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ORIGINAL RESEARCH

Optimization of rotor shaft shrink fit method for motor using "Robust design"

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Abstract
This research is collaborative investigation with the general-purpose motor manufacturer. To review construction method in production process, we applied the parameter design method of quality engineering and tried to approach the optimization of construction method. Conventionally, press-fitting method has been adopted in process of fitting rotor core and shaft which is main component of motor, but quality defects such as core shaft deflection occurred at the time of press fitting. In this research, as a result of optimization design of "shrink fitting method by high-frequency induction heating" devised as a new construction method, its construction method was feasible, and it was possible to extract the optimum processing condition.

Keywords Robust design · Quality engineering · Shrink fitting · High-frequency induction heating

Introduction

In recent years, there are frequent cases of recall problems due to quality problems of consumer electronics products and automobiles in the market and betrayal of consumer confidence. The way of manufacturing is also the problem solving type in most cases, and the recurrence prevention-type development occupies mainstream in actuality. Especially the recall problem of automobiles, such as the complicated structure of the products themselves, the fact that consumers' eyes became more severe and that it was impossible to break down all the problems in the design process in shortening the development period, it shows the limit of conventional quality control in the market environment. The reason why the recall cannot be prevented in terms of quality control is because the factors of the recall problem are put in the design and development stage (Taguchi 1992).

Therefore, it can be said that it is difficult to reduce this problem unless innovating the way of design and thinking into "prevention" concept. To prevent problems in advance, to speed up the development of new products and strengthen the constitution of production technology capabilities, it is desired to advance technology development with high versatility and high reproducibility.

For that purpose, it is important for engineers to acquire the idea of quality engineering and how to proceed and fulfill the role and responsibility of engineers. Therefore, "Robust design" is utilized in technology development and product design that account for most of design responsibility (Koshimizu and Suzuki 2007; Hasebe 2009).

Research purpose

This research is a collaborative with a motor manufacturer, and we tried approach to optimization of construction method by applying Quality engineering for the purpose of reviewing construction method in production process. Figure 1 shows the rotor core and the shaft which are the main components of the motor used in this study (Yano 2004).

In the process of joining the rotor core and the shaft, the press-fitting method has been adopted conventionally, but as shown in Fig. 2, the quality defect of "rotor runout" of the rotor shaft occurring at the time of press fitting has occurred. Simulation analysis reveals that the factor is

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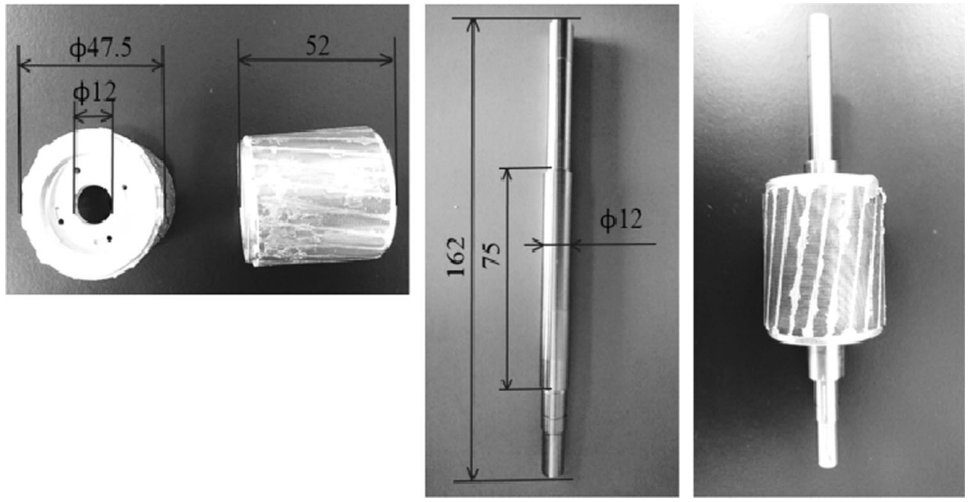


Fig. 1 Rotor core and shaft

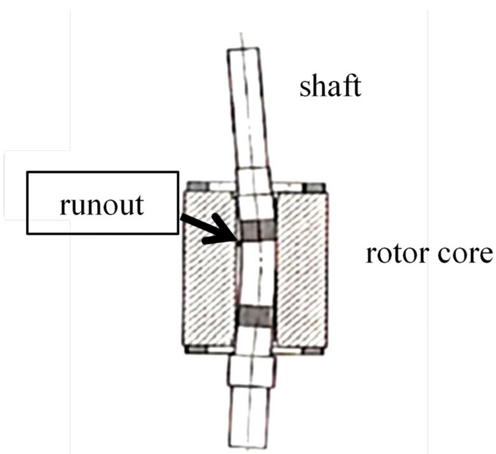


Fig. 2 Inferior quality model

caused by an unbalanced load at the time of press fitting the shaft (Mori 2005; Taguchi 1992).

Figure 3 shows the calculation model of the strength of the required interference at the time of press fitting.

Formula

- Internal pressure between cylinder and shaft after joining (p)

$$p = \frac{d_2^2 - d_1^2}{2d_1 d_1^2} \cdot E \cdot \Delta,$$

where E is the Young's modulus ($= 201[GPa]$) and Δ is the interference.

- Area of junction (A)

$$A = \pi d_1 L,$$

where L is the insertion length.

- Transmission torque (T)

$$T = \mu p A d_1 / 2,$$

where μ is the coefficient of friction (= 0.15).

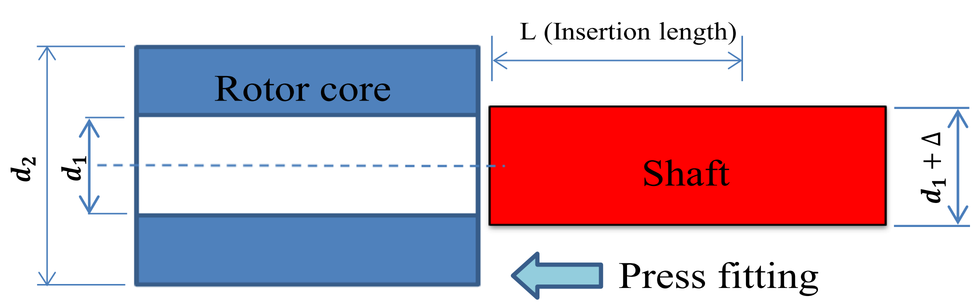
Materials

- Rotor core: aluminum alloy and electromagnetic steel.
- Shaft: carbon steel for machine construction.

Specification

- Required rotation transmission torque: $T = 70$ [N m].
- Drawing load: $F = 5000$ [N].
- Core inner diameter: $d_1 = \varnothing$ 12 [mm].
- Core outer diameter: $d_2 = \varnothing$ 47.6 [mm].

Fig. 3 Press-fitting model



- Insertion length: $L = 40$ [mm].

Calculation result

- Area of junction: $A = \pi d_1 L = 1.51 \times 10^3 [mm^2]$.
  Internal pressure between cylinder and shaft after joining: $p = 51.5 [N/mm^2]$.
- Interference: $\Delta = 64.5 [\mu m]$.
- Required heating temperature: ΔT.
- $$\Delta = d_1 \cdot \alpha \cdot \Delta T \rightarrow \Delta T = \Delta/(\alpha \cdot d_1) = 444[°C]$$
- α: Coefficient of linear expansion $\left(= 12.1 \times 10^{-6} [/°C]\right)$.

As a result of the previous research, it was possible to optimize the press-fitting method by setting the ideal function (Fig. 4) by applying the quality engineering, and extract the processing condition to reduce the occurrence of core runout of the rotor shaft (Yano 2002; Koshimizu and Suzuki 2007).

A summary of research on the optimization of the press-fitting method applying the quality engineering in the previous research is described below.

Experimental system

The outline of the experimental apparatus in the previous research is shown in Fig. 5. Set the shaft and the core in the upper and lower jigs, and semi-automatic press fitting with hydraulic pneumatic actuator. The press-fitting process conditions (each parameter) were set, and the measurement results of the press-fit load and deflection, which are characteristic values, were analyzed and evaluated.

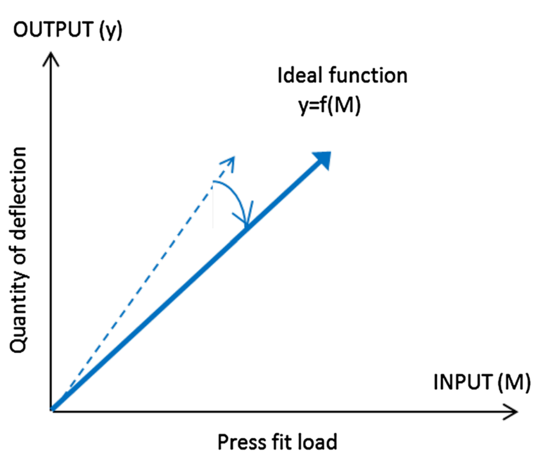


Fig. 4 Relation of ideal function

Experimental method

Tables 1 and 2 show various factors and level tables. "Control factor" assigns press-fitting conditions to each level, and "Noise factor" is accuracy of core inner diameter. Based on these level tables, experiments were conducted based on "L18 orthogonal array" which is a statistical tool for constructing an experiment plan.

Experimental result

Figure 6 shows the SN ratio calculated from experimental results as a factorial effect diagram.

A diagram showing the effect of combinations of factors on characteristic values is called a factorial effect diagram (response graph). The vertical axis of the graph represents the SN ratio, and the horizontal axis represents the level of the factor.

Reliability of experiment

Table 3 shows the evaluation results on reliability of the experiment in the response graph. Based on the benchmark condition and the estimation result of the SN ratio of the condition considered to be optimum, it was judged that the experimental result is reliable. This means that the selected optimum condition is an appropriate level out of several combinations.

However, it turned out that it is necessary to change the processing conditions of the press-fitting method if the target rotor shaft diameter changes according to the standard. Although it was able to suppress core runout, in fact, due to the lack of process capability, 100% non-defective rate could not be achieved, and the current situation is that it has not led to abolishment of all inspections in process. It can be concluded that this is a factor that did not lead to an improvement in robustness, because the characteristic evaluation method in quality engineering in the previous research is a result based on "static characteristics".

There are two types of quality characteristic evaluation in quality engineering, "static characteristic" and "dynamic characteristic". Static characteristic refers to a characteristic that examines the output without changing the input. The target value is a constant quality characteristic, and "the nominal-is-best properties" is the main characteristic evaluation. However, even in the parameter design for the desired characteristic, the target result may not be obtained in some cases. One of the reasons is that the factor allocated to the orthogonal table may not be well separated into the factor for maximizing the SN ratio and the factor for adjusting the average value. In addition, there is a high possibility that the control factor for adjusting the

Fig. 5 Experimental system

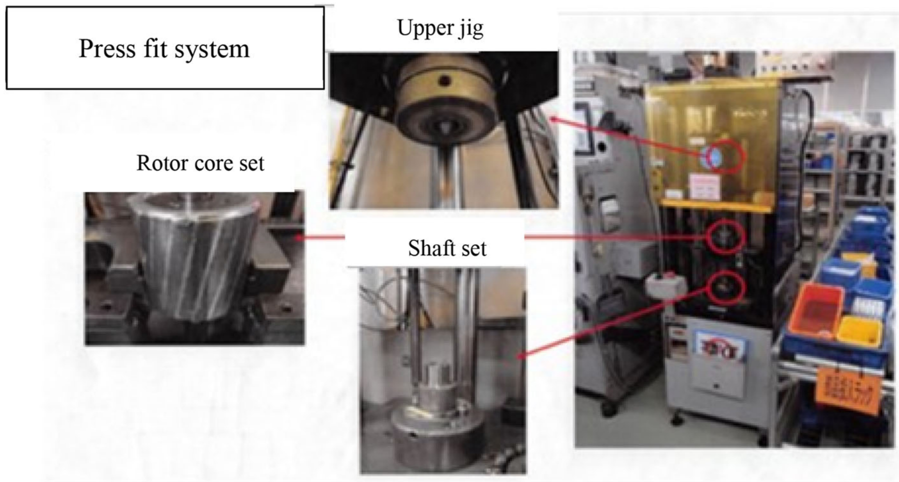


Table 1 Control factor and table of level

Sign	Control factor	1	2	3
A	Lubricant coating	Do	Not	–
B	Cradle precision	Small	Middle	Big
C	Knurl length	8 mm	17 mm	30 mm
D	fastening clearance	ϕ0.03	ϕ0.08	ϕ0.13
E	Shoulder deflection	0 µm	40 µm	80 µm
F	Shaft hardness	S45C	SCM415	Ind. hardening
G	Press fit speed	Low	Middle	High
H.	e	–	–	–

Table 2 Noise factor and table of level

Sign	Noise factor	Level	
		1	2
N	Core inside dia. Prec.	Stand.	High prec.

average value has an interaction with other control factors, and the reliability of the orthogonal table experiment may be low. As a countermeasure, there is an evaluation method by dynamic characteristics. Dynamic characteristics refer to characteristics that change the input and examine the output. Compared to the static characteristic without changing the input, the dynamic characteristic that examines the output by changing the input can be evaluated with more aimed at robustness quality.

Therefore, we devised a new construction method "shrink fitting method by high-frequency induction heating", and optimized construction method by applying dynamic characteristic evaluation in robust design which can efficiently evaluate the feasibility of the construction method. Shrink fitting is a method of heating the rotor to about the recrystallization temperature and smoothly fitting the shaft by expanding the diameter of the shaft insertion hole. Compared with press fitting, this method has the advantage that it does not apply a large load to the shaft, it hardly causes a runout at the time of insertion, and even if the shaft diameter changes, it can deal with the same conditions.

In addition, the high-frequency induction heating method has less influence on the work environment, is easier to control, and makes effective use of the space possible than other methods. In particular, from the

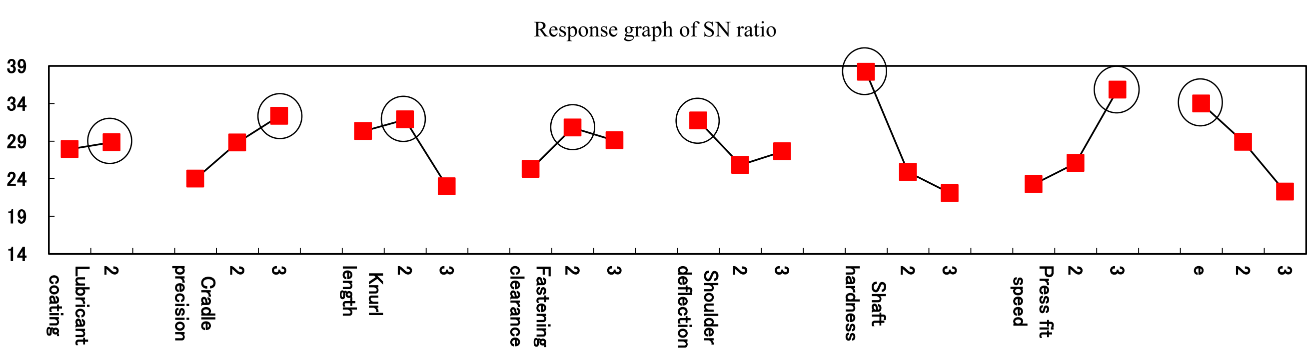


Fig. 6 Response graph

Table 3 Reliability of experiment

L18 experiment SN ratio		Reliability confirmation by reverse estimation	
Maximum	38.19	Average of current condition	29.8
Minimum	22.07	Reverse estimated value	39.73
10% of difference	1.612	>	− 9.930
Judgment		Reliable	

viewpoint of improving productivity, there is a great merit that rapid heating is possible (Mori 2005).

Robust design

The concept of robust design in quality engineering is shown in Fig. 7. Robust design is an idea of improving technology to bring it closer to what it should be, and robust means "stability" in quality engineering (Yano 2002).

Robust design is a method of evaluating the functionality and determining the parameter value of the system. Parameters are design constants and components of the system and are selected as control factors in parameter design experiments. Improve robustness by intentionally generating variations with noise factors among combinations of processing conditions and optimizing the level of strong control factors that can counter the variation (Koshimizu and Suzuki 2007; Hasebe 2013).

Procedure of Robust design

The procedure of robust design is shown in Fig. 8. Robust design begins with clarifying the "function" of the engineering system. Define functions as ideal functions of system input (signal factor) and output (characteristic value). To realize the ideal function, experiments are carried out efficiently using the orthogonal table and grasp the magnitude of the effect of each control factor with SN ratio and sensitivity (Tsuruta 2017).

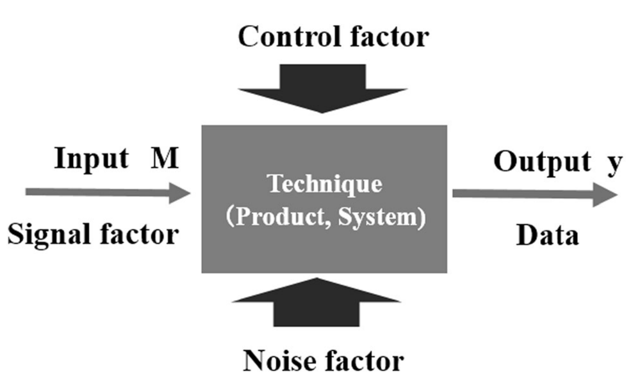


Fig. 7 Robust design

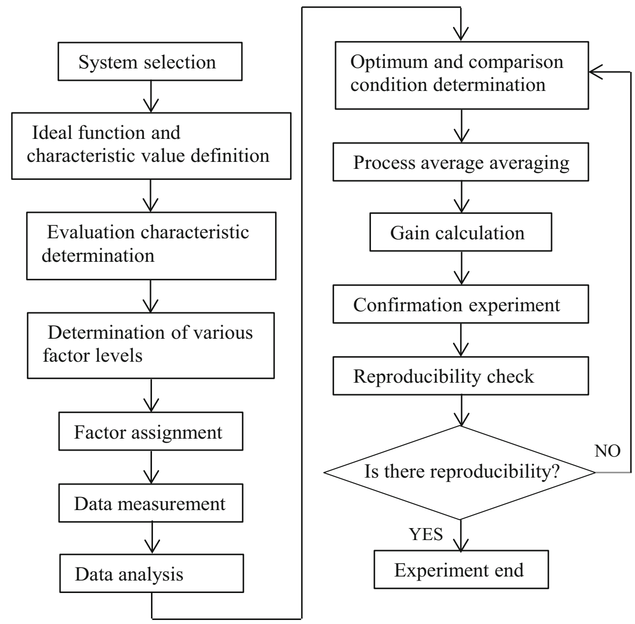


Fig. 8 Robust design procedure

After that, the process of determining the optimum condition and the comparison condition from the factor effect diagram, predicting the magnitude of improvement by finding the average value of each step, and verifying the reproducibility of the optimum condition gain at the end.

Clarification of target function

In parameter design, how to capture the target function is important. Target function refers to the role that the system should play. The quality characteristics are generally divided as follows.

- Smaller-is-better properties (nonnegative and smaller the better).
- Larger-is-better properties (nonnegative and larger the better).
- Nominal-is-best properties (There is a target value).
- Zero nominal-is-best properties (zero is the target value).

By taking up the target function, the design information can be utilized in other similar products, and the versatility of the technology is expanded (Hasebe 2013).

Determination of signal factor

An input signal for changing the output property y is called a signal factor and is represented by M. The signal factor changes the output properties, and selects what can control its value. In general, consider the proportional relation with the ideal relationship of input and output, as shown in Eq. (1) (Taguchi 1992):

$$y = \beta M. \tag{1}$$

Dynamic characteristics and S/N ratio

The SN ratio of the dynamic characteristic is used for functional evaluation. Dynamic characteristics are widely used not only for functionality but also for evaluation of products and processes. Both processes and products should not perform satisfactorily under good conditions, but stable outputs should be obtained even if there are various noises affecting the functional characteristics (Yano 2011; Tsurut 2016).

Functionality evaluation means that by examining the linearity of the output by changing the input signal, this is represented by the SN ratio of the dynamic characteristic. The data-processing method and SN ratio calculation based on this relationship are as follows. The SN ratio of the dynamic characteristics shown here is for the simplest case, and the calculation formula of the SN ratio changes depending on how the signal is given, how the noise is given, and the like (Tsuruta 2016; Koshimizu and Suzuki 2007).

N \ S	M_1 M_2 ⋯ M_k	L
N_1	Y_{11} Y_{12} ⋯ Y_{1k}	L_1
N_2	Y_{21} Y_{22} ⋯ Y_{2k}	L_2

L_1, L_2: linear equation:

$$L_1 = M_1Y_{11} + M_2Y_{12} + \cdots + M_kY_{1k} \tag{2}$$

$$L_2 = M_1Y_{21} + M_2Y_{22} + \cdots + M_kY_{2k} \tag{3}$$

r: Effective divider

$$r = M_1^2 + M_2^2 + \cdots + M_k^2 \tag{4}$$

S_T: Total variation

$$S_T = Y_{1k}^2 + Y_{2k}^2 + \cdots + Y_{2k}^2 \tag{5}$$

S_β: Variation of proportional term β

$$S_\beta = (L_1 + L_2)^2/2r \tag{6}$$

$S_{N\times\beta}$: Variation of noise factor N

$$S_{N\times\beta} = (L_1 - L_2)^2/2r \tag{7}$$

Ve: Noise variance

$$V_e = (2k-2)^{-1}\left(S_e - S_\beta - S_{N\times\beta}\right) \tag{8}$$

V_N: Total noise variance

$$V_N = (2k-1)^{-1}\left(S_T - S_\beta\right) \tag{9}$$

η: SN ratio

$$\eta = 10log\left\{(2r)^{-1}\left(S_\beta - V_e\right)/V_N\right\} \tag{10}$$

S: Sensitivity

$$S = 10log(2r)^{-1}\left(S_\beta - V_e\right). \tag{11}$$

Selection and allocation of factors

In the experiment of robust design, three factors of control factor, signal factor, and noise factor are selected. The control factor is a factor that satisfies the target function and selects the optimum condition for determining a stable system.

In the robust design, as many factors as possible are considered in the experiment, which seems to be effective in improving the SN ratio from the parameters. It is usually allocated inside the orthogonal table and is a factor that can be freely selected by the designer.

Signal factor is a factor used for parameter design of dynamic characteristics and changes in conjunction with characteristics to match with target value. It is allocated to the outside of the orthogonal table to which the control factor is allocated (multiple placement).

The noise factor is a factor that causes the system to deviate from the ideal function and cannot be freely selected by the designer. Like the signal factor, it is allocated to the outside (multiple placement). In general, there are cases, where internal disturbance (such as factors of variations caused within the system, wear and deterioration of parts, etc.), disturbance (factors of variations added from the outside of the system, environmental and usage conditions, etc.), and differences between products (variations between lots etc.) are classified (Koshimizu and Suzuki 2007).

Data analysis

Find the SN ratio (η) and sensitivity of the data obtained in the orthogonal table experiment. To estimate the factor effect, average value by level is obtained and an auxiliary table is prepared. The optimum condition is decided by choosing a level with a high SN ratio from the response graph showing the auxiliary table as a graph.

Next, estimate the factor effect, and obtain the process average of the optimum condition and the current condition using the control factor having a large influence on the SN ratio and the sensitivity, respectively. The gain is estimated from the difference between the process average of the SN ratio of the optimum condition and the current condition (Tsurut 2016).

Confirmation experiment

Confirmation experiment is to perform orthogonal table experiment with two conditions of optimum condition and current condition obtained from data analysis. From the experimental results, SN ratio, sensitivity, and gain are obtained and compared with the estimated value.

If the difference from the estimate is large, it means that there is no reproducibility of the orthogonal table experiment. In this case, since it is considered that the interaction between the control factors is large, a technical reexamination is required for the control factor (Hasebe 2009).

Experimental system

Figure 9 shows the process outline of the experimental system (shrink fit method) in this research. We have devised an automated system by adopting a scalar robot applicable to a practical factory production system.

Test machine for experiment

First, a method of preparing the experimental coil used in this experiment will be described. The coil was manufactured in a shape wound with insulated winding wound around a bobbin large enough to accommodate the rotor core with high heat resistance (Fig. 10). In this experiment, a Teflon bobbin with high heat resistance was adopted, and a magnet wire with high heat resistance was used for the coil winding. Since it is necessary to set the number of turns of the coil according to the allowable inductance of the high-frequency induction heating device to be used, it was adjusted while measuring the inductance in the LCR meter (Fig. 11) (Uemura 2007).

The high-frequency induction heater used in this experiment adopts the IH inverter (3 kW), and the allowable inductance is 60–70 μH. Figure 12 shows measurement results of inductance.

Principle of high-frequency induction heating

Figure 13 shows the principle of high-frequency induction heating. High-frequency induction heating is a method of heating utilizing electricity and magnetism (conversion of electricity to magnetism). It can also be said to self-heat the metal without contact. Magnetic force is generated when an electric current is passed through the coil, and Joule heat is generated by the eddy current flowing in the conductor and the electric resistance of the metal by magnetic flux change and electromagnetic induction, and the metal rapidly self-heats. By applying this principle, we

Fig. 9 Shrink fitting System

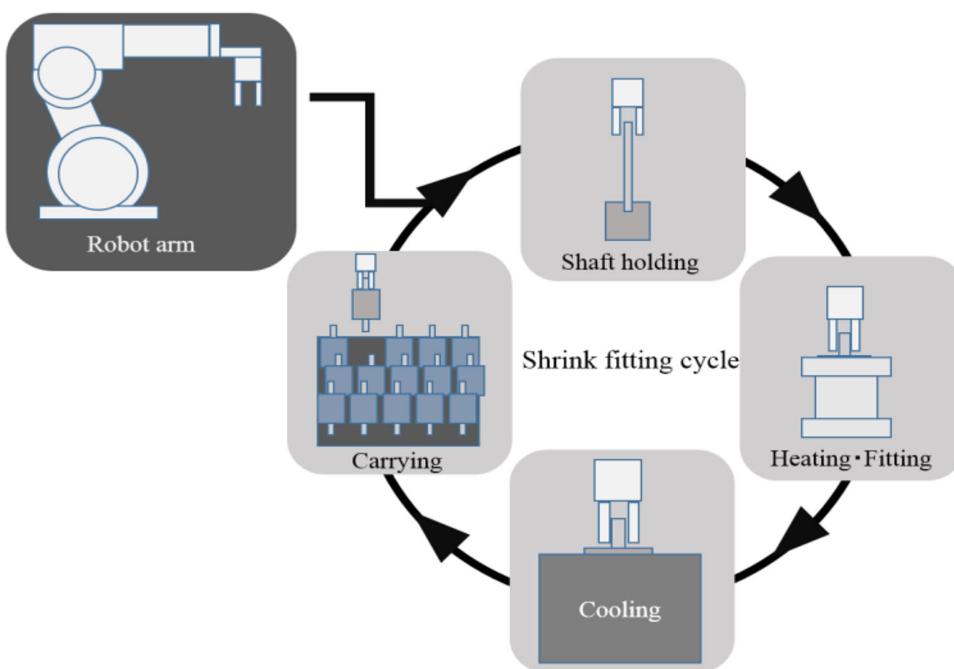


Fig. 10 Bobbin and coil

Fig. 11 LCR meter

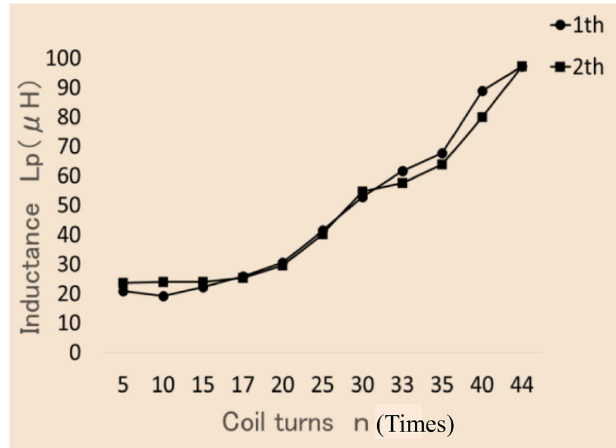


Fig. 12 Relation of coil turns and inductance

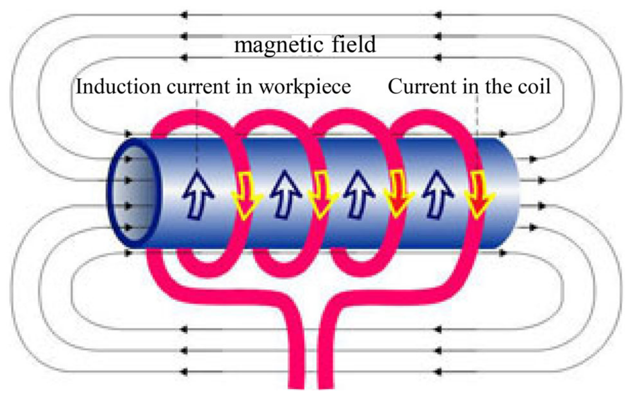


Fig. 13 Principle of induction heating

constructed a high-frequency induction heating system, as shown in Fig. 14 (Uemura 2007).

Experiment by parameter design

Determination of various factors

Table 4 shows various factors of this experiment. As for the control factor, the shrink fitting condition of the rotor shaft is allocated to each level, the signal factor is three types of shaft diameters $\varphi 12$(mm), $\varphi 12.5$(mm), $\varphi 15$(mm) with different outer diameters, and the error factor is 30 and 60 µm.

Risk factors of different rotor cores (for example, melting at high temperature and demagnetization effect) are assumed for motor function, but we plan to work as future research subjects based on the results of this research (Ono 2013).

Creation of a level table

The three levels of IND power and heating time are extracted from the results of preliminary experiments with a high-frequency induction heating device (Table 5). The shape of the coil jig was set to three with short winding width, standard one, and long one. From this level table, we created an "orthogonal array", a statistical tool for optimization methods, to formulate an experimental plan.

Assignment to orthogonal array and experiment

An orthogonal array is a table defining assignments, such that combinations of levels of arbitrary factors appear the same number of times in combinations of experimental levels. The number of experiments is determined by the scale of the orthogonal array and is represented by the experiment number shown at the left end of the orthogonal array. The number of experiments this time is $9 \times 6 = 54$ times, and the upper row in the horizontal direction represents the type of control factor allocated. The numerical values and letters listed below represent the level of each control factor. The advantage of using an orthogonal array is reduction of the number of experiments. In the case,

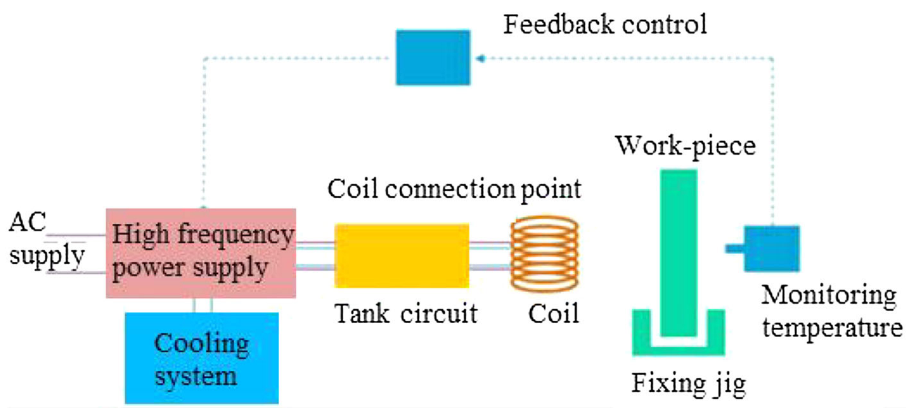


Fig. 14 System configuration of high-frequency induction heating device

Table 4 Various factors

Control factor	
IND power (%) heating time (s)	
Coil type	
Leave time after insertion (min)	
Cooling system	
Signal factor	
M1	φ12
M2	φ12.5
M3	φ15
Noise factor	
N1	30 μ
N2	60 μ
N0	Average

Table 5 Table of level

Control factor	Level 1	Level 2	Level 3
IND power(%) heating time(s)	30 × 240	60 × 20	90 × 95
Coil type	Short	Standard	Long
Leave time after insertion (min)	0	0.5	1
Cooling system	Air	Water	Mist

where the orthogonal array L9 is not used, the number of times of the experiment is $3^4 \times 6 = 486$ times. Table 6 shows the L9 orthogonal array with the level assigned (Ono 2013).

Calculation of experiment result and SN ratio

Table 7 shows the calculation process of SN ratio calculated from experimental data, and Table 8 shows experimental data and SN ratio values. The SN ratio is an evaluation index of robustness, which is calculated as a signal-to-noise ratio taking the ratio of useful component and harmful component, and it is preferable that the numerical value is large. The factor effect of a harmful component represents a variation effect from an ideal function with a component, whose output unintentionally changes.

In the robust design, the scale of the evaluation called SN ratio is obtained, and ultimately, the presence or absence of the effect is judged on the response graph to obtain the optimum condition.

Creating response graph

Figure 15 shows the SN ratio (upper figure) and sensitivity (lower figure) for each control factor in a response graph. The factor effect represents the influence of a factor or a combination of factors on a characteristic value, and this diagram is a response graph. The vertical axes of the upper and lower figures show the values of SN ratio and sensitivity. The meaning of this diagram shows that a control factor with a large SN ratio in the vertical direction is effective in suppressing the shaft runout in the shrink fitting. The SN ratio represents an evaluation index of robustness, and it is desirable that its value is linearly larger. In addition, because the sensitivity represents the index of the magnitude of the system output as the experiment object, the optimum condition was determined based on the comprehensive evaluation by comparing response graph of SN ratio and sensitivity (Koshimizu and Suzuki 2007; Watanabe 2006).

Finally, the levels judged to be optimum in Fig. 13 are the factors “IND Power: 90 (%) [95 (s)]”, “Coil Jig Shape: Length”, “leaving time: 1 (min)”, and “cooling method: mist”.

Table 6 Orthogonal array

No.	IND power (%) × heating time (s)	Coil type	Leave time after insertion(min)	Cooling system
1	30 × 240	Short	0	Air
2	30 × 240	Standard	0.5	Water
3	30 × 240	Long	1	Mist
4	60 × 120	Short	0.5	Mist
5	60 × 120	Standard	1	Air
6	60 × 120	Long	0.5	Water
7	90 × 95	Short	1	Water
8	90 × 95	Standard	0	Mist
9	90 × 95	Long	0.5	Air

Table 7 Calculation process of SN ratio

No.	ST	*L*1	*L*2	*r*	Sp	SN × β	Se	Vn	Ve	η (db)
1	483.0	269.0	60.5	164.8	219.6	131.9	131.5	52.7	32.9	10.24
2	209.3	70.5	114.1	92.3	184.6	10.3	14.3	4.9	3.6	15.65
3	562.3	305.1	252.0	278.6	557.1	5.1	0.1	1.0	0.0	27.35
4	137.0	55.0	67.5	61.3	122.5	1.3	13.2	2.9	3.3	16.14
5	656.0	358.0	246.0	302.0	604.0	20.8	31.2	10.4	7.8	17.58
6	45.0	21.0	17.5	19.3	38.5	0.3	6.2	1.3	1.5	14.54
7	436.0	253.0	149.0	201.0	402.0	26.9	7.1	6.8	1.8	17.70
8	362.6	101.5	217.2	159.4	318.7	42.0	1.9	8.8	0.5	15.59
9	184.0	78.0	102.0	90.0	180.0	3.2	0.8	0.8	0.2	23.52

Extraction of optimal conditions

Table 9 shows the extraction results of combinations of control factor levels considered to be optimum in the experiment from the response graph of the previous section.

However, this is the extraction result obtained from the L9 experimental results, and it is necessary to confirm and evaluate the reliability and reproducibility of the experiment by confirmatory experiment (Inoue and Nakano 2008).

Confirmation of reliability

Table 10 shows calculation results of estimated values under optimum conditions, current conditions, and reference conditions. The estimated value of the optimum condition was higher than the other conditions. Based on this result, it was confirmed whether the L9 orthogonal array test result is reliable (Hasebe 2009).

The maximum value and the minimum value of the SN ratio obtained in the L9 orthogonal array are determined, and from the value of 10% of the difference, if the difference from the estimated SN ratio is within the range of 10%, if it is reliable.

Table 11 shows the evaluation results of reliability. In the evaluation method in this experiment, it was judged that reliability is given to orthogonal table experiment by adopting evaluation of characteristic value (nominal-is-best properties) against a certain target value.

Confirmation of reproducibility

In the confirmation experiment, the estimated value of the SN ratio of the selected optimum condition and the current condition was obtained, and experiments were conducted again on the same two types as the orthogonal array experiment to acquire the SN ratio, and the difference between the estimated values of both and confirmation experiment comparing the difference (gain) investigate whether the experiment is reproducible or not.

The purpose of the confirmatory experiment is to confirm whether or not to reproduce even when the time, place, environment, etc. change, compared with the orthogonal array experiment. If there is no repeatability, it can be said that it is a poor technology which is highly likely to cause some troubles in the future (Yano 2011).

The evaluation results of the confirmation experiment are shown in Table 12. For the condition of reproducibility in confirmatory experiments in robust design, the difference between the estimated value of the optimum condition and the gain is within ± 30% (Ono 2013; Koshimizu and Suzuki 2007).

Table 8 Experimental result

No.	Signal factor	Deflection(nm)			SN ratio (db)
		M1 12	M2 12.5	M3 15	
1	N1	16	5	13	10.24
	N2	1	4	4	
	N0	8.5	4.5	8.5	
2	N1	6	4	3	15.65
	N2	12	0.5	2	
	N0	9	2.25	2.5	
3	N1	12	10	9.5	27.35
	N2	10	8	8	
	N0	11	9	8.75	
4	N1	4	6	2	16.14
	N2	4	4	7	
	N0	4	5	4.5	
5	N1	10	14	12	17.58
	N2	10	4	10	
	N0	10	9	11	
6	N1	3	1	4	14.54
	N2	3	3	1	
	N0	3	2	2.5	
7	N1	4	15	9	17.70
	N2	4	7	7	
	N0	4	11	8	
8	N1	7.5	0.6	3	15.59
	N2	16	4	5	
	N0	11.75	2.3	4	
9	N1	4	4	6	23.52
	N2	4	6	8	
	N0	4	5	7	

The aim of judging the reproducibility by gain in the confirmation experiment is to take the idea that the improvement effect of the control factor should be consistently reproduced even if the environment is different. As a guideline, if the difference between the estimated value of the optimum condition and the gain of the confirmatory experiment is within the range of about ± 30%, it is difficult to be affected by the interaction and judged that reproducibility of the experimental effect can be obtained. Therefore, from the results in Table 9 ($|50–73| = \pm 23\% \le \pm 30\%$), this experiment was judged to have reproducibility. Furthermore, from the results in Tables 10 and 11, the orthogonal table experiment is reliable and the experimental error is small, so it can be judged that the evaluation of the reproducibility in the confirmation experiment is valid.

The main purpose of this experiment is to determine whether the shrink fit method is established or not. Figure 16 shows a graph comparing the optimum condition in functional evaluation and the degree of variation in the current condition. It shows the change in the output (core deflection) with respect to the input (shaft diameter) of the noise factor (N1, N2, and N0), indicating that the dispersion of the optimum condition is smaller than the current condition.

From this result, it became clear that the shrink fitting method is a robust construction method capable of coping with the change of the shaft diameter.

Conclusion

In this research, attention was paid to the shrinkage fitting method by high-frequency induction heating, and an approach was tried on the feasibility of the shrinkage-

Fig. 15 Response graph

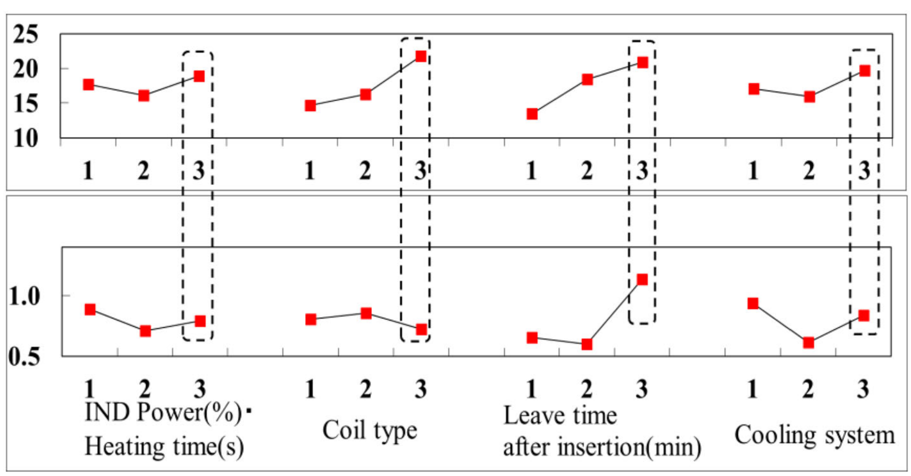


Table 9 Optimum condition

Optimum condition			
IND Power(%) × heating time(s)	Coil type	Leave time after insertion(min)	Cooling system
90 × 95	Long	1	Mist

Table 10 Estimated value

	IND Power (%) × heating time (s)	Coil type	Leave time after insertion (min)	Cooling system	Estimated value	
Optimum condition	level	3	3	3	3	28.54
	SN ratio	18.94	21.80	20.88	19.69	
Current condition	level	2	2	2	2	13.99
	SN ratio	16.09	16.28	18.44	15.96	
Reference condition	level	2	3	1	2	14.54
	SN ratio	16.09	21.80	13.45	15.96	

Table 11 Reliability confirmation

L9 experiment SN ratio	Reliability confirmation by reverse estimation		
Maximum	27.35	Average of current condition	13.99
Minimum	10.24	Reverse estimated value of Response graph	28.54
Difference	17.11		–
10% of difference	1.711	>	− 14.55
Judgment		Reliable	

Table 12 Reproducibility

		Deflection (nm)			Estimated value	Confirmation value	Reproducibility (%)
		M1	M2	M3			
Optimum condition	N1	16.5	2	14	28.54	20.91	73
	N2	14	3	7			
	N0	15.5	2.5	10.5			
Current condition	N1	8	7	20	13.99	13.61	97
	N2	18	4	6			
	N0	13	5.5	13			
Reference condition	N1	14	1	2	25.69	15.79	61
	N2	11	9	6			
	N0	13	5	4			
Gain					14.55	7.31	50

fitting method applying robust design which is a representative method of quality engineering. As a result of the research, the SN ratio was obtained from the result of the orthogonal array experiment, and it was possible to extract the combination of the optimum processing condition level from the response graph. Finally, the shrink fitting method can be practically applied by the confirmation experiment, it is superior to the current construction method, and it is clear that the quality assurance can be technically guaranteed.

However, the future research topic is the performance evaluation on the relation between the risk factor of the thermal core effect of the rotor core due to induction heating and the motor performance. It is important how to solve the problem of temperature rise to realize high efficiency and high output of the motor. It is the rotor core that

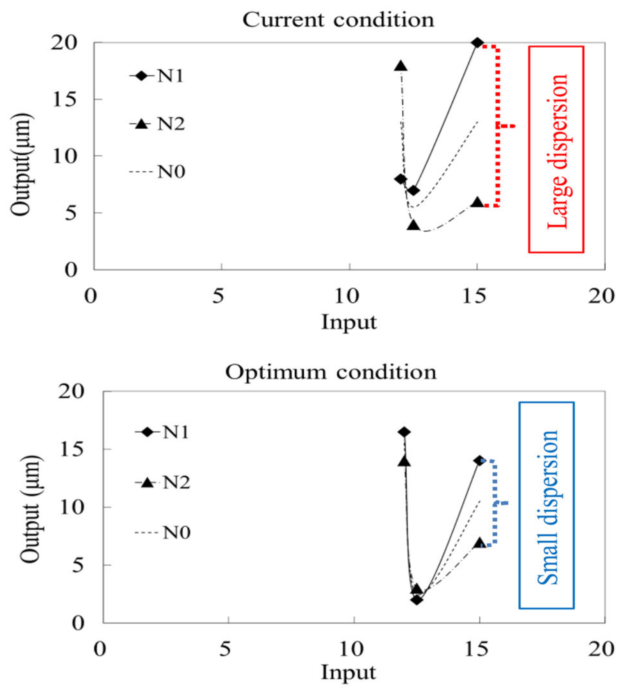


Fig. 16 Functionality evaluation graph

the characteristic change with temperature is great. In particular, in the case, where the motor is producing a large torque under an overload condition, the possibility of demagnetization increases. Although the residual magnetic flux density and the coercive force of the rotor core are both lowered due to the temperature rise, it is necessary to secure the coercive force in a high-temperature environment.

In the future, we will study the optimization of motor performance by influence on torque waveform and magnetic flux density distribution by grasping demagnetization characteristics of material by integration of quality engineering and magnetic field analysis simulation using finite-element method.

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