shape of the pole piece which minimizes the following objective function is obtained using FEM and the simulated annealing method.

$$W = \sum_{i=1}^{n}\left\{\left(B_{xi} - B_{xio}\right)^2 + \left(B_{yi} - B_{yio}\right)^2\right\} \qquad (1)$$

where n is the number of specified points. The convergence criterion of the step size Δx is chosen as 10^{-2}mm as shown in Fig.1.

III. FACTORS AFFECTING CONVERGENCE OF OPTIMAL DESIGN METHOD

Table I shows the effect of the maximum numbers Ns, Nt on the number of iterations, CPU time and the value Wopt of objective function at the optimal shape (rt=0.9) . If the total number of iterations exceeds 50000, the iteration is stopped. As the result of Ns=Nt=10 is the same as that of Ns=Nt=25, twice(=10) of the number of design variables(=5) may be sufficient for Ns and Nt. Table II shows the effect of rt (Ns=Nt=10). Fig.3 shows the process of convergence of the objective function W. The objective function W may not reach the value of the global minimum if the reduction factor rt is small. The table suggests that rt=0.9 may be suitable.

Table I Effect of Ns and Nt(rt=0.9)

Ns	Nt	number of iterations	CPU-time (s)	Wopt ($\times 10^{-5}$)
5	5	2442	632	83.9
10	10	11892	3100	9.86
15	15	25442	6590	9.87
20	20	44282	11500	10.3
25	25	50000	13000	9.87

Table II Effect of parameter rt(Ns=Nt=10)

rt	number of iterations	CPU-time (s)	Wopt ($\times 10^{-5}$)
0.7	3302	846	20.8
0.9	11892	3100	9.86
0.95	20222	5210	14.0
0.98	44762	11517	9.87

Table III shows the effect of k. If k is large, the possibility for obtaining the value of global minimum is increased. From Table III, k=0.01 may be suitable. The computer used is HP735(125MIPS).

VI. OPTIMAL DESIGN OF DIE MOLD FOR ORIENTATION OF MAGNETIC POWDER

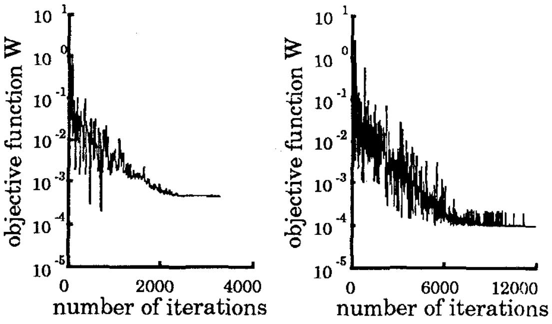
Fig.4 shows a model of die press with electromagnet for orientation of magnetic powder [3]. This is used for producing anisotropic permanent magnet. The die press is made of steel. The die molds are set to form the radial flux distribution. The magnetic powder is inserted in the cavity. The ampere-turns of each coil are 9720AT. x- and y-components Bx and By of flux density at the points along the line e-f in the cavity are specified as follows:

$$\left.\begin{aligned} Bx &= 0.35\cos\theta\,(T) \\ By &= 0.35\sin\theta\,(T) \end{aligned}\right\} \qquad (2)$$

where θ is the angle measured from the x-axis.

The shape of the inner die mold is assumed as a circle. The inside shape of the outer die mold is represented by the ellipse and a line parallel to the x-axis as shown in Fig.4. Then, the radius L_1 of the inner die and the long and short axes L_2 and L_3 of ellipse and the dimension L_4 are chosen as design variables.

The maximum numbers Ns, Nt, reduction factor rt and the coefficient k are chosen as 50, 50, 0.9 and



(a) rt=0.7 (b) rt=0.9

Fig.3 Convergence of objective function W.

Table III Effect of parameter k(Ns=Nt=10)

k	number of iterations	CPU-time (s)	Wopt ($\times 10^{-5}$)
0.001	8022	2100	9.95
0.01	11892	3100	9.86
0.1	12202	3160	14.0

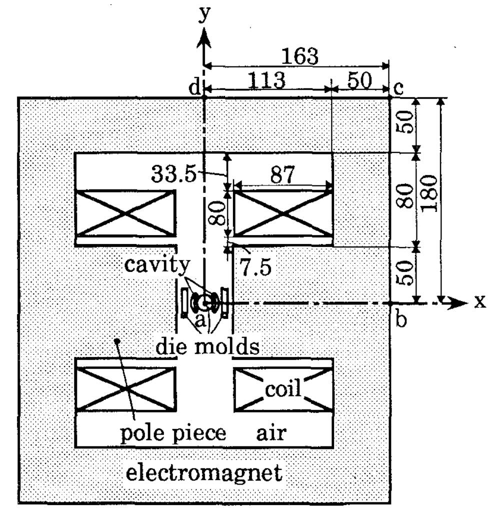
0.01, respectively.

Fig.5 shows the flux distributions at the initial (L_1=7, L_2=15, $L_3=\infty$, L_4=5 mm) and final shapes (L_1=9.3, L_2=17.9, L_3=15.4, L_4=17.3 mm) of the die mold which is obtained using the simulated annealing method. Fig. 6 shows the distributions of flux density of initial and final shapes. Figs.5 and 6 show that the search for optimal shape is possible by using the method denoted in this paper, even if the initial shape is considerably different from the final shape. The average values ε_B and ε_θ of the errors of the flux density B and the direction θ_B of the flux density vector compared with the specified values are given by

$$\varepsilon_B = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{B_i - B_{io}}{B_{io}}\right| \times 100(\%) \tag{3}$$

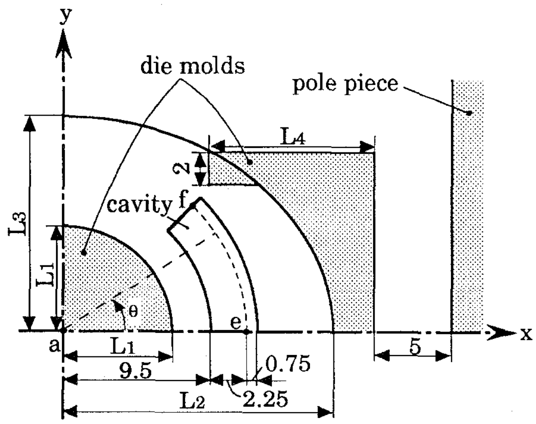
$$\varepsilon_\theta = \frac{1}{n}\sum_{k=1}^{n}\left|\theta_{Bk} - \theta_{Bko}\right| \tag{4}$$

where n(=10) is the number of the specified points of B_{io} and θ_{Bko}. Table IV shows the errors ε_B and ε_θ. As the errors of the simulated annealing method is within 1% and 0.4°, the obtained result in Fig.5(a) is acceptable from a practical point of view.



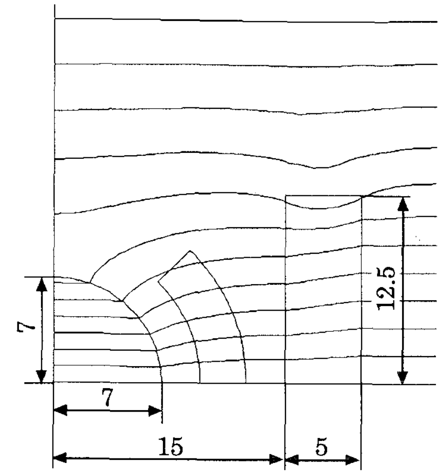
a-b-c-d: Dirichlet boundary
d-a: Neumann boundary

(a) whole view

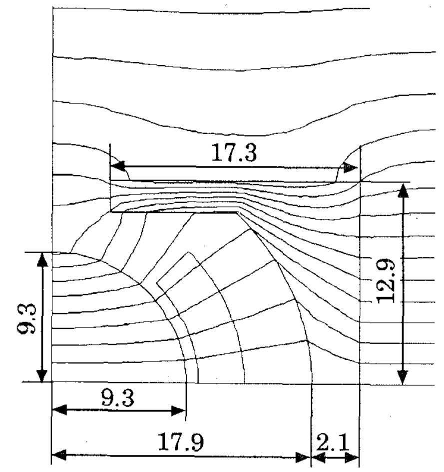


(b) enlarged view

Fig.4 Model of die press with electromagnet.



(a) initial



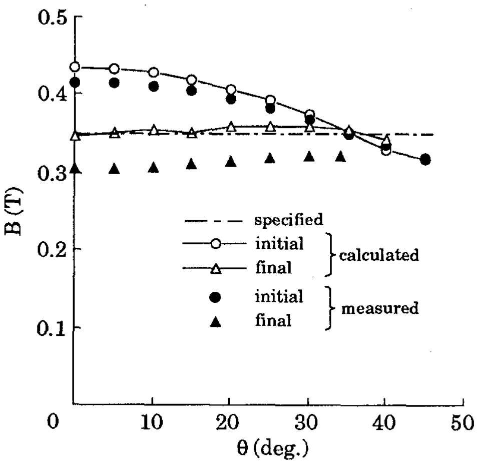
(b) final

Fig.5 Flux distributions for initial and final shapes.

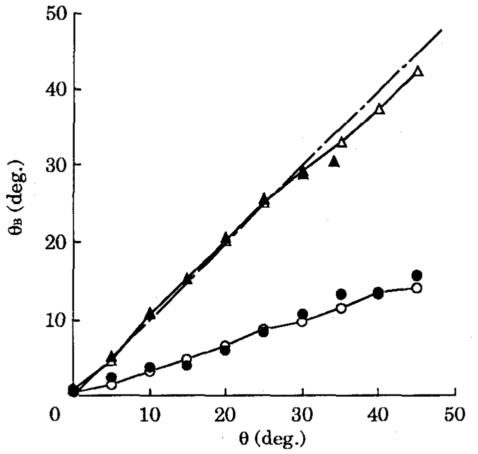
V. EXPERIEMENTS

The die molds of initial and final shapes are produced and the flux distribution in the cavity is measured. The number of turns of each coil is 486. The thickness of the electromagnet is 100mm(2-D model). The x- component of flux density is measured using a Hall probe at 0°, and the y-component is measured by rotating a Hall probe at 90° using a goniometer.

The measured results are shown in Fig.6. The measured values are similar to the calculated ones.



(a) amplitude



(b) direction

Fig.6 Amplitude and direction of flux density vector.

Table IV Discretization data and error

number of elements		3053
number of iterations		1345
CPU-time(s)		6184
error	ε_B (%)	1.05
	ε_θ (deg.)	0.38

computer used : Hp735 workstation (45MFLOPS)

VI. CONCLUSIONS

The optimal values of parameters for the simulated annealing method are discussed using a typical simple model.

It is shown that the optimal shape of the die mold for orientation of magnetic powder can be obtained using the finite element and simulated annealing. The validity of analysis is shown by experiment.

As the parameters of the simulated annealing method depends on problems, more systematic analysis should be carried out using various kinds of models.

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