Journal of Magnetics 5(3), 106-109 (2000)

Taguchi Parameter Design for the Fabrication Process of Anisotropic NdFeB Magnet by Single Stroke Hot Deformation

Ying Li[1,2], Y. B. Kim[1], Lin-shan Wang[3], M. J. Kim[1,2], M. S. Song[1,2], J. H. Yang[1,2], D. S. Suhr[2], T. K. Kim[2] and C. O. Kim[2]

[1]*Korea Research Institute of Standards and Science*
[2]*Chungnam National University, South Korea*
[3]*Science College, Northeastern University, P. R. China*

(Received 14 April 2000)

The single stroke hot deformation is a simple method for the fabrication of anisotropic NdFeB magnets. In order to obtain the optimum conditions, Taguchi method of experimental design was applied in this work. The optimum conditions obtained on the basis of coercivity in Taguchi analysis was a little different from those of remanence and maximum energy product. The contribution of each factor to magnetic properties was calculated in detail.

1. Introduction

Hard magnetic properties of the materials, such as coercivity (*i*Hc), remanence (B*r*), and maximum energy product $[(BH)_{max}]$ strongly depend on the composition and the processing conditions. One of the general methods for manufacturing NdFeB magnet thus far is rapidly quenched melt-spining [1-6]. The magnet produced by such method has isotropic properties, i.e., equiaxed and randomly oriented $Nd_2Fe_{14}B$ grains. In order to obtain anisotropic NdFeB grain, hot deformation is generally applied. It consists of two steps, hot-pressing and die-upsetting one after another. Hot pressing is for achieving complete densification and the desired shape while maintaining essentially an isotropic structure and magnetic properties. The subsequent die-upsetting process modifies the equiaxed grains to platelets, and develops the c-axis texture parallel to die-upsetting direction. It is known that the anisotropic properties are due to c-axis alignment by the combination of grain boundary sliding and grain rotation when they deform plastically.

In this work, we simplified the process with one touch hot pressing. This method has advantages in efficiency, cost, and manufacturing period. We applied Taguchi experimental design method to optimize the fabricating conditions. Taguchi method has demonstrated its practical success in actual applications for dozens years and has been known as one of the most cost-effective tools to improve process quality [7-10]. The present work investigates the influences of a number of fabricating parameters, such as temperature, sample height, deformation percentage, press time, on the magnetic properties (*i*Hc, Br, $(BH)_{max}$).

2. Experimental

The starting isotropic material was MQPA powder. The anisotropic NdFeB materials were manufactured by single stroke hot deformation, in which the ribbon powder was filled into the copper tubes (13 mm in diameter with different heights) with the pressure of 3000 psi, then pressed in an Ar atmosphere at the temperature range from 600 to 750 °C. The process is shown in Fig. 1. The initial deformation rate was 16 mm/s and applied pressure was 1700 psi. The magnetic properties were measured by a hysteresisgraph system with the maximum field of 20 kOe after premagnetization at 90 kOe.

The Taguchi method of experimental design applied in this study was the standard L9 array, which consisted of nine runs in total and allowed up to four factors to be varied at three levels. Table 1 shows the Taguchi array developed for the investigation of the manufacturing of anisotropic magnet. In Taguchi array, the results of each run were

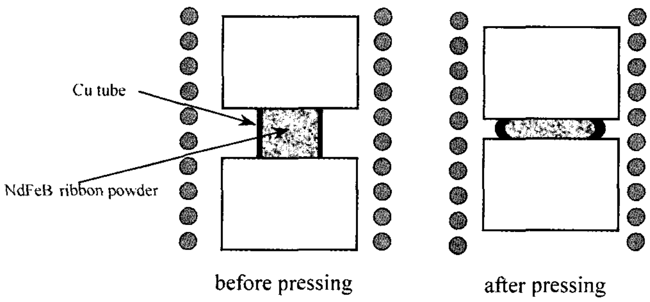

Fig. 1. The schematic of single stroke hot deformation.

Table 1. Taguchi L9 array developed for detailed investigation of the anisotropic NdFeB magnet fabrication

Run No.	Temp. (°C) Factor A	Height (mm) Factor B	Def. Pct. (%) Factor C	Press time (s) Factor D	*i*Hc (kOe)	Br (kG)	$(BH)_{max}$ (MG.Oe)
1	650	7.9	70	5	7.9	10.3	22.8
2	700	7.9	50	0	11.5	9.4	18.3
3	750	7.9	60	10	9.2	7.7	10.4
4	650	9.9	60	0	11.9	10.5	24.5
5	700	9.9	70	10	6.8	8.2	11.0
6	750	9.9	50	5	3.8	5.0	0
7	650	15.1	50	10	14.8	8.6	16.0
8	700	15.1	60	5	24.2	9.7	22.4
9	750	15.1	70	0	5.7	6.9	5.7

assessed in terms of response variables. In this work, we chose press temperature, copper tube height, deformation percentage, press time as the experimental factors. The magnetic properties such as coercivity, remanence and maximum energy product were chosen as response variables. Here, the press time indicates the time maintained for hot pressing, and press time zero means the instant pressing. The deformation percentage indicates the ratio of height reduction. The results were then analyzed and the effect of each factor on the response variable in the array was estimated.

3. Results and Discussion

3.1. Coercivity

Taguchi analysis was carried out using coercivity as the response variable. As can be seen in Fig. 2, there exists the optimum value of the parameters, such as temperature, deformation percentage, press time in this work. The value larger or less than the optimum is not suitable to obtain higher coercivity. For the high coercivity of the magnet, the optimum fabrication conditions are the press temperature of 700 °C, height of 15.1 mm, deformation percentage of 60% and press time of 5 seconds. Further results of Taguchi ANOVA calculation are summarized in Table 2. The formulations used in Table 2 are as follows.

$$C.F. = T^2/n \quad (1)$$

Here, T is the total of all response value (coercivity), $C.F.$ is the correction factor, and n is the number of the array, i.e., $n = 9$.

$$S_F = F_1^2/3 + F_2^2/3 + F_3^2/3 - C.F. \quad (2)$$

Here, S_F is sum of squares of the factor F. F indicates the factor A, B, C and D. The numbers 1, 2, and 3 are the order of the levels. F_i is the sum of the response values of the factor F and the level i in L9 array. The f is the degree of the freedom, i.e.:

$$f = \text{the number of the levels} - 1 \quad (3)$$

$$\text{Further, } V_F = S_F / f_F \quad (4)$$

$$P_F = S_F / S_T \quad (5)$$

Here, V_F is the mean square of the factor F, P_F is the contribution percentage of the factor F, S_T is the total sum of squares, i.e., sum of S_F.

Table 2. ANOVA table for coercivity as response variable

Column	Factors	f	S	V	P
1	A (Temp., °C)	2	97.962	48.981	32.8
2	B (Height, mm)	2	87.695	43.848	29.3
3	C (Def. Pct., %)	2	105.015	52.508	35.1
4	D (Press time, s)	2	8.349	4.174	2.8
Total			299.022		100.0

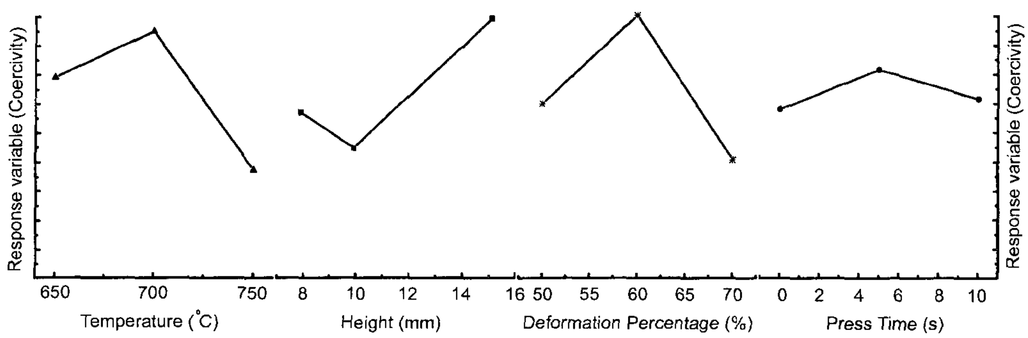

Fig. 2. Taguchi analysis of L9 array using coercivity as the response variable.

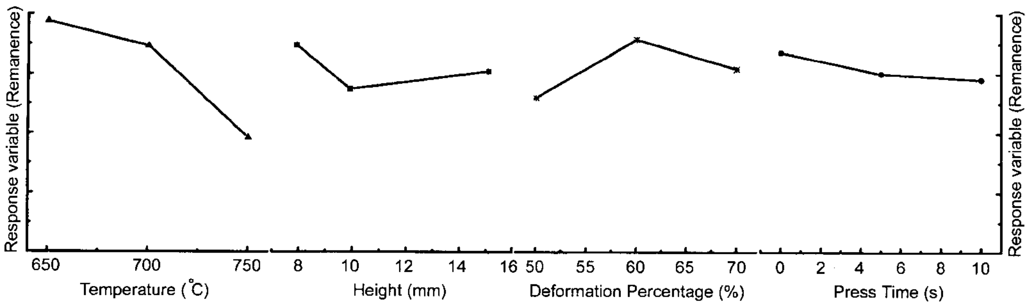

Fig. 3. Taguchi analysis of L9 array using remanence as the response variable.

Table 3. ANOVA table for remanence as response variable

Column	Factor	f	S	V	P
1	A (temp., °C)	2	17.749	8.875	70.9
2	B (Height, mm)	2	2.309	1.155	9.2
3	C (Def. Pct., %)	2	4.003	2.002	16.0
4	D (Press time, s)	2	0.976	0.488	3.9
Total			25.036		100.0

Table 2 gives the contribution of each factor to coercivity. The order of significance to the coercivity from large to small is factor $C > A > B > D$, and the difference among factors *A*, *B*, and *C* is small. So it may be concluded that those three factors (deformation percentage, temperature, height of copper tube) play almost the same important role for coercivity.

3.2. Remanence

Taguchi analysis was carried out with remanence as the response variable. The results are shown in Fig. 3. It shows that only one parameter, deformation percentage, has optimum value, i.e., 60%. And for the remanence property, the optimum conditions of the fabricating in this work are temperature of 650 °C, sample height of 15.1 mm, deformation percentage of 60%, and instant press. Further calculations similar to section 3.1 are shown in Table 3. It shows that the factor *A* (temperature) is the most significant. Its contribution is more than 70%, followed by the factor *C*, *B* and *D* in the order from large to small.

3.3. Maximum Energy product

Taguchi analysis was carried out with maximum energy product as the response variable, and the results are shown in Fig. 4. Other results calculated similar to section 3.1 are shown in Table 4. All the results calculated above show similar trend to the case of remanence. The temperature is the most significant factor, and its contribution is about 70 %.

4. Conclusion

According to Taguchi experimental design and ANOVA calculation, we know that those four factors of the single stroke hot deformation have different effect to hard magnetic properties, such as coercivity, remanence and maximum energy product. Each of the factors temperature, height of copper tube and deformation percentage has approximately one-third contribution to coercivity, respectively. However, the key parameter for remanence and maximum energy product is temperature with the contribution more than 70%, and the next is deformation percentage with the contribution of about 17%.

Table 4. ANOVA table for maximum energy product as response variable

Column	Factors	f	S	V	P
1	A (temp., °C)	2	403.307	201.653	71.4
2	B (Height, mm)	2	42.747	21.373	7.6
3	C (Def. Perc., %)	2	96.987	48.493	17.2
4	D (Press time, s)	2	21.660	10.830	3.8
Total			564.764		100.0

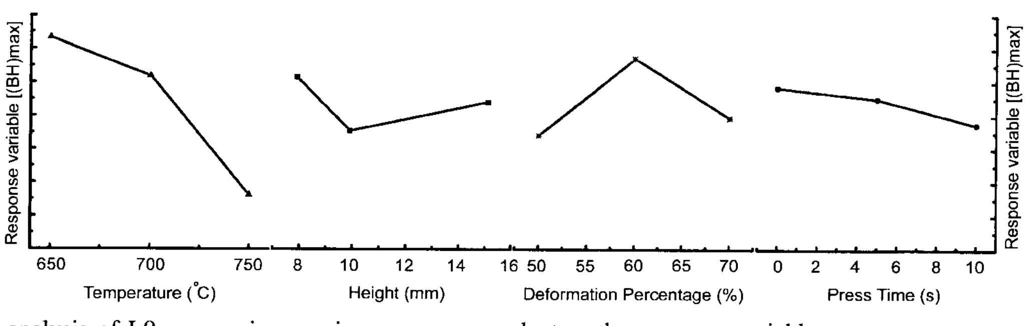

Fig. 4. Taguchi analysis of L9 array using maximum energy product as the response variable.

Acknowledgement

This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the Research Center For Advanced Magnetic Materials at Chungnam National University.

References

[1] Yoonbae Kim, et al., United Stated Patent, No. 5,516,371, May 14, 1996.
[2] S. Guruswamy, Y. R. Wang, and V. Panchanathan, J. Appl. Phys., **83**, 6393 (1998).
[3] O. Gutfleisch and A Kirchner, J. Phys. D: Appl. Phys., **31**, 807 (1998).
[4] Y. R. Wang, S. Guruswamy, and V. Panchanathan, J. Appl. Phys., **81**, 4450 (1997).
[5] J. J. Croat, J. F. Herbst, R. W. Lee, and F. E. Pinkerton, Appl. Phys. Lett., **44**, 148 (1984).
[6] Y. Yoshida, Y. Kasai, T. Watanabe, S. Shibata, V. Panchanathan, and J. J. Croat, J. Appl. Phys., **69**, 5841 (1991).
[7] Ranjit K. Roy, A primer on the Taguchi Method, Van Nostrand Reinhold Reinhold Publishers, New york, 1990.
[8] Sornkrit Rungroekrit, Proceedings of the 2nd Annual International Conference on Industrial Engineering Applications and Practice II, California, USA, **1**, 1997, p. 657.
[9] P. J. Kellym and R. D. Arnell, Surface & Coatings Technology, **86-87**, 425 (1996).
[10] V. N. Gaitonde, Proceedings of the 14th International Conference on CAD/CAM, Robotics and Factories of the Future, Narosa, Japan, 1998, p. 509.