17 Robust Technology Development

17.1. Introduction

Robust technology development is a revolutionary approach to product design. The idea is to develop a family of products so that development efforts do not have to be repeated for future products in the same family. This is possible because the generic function of the entire family of products is the same. Once the robustness of this generic function is maximized, all that remains to be done for a newly planned product is to adjust the output.

The optimization of a generic function can be started before product planning in the research laboratory. Since there are no actual products, a generic function can be studied using test pieces, which are easier to prepare and less expensive.

Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

Robust design is the design of the product that will be least affected by user conditions. Noise conditions must therefore be considered in the development. Since the development is conducted in a small-scale research laboratory, the conclusions obtained must be reproducible downstream, that is, in large-scale production and under a customer's conditions. To check reproducibility, the concepts SN ratio and orthogonal array are used.

The most direct benefit of robust technological development is that the product development cycle time can be reduced dramatically. At the Quality Engineering Symposium in Nagoya, Japan, in 1992, the theme was: Can we reduce R&D cycle time to one-third? Case studies presented at the symposium offered convincing proof that it is possible to do so. If a product was shipped one year earlier than a competitor's, the profit potential would be enormous.

17.2. Concepts of Robust Technology Development

Some key concepts in robust technology development are two-step optimization, selection of what to measure, generic function, SN ratio, and orthogonal arrays. These concepts are described below.

Two-Step Optimization

There are two common paradigms among engineers: (1) Hit the target first at the design stage, then make it robust; and (2) to improve quality, higher-grade raw materials or component parts must be used.

Because of competition, there is always a deadline for the completion of product development. In many cases, therefore, drawings and specifications are made right after the target for the product to be developed is hit, and production starts immediately without any study of robustness. After receiving warrantee returns or complaints from the market, firefighting is begun.

A good product design engineer considers robustness after the target is hit. Assume that there are 10 or 15 extreme customer conditions. The test under the first extreme condition shows a deviation from the target. Therefore, the engineer changes some design parameters and the target is hit. The test under the second extreme condition deviates again. The engineer changes the same or other design parameters to hit the target to satisfy the first and second extreme conditions. In this way, the engineer tries to satisfy all extreme conditions. This is very difficult and time-consuming work. It is similar to solving 10 or 15 simultaneous equations through hardware experimentation. It is difficult, even when the study is conducted by simulation.

Using Taguchi methods, the followings are new paradigms:

1. Robustness is first, adjusting average is last.
2. To improve quality, parameter design is first, tolerance design is last.

In golf, for example, the most important thing is to reduce variability in flight distance and direction, not to improve the average distance. Using a driver, one may hit the ball to a respectable average of 200 yards, with a range of ±50 yards. Using the parameter design approach, by changing the levels of control factors such as stance, grip, or swing, variability can be reduced. After variability is reduced, adjusting the average distance is accomplished simply by selecting the proper club. This parameter design approach is now widely recognized as *two-step optimization.*

Selection of What to Measure

In the 1989 ASI Taguchi Methods Symposium, the following was selected as the theme: To get quality, don't measure quality! The second *quality* here refers to the *symptom* or subjects measured in firefighting. Typical examples are audible noise level and chattering or vibration of a machine or a car.

In the case of a company manufacturing thermosetting and steel laminated sheets, cracking was measured before shipment [1]. No cracking was detected in the final product inspection, but cracking was noticed two or three years after shipment at the rate of 200 ppm in the market. According to the method of testing before shipment, the problem would not have been noticed, even after an 80-hour test.

Parameter design was conducted by measuring the following generic function of the product: *Load is proportional to deformation.*

In the study, evaluation of cracking was made using an 18-hour test instead of 80 hours without observing cracks. A 4.56-dB gain was confirmed from the study.

Quality is classified into the following four levels:

1. Downstream quality (customer quality)
2. Midstream quality (specified quality)
3. Upstream quality (robust quality)
4. Origin quality (functional quality)

Downstream quality refers to the type of quality characteristics that are noticed by customers. Some examples in the auto industry are gasoline mileage, audible noise, engine vibration, and the effort it takes to close a car door. Downstream quality is important to management in an organization. However, it is of limited value to engineers in determining how to improve the quality of a product. Downstream quality serves to create a focus on the wrong thing and is the worst type of quality characteristic to use for quality improvement. Downstream quality, however, is easy to understand. If such quality characteristics were used for quality improvement, the statement would be: To improve quality, measure that quality.

Midstream quality is also called *specified quality*, since it is specification-related quality, such as dimension, strength, or the contents of impurities in a product. Midstream quality is important for production engineers, since it is essential to "make the product to print." But many engineers today have begun to realize that making to specifications (print) does not always mean that good quality is achieved. It is slightly better to measure these downstream quality characteristics—but not much.

Upstream quality is expressed by the nondynamic SN ratio. Since the nondynamic SN ratio relates to the robustness of a fixed output, upstream quality is the second-best quality characteristic to measure. It can be used to improve the robustness of a particular product instead of a group or a family of products. However, the concept of SN ratio is not easily understood by engineers.

Origin quality is expressed by the dynamic SN ratio. This is the best and most powerful type of quality and is the heart of robust technology development. In contrast to nondynamic SN ratios that are used to improve the robustness of the average, the output of a particular product, the dynamic SN ratio is used to improve the *generic* function of a product, the outputs of a *group* of products. By using this type of quality characteristics, we can expect the highest probability of reproducing the conclusions from a research laboratory to downstream, that is, to large-scale production or market. The use of origin quality therefore improves the efficiency of R&D. However, this type of quality level is hardest for engineers to understand.

Why is downstream quality the worst, midstream the next worst, upstream the next best, and origin quality the best? This concept is based on philosophy as well as on actual experiments over the years. Origin quality can be described from the viewpoint of interactions between control factors, which we try to avoid, because the existence of such interactions implies that there is no reproducibility of conclusions. When downstream quality is used, these interactions occur most frequently. Such interactions occur next most frequently when midstream quality is used, less in upstream quality, and least in origin quality.

The most important quality, origin quality, is the SN ratio of dynamic characteristics, the relationships between an objective function and a generic function.

Objective Function versus Generic Function

An *objective function* is the relationship between the signal factor input used by a customer and the objective output. In an injection molding process, for example, the user (production engineer) measures the relationship between mold dimension and product dimension. Mold dimension is the input signal, and product dimension is the objective output. It is the relationship between the user's intention and the outcome.

A *generic function* is the relationship between the signal factor input and output of the technical mean (method) the engineer is going to use. In the case of an injection molding process, the process is the mean (material) used to achieve a certain objective function. The engineer expects the material to have a certain physical property, such as the relationship between load and deformation.

In another example, the objective function of a robot is the relationship between the programmed spot the robot is supposed to travel to and the spot actually reached. If an engineer used an electric motor to move the arm of the robot, this is the technical means. The generic function would be the relationship between the input rpm and the angle change of the robot's arm.

Generic function is related to physics. It is energy-related; therefore, there is additivity or reproducibility. We want additivity for reaching conclusions before product planning. Conclusions from a small-scale study should be reproducible in large-scale manufacturing and under the customer's conditions. Therefore, generic functions are better to study than are objective functions.

In some cases, generic function cannot be used for reasons such as lack of technology to measure the input or output. In such a case, objective functions may be used, but it is always preferable to study generic functions.

SN Ratio

The SN ratio has been used since the beginning of the last century in the communications industry. For example, a radio measures the signal from a broadcasting station and reproduces the original sound. The original sound from the broadcasting station is the *input*, and the sound reproduced from the radio is the *output*. But there is noise mixed with the sound reproduced. A good radio catches mostly original sound and is least affected by noise. Thus, the quality of a radio is expressed by the ratio of the power of the signal to the power of the noise. The unit decibel (dB) is used as the scale. For example, 40 dB indicates that the magnitude of the signal is 10,000 and the magnitude of noise is 1; 45 dB indicates that the power of the signal is approximately 30,000 times the power of noise. It is important to remember that the higher the SN ratio, the better the quality. In quality engineering, every function is evaluated by the SN ratio: the power of the signal to the power of the noise.

The objective of design of experiments is to search for the relationship between various factors and the objective characteristic (response). In design of experiments, it is important to find the correct relationship (model) precisely and efficiently. When the interactions between factors (causes) are significant, these terms must be included.

The primary uses of parameter design in quality engineering are (1) to introduce the SN ratio, the measure of functionality; and (2) to use orthogonal arrays to check the significance of the interactions between control factors. If such interactions are significant, the reproducibility of conclusions is questionable.

The SN ratio gives the interactions between a control factor, the signal factor, and noise factors. Introduction of the SN ratio enables one to avoid interactions between control factors. However, it is not known whether or not the interactions between control factors are significant just from the introduction of SN ratio, so orthogonal arrays are used to check the existence of significant interactions.

Traditionally, technology has been developed to find the following equations:

$$y = \beta M \tag{17.1}$$

$$y = f(M, x_1, x_2, \ldots , x_n) \tag{17.2}$$

where y is the response, M the signal, and $x_1, x_2, \ldots , x_n$ are noise factors. In such a study it is important to find an equation that expresses the relationship precisely. A product with good functionality means has a large portion of equation (17.1) included in equation (17.2). In quality engineering, the responses of equation (17.2) are decomposed into the useful part: equation (17.1), and the harmful part, the rest: equation (17.2) − equation (17.1). The latter is the deviation from the useful part:

$$f(M, x_1, x_2, \ldots , x_n) = \beta M + [f(M, x_1, x_2, \ldots , x_n) - \beta M] \tag{17.3}$$

In traditional design of experiments, there is no distinction between control and noise factors. Error is assumed to be random, and its distribution is discussed seriously. In quality engineering, neither random error nor distribution is considered. Thus, quality engineering differs entirely from the traditional design of experiments in this aspect.

Orthogonal Array

In technology development, studies are conducted in research laboratories using test pieces. This method is used to improve and forecast actual product quality: for both large-scale manufacturing and for quality in the market. Therefore, it is extremely important that the conclusions from the laboratory be reproducible.

Reproducibility does not mean that an effect is reproduced under the same conditions, as are repetitions in a laboratory. Instead, it means the effects can be reproduced in the following situations:

1. The conclusions from the test piece study are reproduced in the actual product.

2. The conclusions from a small-scale study are reproduced in large-scale manufacturing.
3. The conclusions from limited conditions are reproduced under various other customers' conditions.

Since conditions in the laboratory are different from those downstream (large-scale manufacturing or the market), the output response measured in the laboratory is different from the targeted response in manufacturing or in the market. Such differences must be adjusted later in the product design so that the output hits the target. This is the second-stage tuning process in two-step optimization. At the first stage, only functionality is improved.

Suppose that there are two different designs (such as different control factor levels or different conditions: initial and optimum). The SN ratios of these designs are calculated, and their difference, the gain, is calculated. Since the SN ratio is the measure of the stability of a function, it is expected that the gain may be reproduced downstream. However, there is no guarantee, and it is necessary to check reproducibility. That is why orthogonal arrays are used.

For experimentation, orthogonal array L_{18} is used most of the time. For two-level control factors, L_{12} is used. For simulation, L_{36} is used. Using orthogonal arrays does not improve the efficiency of experiments. Indeed, it can take longer. In the arrays above, the interactions between control factors are distributed to other columns and confounded with main effects. It is important to conduct an experiment in such a fashion that interactions between control factors are purposely confounded with control factors. When interactions are found between control factors, main effects are affected and deviate. Therefore, the gain between estimation from an orthogonal array experiment and the confirmatory experiment changes. If the gains between the two do not change significantly, we can expect good reproducibility.

The one-factor-at-a-time approach has been used widely in experimentation. Using this method, however, one cannot know whether the main effect will be reproduced under other conditions. Therefore, the one-factor-at-a-time method is successful only when there are no interactions.

The same is true with assigning only main effects to an orthogonal array. The experiment will be successful only if there are no interactions. Therefore, the possibility of success using this approach is the same as that for using the one-factor-at-a-time approach. In other words, if there are no interactions between control factors, it does not matter whether an orthogonal array or a one-factor-at-a-time approach is used.

The reason for using an orthogonal array without assigning interactions is to check the existence of interactions by checking for reproducibility. In other words, orthogonal arrays are used to see if the experiment is a success or a failure. It is the same as inspecting product quality during manufacturing. If the product passes the test, the inspection was a waste, since the product is a good one without inspection. Inspection is beneficial or valuable only when a defective product is found. Inspection is not useful to improve quality, but it can prevent the problems caused by quality.

Similarly, the objective of using orthogonal arrays is to find bad experiments. It is to prevent improper technology or a bad design from being transferred forward and causing problems downstream.

If an orthogonal array is used and the gain shows good reproducibility, it was a waste to use the array. The benefit is when the gain shows no reproducibility. Then we should be thankful for the discovery.

To be successful using orthogonal arrays for experimentation, it is necessary to find a characteristic to be measured that has minimum interactions between control factors, that is, the SN ratio derived from functionality. From the viewpoint of quality engineering, the dynamic SN ratio of a generic function is superior to the dynamic SN ratio of an objective function, and the dynamic SN ratio of an objective function is superior to the nondynamic SN ratio of an objective characteristic. Of course, these are still much superior to midstream quality and downstream quality characteristics.

17.3. Advantages of Using Robust Technology Development

There are three main features in using robust technology development: technology readiness, flexibility, and reproducibility.

Technology Readiness

Problem solving or firefighting, on which engineers spend most of their time, is conducted based on customer complaints or dissatisfaction. But it is too late by then. *Quality must be built into a product before the product design stage by first studying the function of the product.*

This has been a distinctive advantage that U.S. engineers have had over Japanese engineers, who have done most research by studying actual products. Research conducted based on the ideal product function enables manufacturers to be technologically ready and be able to bring new products to the market ahead of competitors.

In the development of a soldering process, for example, research has been done on test pieces in U.S. laboratories. The process was developed without actual products. Once this process is optimized, the technology is ready to produce future products.

Flexibility

The nondynamic SN ratio was used widely and successfully in the 1970s to optimize the robustness of one target or one particular product. But it would be much better and more powerful if multiple targets were optimized in one study. Dynamic SN ratios are used for this purpose. The dynamic SN ratio can improve linearity, improve sensitivity, and reduce variability, as we have said.

In the case of an injection molding process, the objective function is that the input dimension be proportional to the output dimension. If linearity, sensitivity, and variability are all improved, the change is as shown in Figure 17.1 from *a* to *b*.

After optimization, the process can produce any product having dimensions within the range of the outputs studied. Therefore, one study is good enough to optimize a group of the products. In other words, one dynamic SN ratio is used to evaluate all three aspects for the products within the ranges in the study.

A generic function may be used to optimize the same injection molding process. For example, the input and output may be load and deformation, respectively; or the input and output could be the weight of the product measured inside and the one outside the water. What type of generic function should be used depends on

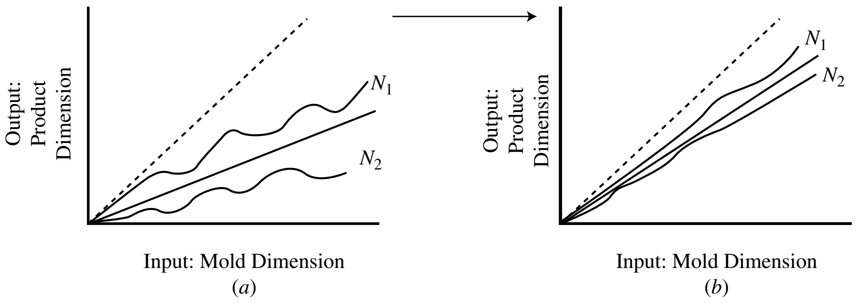


Figure 17.1
Input/output for an objective function

the reproducibility of conclusions. If the linearity, sensitivity, and variability are improved, the change is as shown in Figure 17.2 from *a* to *b*.

In this way, one-shot optimization enables engineers to utilize the database over and over without repeating similar research from product to product. This means a potentially huge savings in time, work power, and capital.

Reproducibility

As shown earlier, interaction (between control factors) is synonymous with poor reproducibility and also with lack of additivity, because downstream quality gives us the best chance of having interactions and origin quality the least. If an appropriate generic function is selected and the system is optimized, a minimum chance of having interactions, that is, maximum chance of downstream reproducibility, can be expected.

17.4. How to Apply Robust Technology Development

Here are some guidelines to follow for the application of robust technology development, based on the explanations presented earlier.

Paradigm Shift

Quality control activities have traditionally been performed within the manufacturing organization. Quality engineers, production engineers, and statisticians have played a major role in quality improvement. In contrast, R&D and product design engineers have been less involved in quality activities. It is said that a definition of R&D in the United States has wrongly excluded the issue of quality.

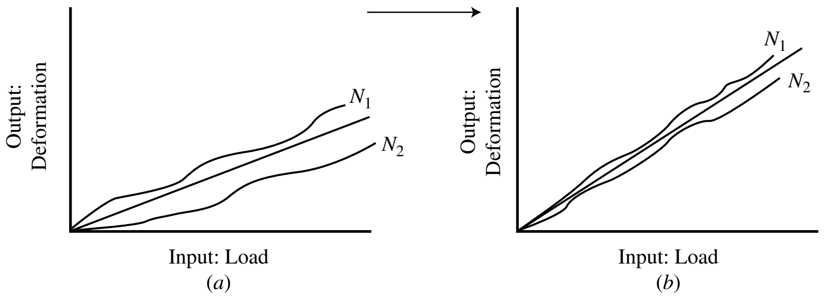


Figure 17.2
Input/output for a generic function

This paradigm has to be changed. The traditional approach to quality control issues has largely been synonymous with problem solving or firefighting. Utilizing the robust technology development approach, one does not focus on the symptoms or on the basic causes of variation. Instead, as we have said, the focus is on the study of the generic function of a product.

Another paradigm for product development or product design is trying to hit the target first, then considering how to reduce variation. In quality engineering, variation must be reduced first, then the average is adjusted to the target. This is the concept of two-step optimization.

Identification of the Generic Function

Problems cannot be solved by observing symptoms. In one case in the auto industry, for example, the audible noise level of a brake system was observed to solve the problem of squealing, but this did nothing to solve the problem in the long term. In another case, symptoms such as wear and audible noise level were observed in a study of timing belts. Those problems disappeared completely after dynamic SN ratios were used for evaluation rather than inspection and observation.

Ideally, the generic function would be used to calculate the dynamic SN ratio. If technology is lacking, the objective function of a system may be used instead. For computer simulation, nondynamic SN ratio may be used, since nonlinearity is not reflected in the software in most cases.

SN Ratio and Sensitivity

Maximizing the SN ratio is to maximize robustness. Sensitivity is analyzed to adjust slope in the case of dynamic characteristics or to adjust the average in the case of nondynamic characteristics.

Use of Test Pieces

Since robust technology development is applied before product planning, there are no products yet, and test pieces must be used for development. The advantages of using test pieces are low cost and shorter time frame.

Compounding Noise Factors

To conduct a study efficiently, noise factors are compounded to set two or three conditions, such as:

N_1: negative-side extreme condition

N_2: positive-side extreme condition

or

N_1: negative-side extreme condition

N_2: standard condition

N_3: positive-side extreme condition

In the case of simulation, noise factors may not have to be compounded since calculations are easier than physically conducting experiments. But in simulation, it is hard to include deterioration or customer conditions. Piece-to-piece variability may be used to simulate these two types of noise factors.

It is unnecessary to include *all* noise factors in a study. One can use just a few important noise factors, either to compound or not to compound. Generally, noise factors related to deterioration and customer conditions are preferable for experimentation rather than the factors related to piece-to-piece variation.

Use of Orthogonal Arrays

Orthogonal arrays are used to check the existence of interactions. It is recommended that one use L_{12} and L_{18} for experimentation or L_{36} arrays for simulation.

Calculation of Response Tables

Response tables for the SN ratio and sensitivity are used for two-step optimization. No ANOVA tables are necessary for selection of the optimum levels of control factors.

Optimization and Calculation of Gains

The optimum condition is determined from the two response tables: tables of SN ratio and sensitivity. The SN ratios of the current condition and the optimum condition are calculated. The predicted gain is then calculated from the difference. The same is done for sensitivity.

Confirmatory Experiment

Under the current and optimum conditions, confirmatory experiments are run, along with their SN ratios and sensitivity; then the gain is calculated. The gain must be close enough to the predicted gain to show good reproducibility. How close it should be is determined from the engineering viewpoint rather than by calculating percent deviation. If the two gains are not close enough, it indicates poor reproducibility, and the quality characteristic used must be reexamined.

❒ Example [2]

To save energy for copy machines and printers, a new fusing system was developed using a resistant heater that warms up in a short period of time. This project was scheduled to be completed in one year. In the midst of development, there were design changes both mechanically and electrically that affected the progress. By the use of robust technology development approaches, however, development was completed within the scheduled time. From past experience it was estimated that the development would have taken two years if the traditional approaches had been used.

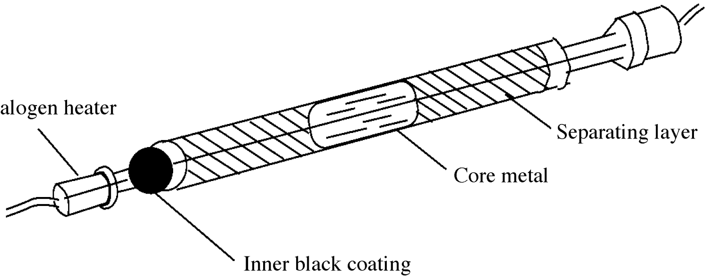
The electrophotographic system requires a high-temperature roller that fixes resin toner to the paper by heat fusion. In this system, 90% of the power is consumed for idle time (the time to wait when the machine is not running). To save energy, it would be ideal that no heating be applied during waiting and heat applied only when needed. But heating takes time that makes users wait.

To solve this problem, a new system, which heats up the system to a high temperature in a short period of time, was to be developed in one year. This system was named the Minolta advanced cylindrical heater (MACH).

Traditional Fixing System

Figures 17.3 and 17.4 show the structure of the traditional and the MACH heat roller, respectively. The differences between the two systems are in the heat source and the method of power transformation. In the former system, heat is transferred

Figure 17.3
Traditional roller



by the radiation from a halogen heater. In the latter case, it is transferred directly by a resistor. To heat the heat roller surface to 180°C requires that the surface temperature of the halogen lamp reach 350°C. But using the resistor heater, its surface temperature needs only to be 180°C.

Functions to Be Developed

Figure 17.5 shows the functions of the system. Of those functions, the following four were selected to develop:

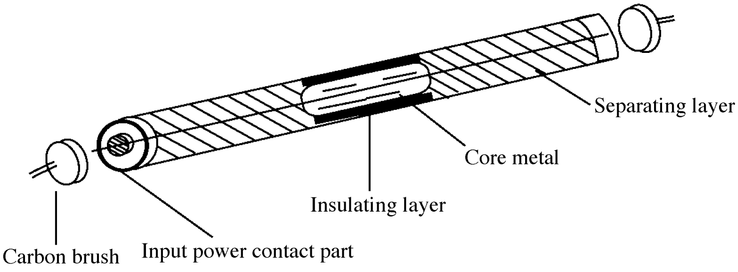
- ☐ Power supply function
- ☐ Heat-generating function
- ☐ Separating function
- ☐ Temperature-measuring function

These functions were developed independently and concurrently because (1) there was a short period of time for development, (2) several suppliers would be involved, (3) any delay of one supplier affects the entire project, and (4) no technological accumulations was available.

Development of the Power Supply Function

This system was constructed by a carbon brush and power receiving parts. It was considered to be ideal that the power be transformed without loss.

Figure 17.4
MACH heat roller



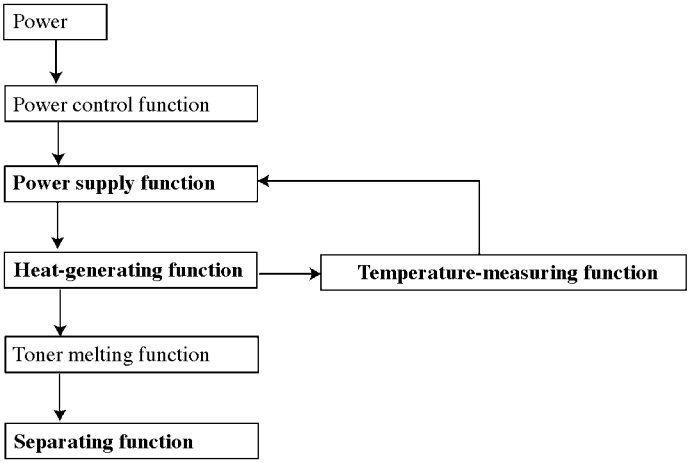


Figure 17.5
Functions of the system

- ❏ *Input:* square root of input power (five levels)
- ❏ *Output:* square root of output power
- ❏ *Noise:* not compounded (eight levels)
- ❏ *Duration time:* 0, 750 hours
- ❏ *Temperature:* 20, 200°C
- ❏ *Contact pressure:* small, large

Figure 17.6 shows the ideal function, Figure 17.7 shows the test piece prepared for the study, and Table 17.1 shows the control factors and their levels. Orthogonal array L_{18} was used to assign control factors. The SN ratios and sensitivity of the 18

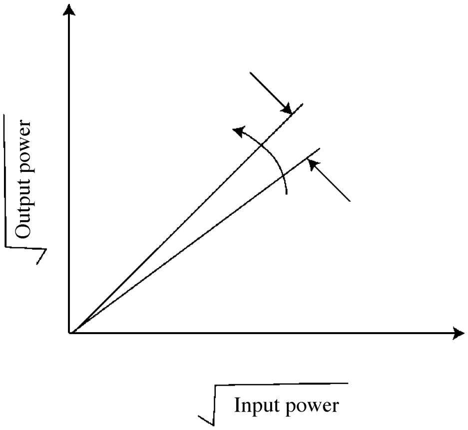


Figure 17.6
Ideal function of power supply

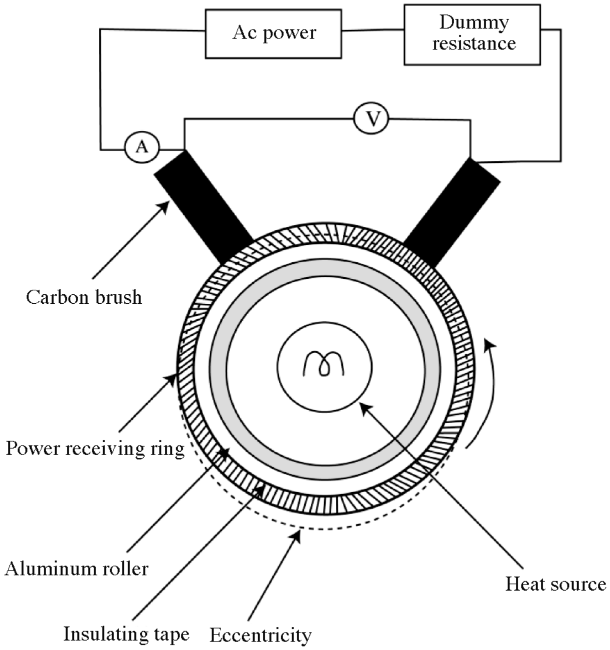


Figure 17.7
Test piece for power supply function

runs were calculated, and response curves were drawn as shown in Figures 17.8 and 17.9.

The levels with "o" marks in the figures were selected as the optimum conditions. Table 17.2 shows the results of the confirmatory experiment. Factors *A*, *C*, and *E* were used for estimation. The gain of the SN ratio was fairly reproduced.

Table 17.1
Control factors for power supply function

Factor		Level 1	Level 2	Level 3
A	Temperature during deterioration	Low	High	—
B	Brush shape	I	II	III
C	Pressure	Weak	Medium	Strong
E	Brush material	A	B	C
F	Lead wire cross-sectional area	Small	Medium	Large
G	Bush area	Small	Medium	Large
H	Holder distance	Small	Medium	Large

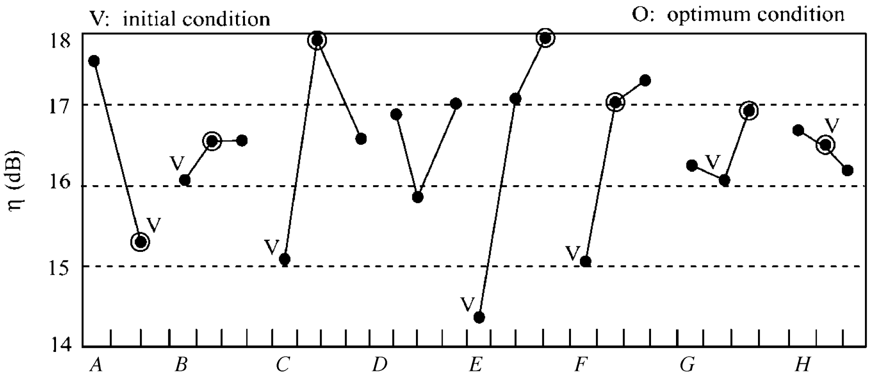


Figure 17.8
SN ratio of power supply function

The gain of sensitivity was small, but the power loss at the brush was reduced by half.

Figures 17.10 and 17.11 are the results of confirmation under current and optimum conditions where twice the range of signal factor in the orthogonal array experiment was used. It shows a higher power transformation efficiency and a smaller variation due to noise.

Development of the Heat-Generating Function

The heat-generating part is constructed by a lamination of core metal, insulating layer, and heat-generating element. The ideal function is to transfer power to heat efficiently and uniformly.

- ☐ *Input:* square root of input power (three levels)
- ☐ *Output:* square root of temperature rise
- ☐ *Noise:* four measuring positions and one non-heat-generating position (five levels)

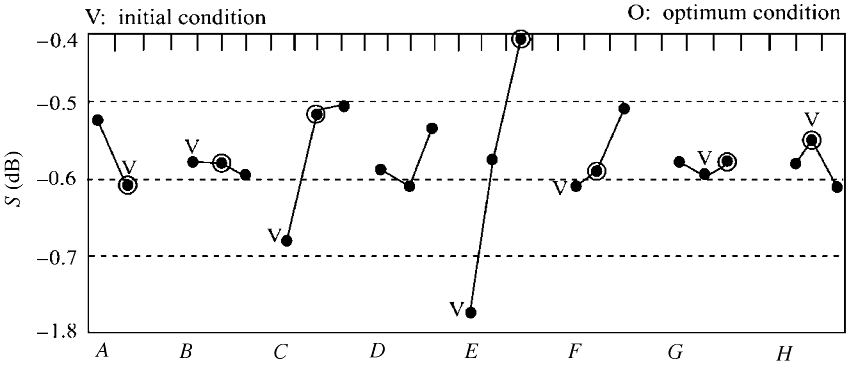


Figure 17.9
Sensitivity of power supply function

Table 17.2
Results of confirmation

	SN Ratio		Sensitivity	
	Estimation	**Confirmation**	**Estimation**	**Confirmation**
Initial condition	12.18	6.16	−0.89	−0.93
Optimum condition	18.22	10.98	−0.40	−0.81
Gain	6.04	4.82	0.49	0.12

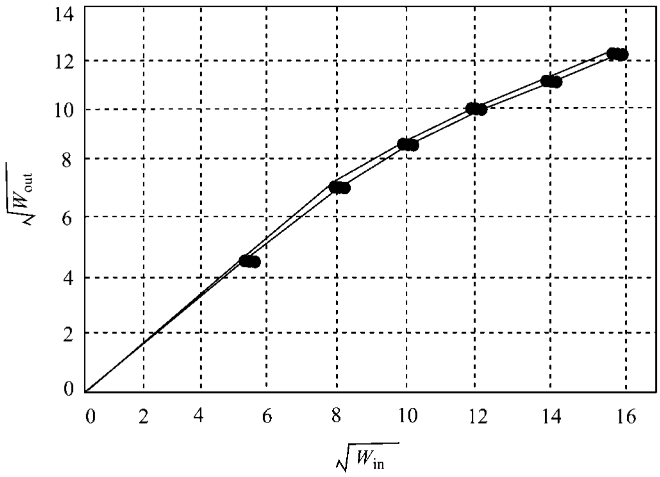


Figure 17.10
Input/output of initial condition

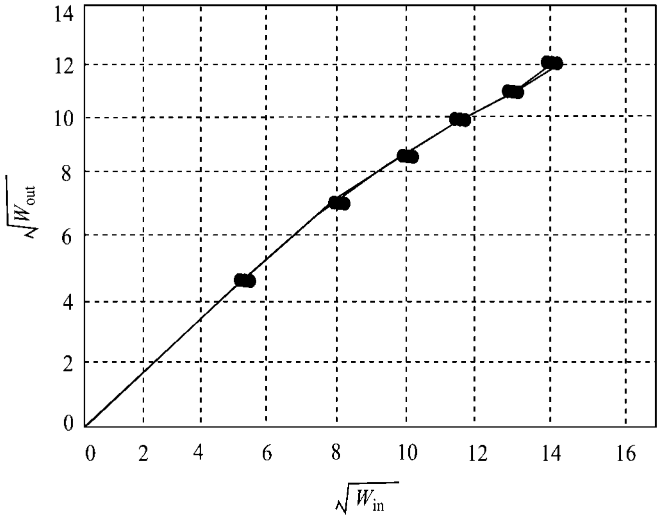


Figure 17.11
Input/output of optimum condition

Figure 17.12 shows the ideal function, and Figure 17.13 shows the test piece for heat-generating function. Heat-generating positions and materials were cited as control factors as shown in Table 17.3. From the results of SN ratio and sensitivity, response graphs were plotted as shown in Figures 17.14 and 17.15. Factors *A*, *B*, *C*, *D*, and *F* were used to estimate the SN ratio and sensitivity of the optimum condition. The results of confirmatory experiments are shown in Table 17.4.

The input/output characteristics of the initial and optimum conditions are plotted in Figures 17.16 and 17.17. From the figures, it can be seen that the temperature variation of the optimum condition was improved significantly compared with the initial condition.

Development of the Peel-Off Function

The peel-off unit is constructed by a core metal coated by primer and fluorine resin layers. It is ideal that the peel-off force of melted toner from the unit is small, as shown in Figure 17.18. For test pieces, plain peel-off layers were used for simplicity and easy preparation. The plates were heated, and unfixed toner layer was pressed and melted, then peel-off force was measured. Figure 17.19 shows the test piece.

Table 17.5 shows the control factors. Since the time to complete development is limited, the control factors related to fluorine resin were not studied and only manufacturing-related control factors were studied. The optimum condition was determined from response graphs in Figures 17.20 and 17.21.

Results of the confirmatory experiment are shown in Table 17.6. They show poor reproducibility. But from Figures 17.22 and 17.23, one can see that the

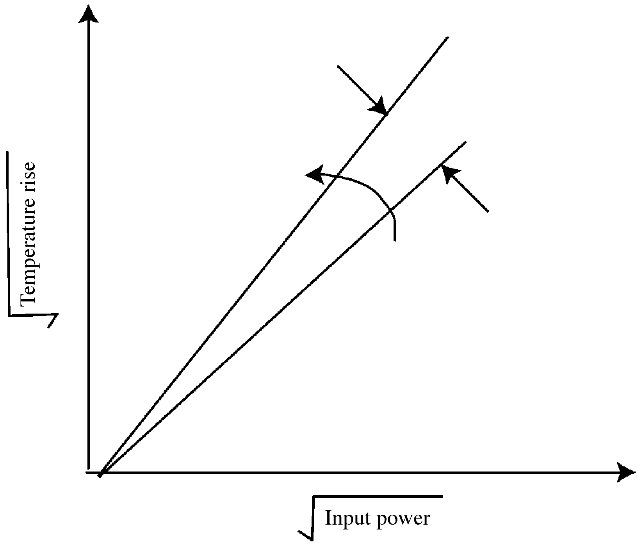


Figure 17.12
Ideal function of heat-generating function

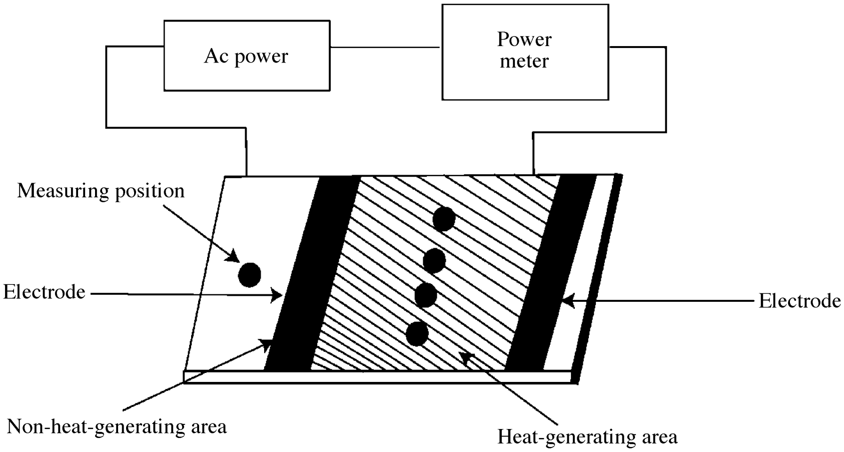


Figure 17.13
Test piece for heat-generating function

Table 17.3
Control factors for heat-generating function

	Factor	Level 1	Level 2	Level 3
A	Position of heat-generating element	Face	Reverse	—
B	Material I	A	B	C
C	Material II	Small	Medium	Large
D	Material III	Small	Medium	Large
F	Material IV	*X*	*Y*	*Z*

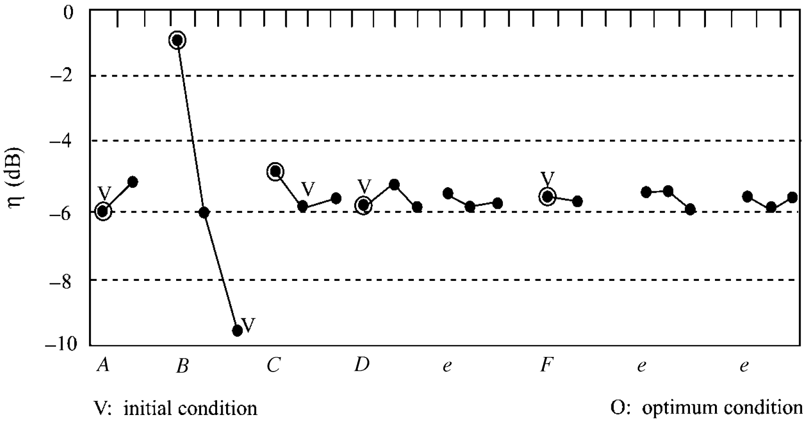


Figure 17.14
SN ratio of heat-generating function

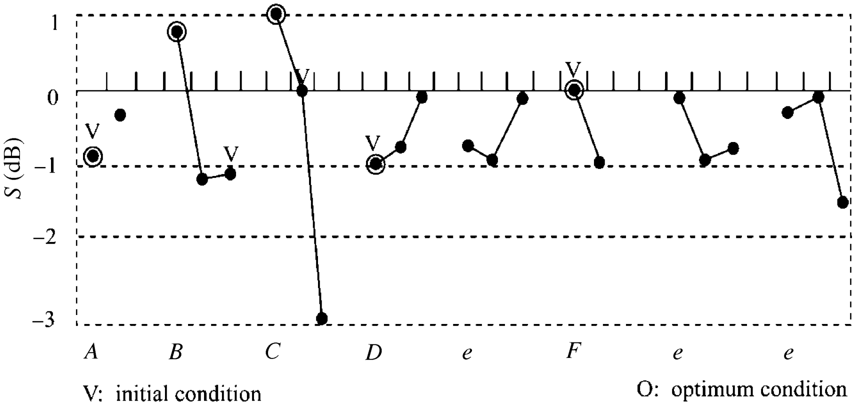


Figure 17.15
Sensitivity of heat-generating function

peel-off force under the optimum condition became smaller. As a result, a peel-off force that would satisfy the product requirement was obtained. The poor reproducibility was probably caused by uneven setting of noise factor conditions in the experiment.

Development of the Temperature-Measuring Function

A unit constructed by a thermistor and a sponge measures temperature (Figure 17.24). The ideal function is that the temperature of the object measured be proportional to the reading, as shown in Figure 17.25. Temperature reading was transformed from the reading of voltage. The construction of thermistor, resistance, and so on, was studied as control factors, as shown in Table 17.7.

From the response graphs shown in Figures 17.26 and 17.27, the optimum conditions were selected from the SN ratio. Factor *B* was selected based on the situation of self-heat generation. Factors *G* and *H* was selected based on the cost aspect.

Table 17.8 shows the results of confirmation. All factors were used to estimate both the SN ratio and sensitivity. Both gains showed good reproducibility. From Figures 17.28 and 17.29, the optimum condition has a better linearity. The study

Table 17.4
Results of confirmation

	SN Ratio		Sensitivity	
	Estimation	**Confirmation**	**Estimation**	**Confirmation**
Initial condition	−10.32	0.01	−0.02	−0.05
Optimum condition	−0.79	10.94	1.70	3.26
Gain	9.53	10.93	1.72	3.31

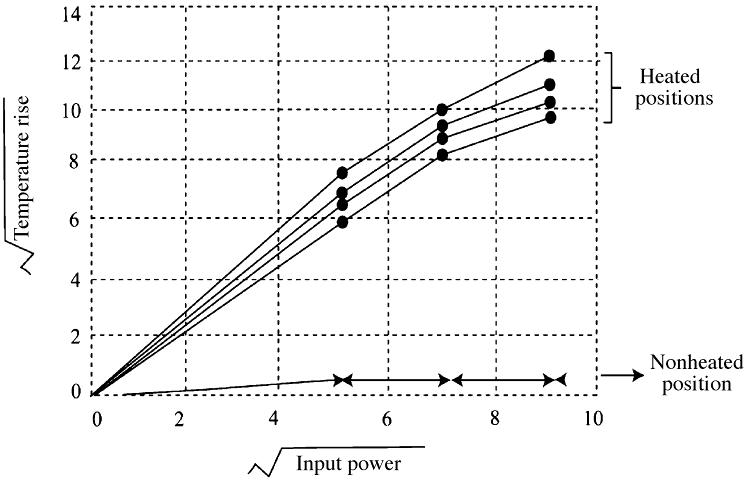


Figure 17.16
Input/output of initial condition

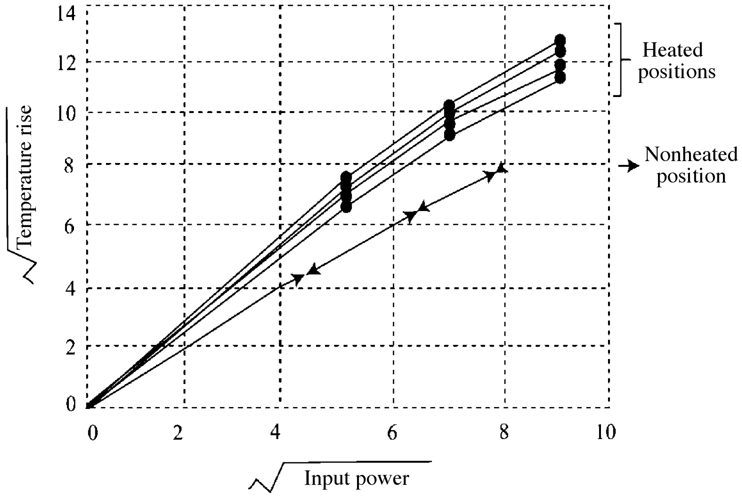


Figure 17.17
Input/output of optimum condition

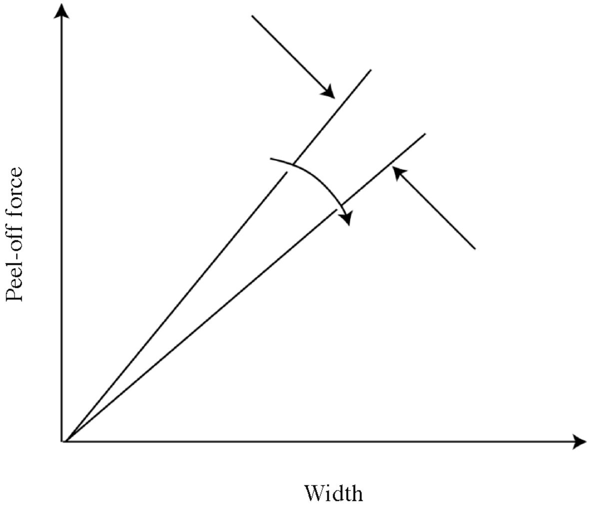


Figure 17.18
Peel-off function

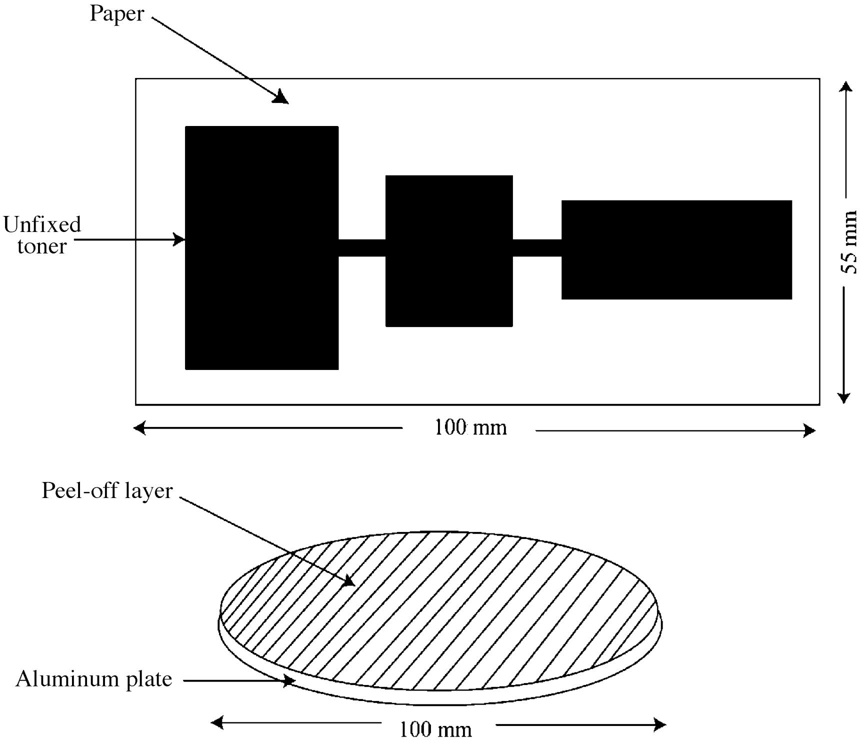


Figure 17.19
Test piece for peel-off function

Table 17.5
Control factors for peel-off function

	Factor	Level 1	Level 2	Level 3
A	Heat treatment	Yes	No	—
B	Baking condition 1	Small	Medium	Large
C	Material	*A*	*B*	*C*
D	Baking condition 2	Small	Medium	Large
E	Film thickness	Small	Medium	Large
F	Baking condition 3	Small	Medium	Large
G	Baking condition 4	Small	Medium	Large
H	Pretreatment	No	Small	Large

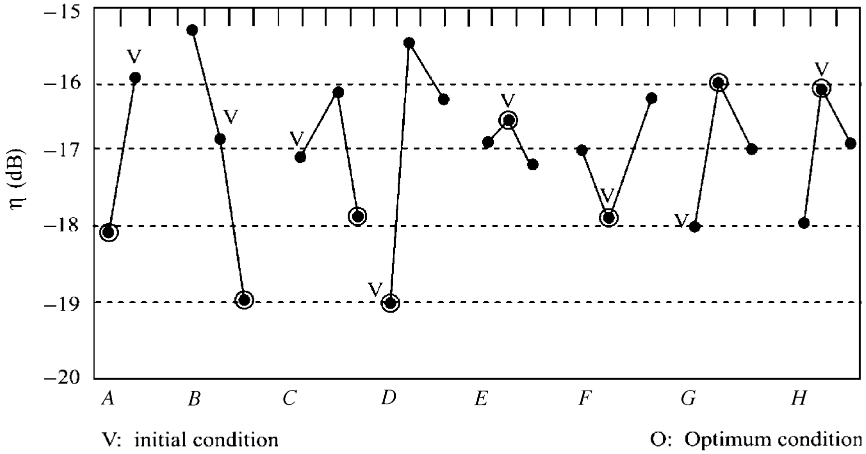


Figure 17.20
SN ratio of peel-off function

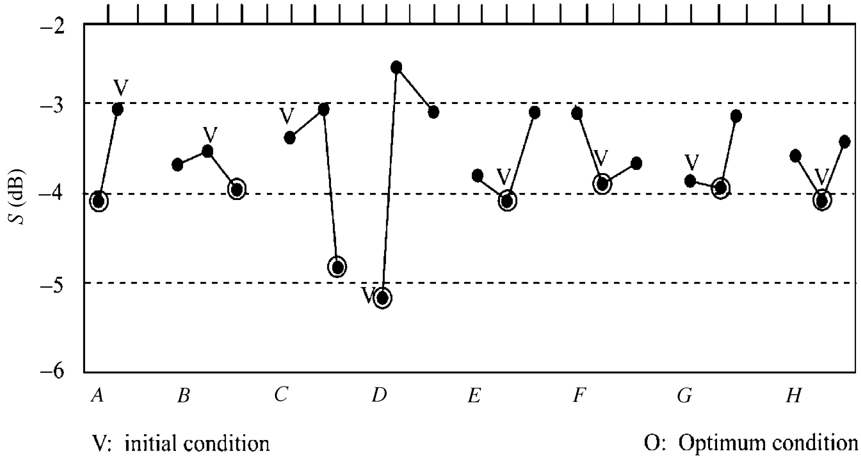


Figure 17.21
Sensitivity of peel-off function

Table 17.6
Results of confirmation

	SN Ratio		Sensitivity	
	Estimation	**Confirmation**	**Estimation**	**Confirmation**
Initial condition	−14.03	−21.25	−4.51	0.23
Optimum condition	−22.22	−24.66	−7.00	−8.84
Gain	−8.19	−3.41	−2.49	−9.07

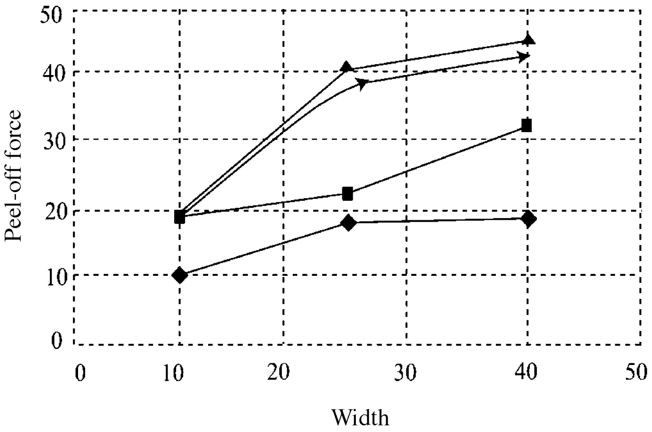


Figure 17.22
Input/output of initial condition

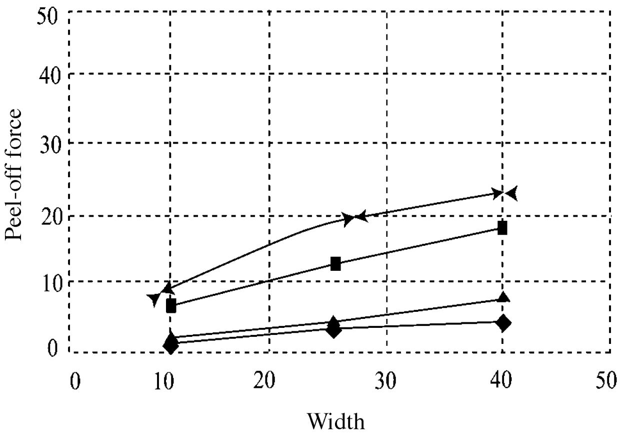


Figure 17.23
Input/output of optimum condition

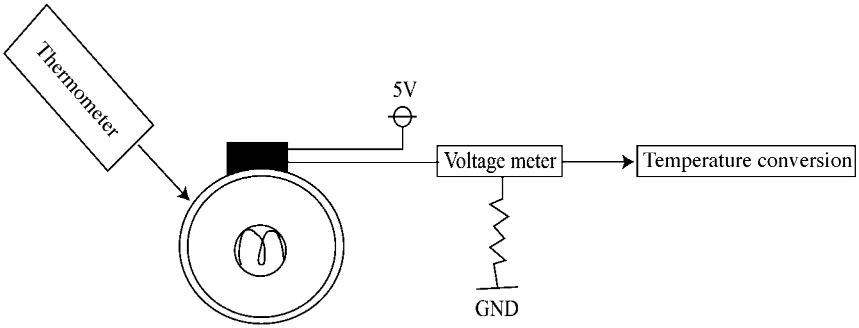


Figure 17.24 Test piece for temperature-measuring function

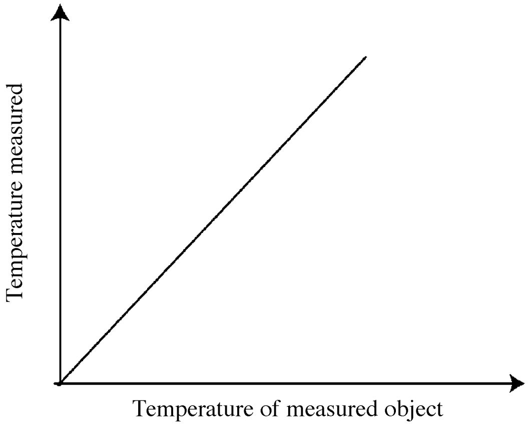


Figure 17.25 Ideal function of temperature measurement

Table 17.7
Control factors for the temperature-measuring function

	Factor	Level 1	Level 2	Level 3
A	Surface film	*A*	*B*	*C*
B	Pressure-dividing resistor	2 kΩ	4 kΩ	8 kΩ
C	Thermistor chip	I	II	III
D	Thermistor resistor	0.3 kΩ	0.55 kΩ	1 kΩ
E	Sponge	*X*	*Y*	*Z*
F	Plate material	*a*	*b*	*c*
G	Plate thickness	Small	Medium	Large
H	Plate area	Small	Medium	Large

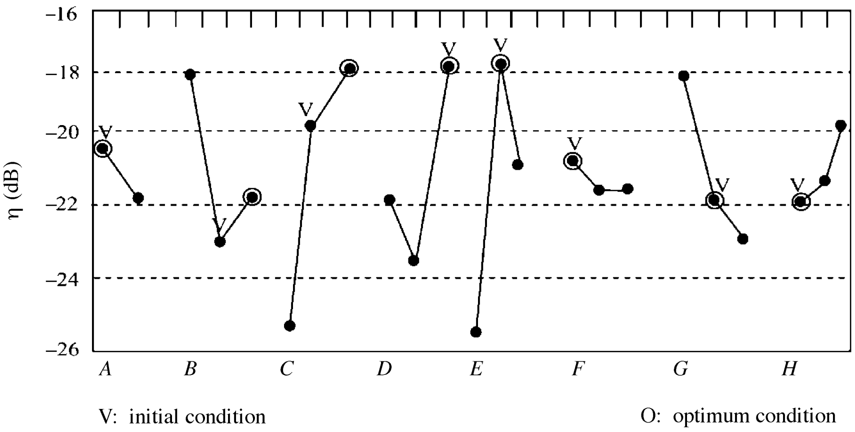


Figure 17.26
SN ratio of the temperature-measuring function

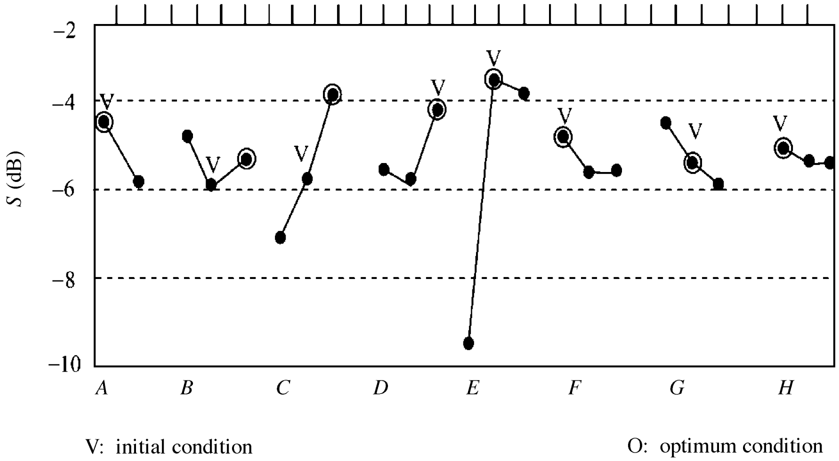


Figure 17.27
Sensitivity of the temperature-measuring function

Table 17.8
Results of confirmation

	SN Ratio		SN Ratio	
	Estimation	**Confirmation**	**Estimation**	**Confirmation**
Initial condition	−16.39	−23.95	−2.39	−4.2
Optimum condition	−13.01	−20.87	0.12	−2.75
Gain	3.38	3.08	2.51	1.67

Figure 17.28
Input/output of initial condition

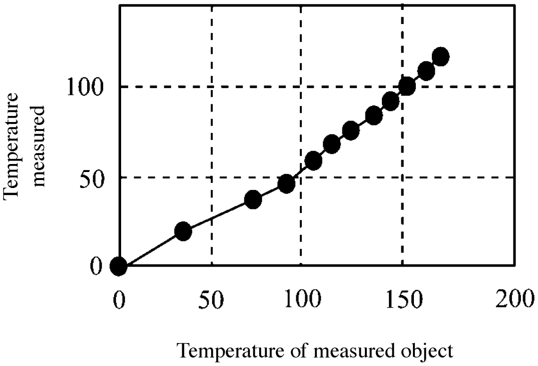
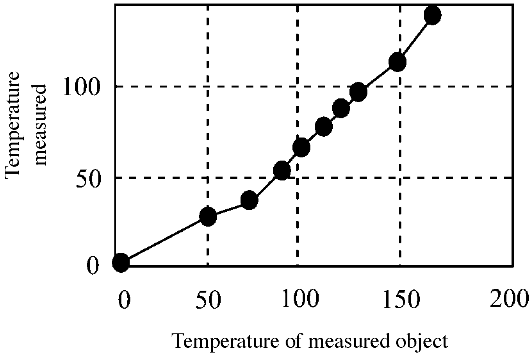


Figure 17.29
Input/output of optimum condition



was continued and the sensitivity could be improved almost to 1, so it was concluded that no forecasting control or adjustment would be necessary.

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2. Eiji Okabayashi et al., 2000. Development of a new fusing system using four types of test pieces for four generic functions. *Journal of Quality Engineering Society*, Vol. 8, No. 1.