

Optimization of Endmill Cutting Conditions for Nickel-Based Super Alloys

Sachio KAJIURA*

Yasuhiko JINBU*

Kazuya KUWABARA**

ABSTRACT

Parameter design based on the Taguchi Method was applied to the endmill cutting process for nickel-based super alloys rather than the conventional sequential methods or experimental design methods in order to optimize the cutting conditions.

“Machining transferability”, which compares the preset removal volume to the actual removed volume, was selected as the evaluation characteristic used in this method.

As a result, if an alloy is cut with the optimized conditions obtained with parameter design, an approximately 60% reduction in variations in machining transferability, in terms of the standard deviation, can be achieved as compared to the conventional conditions.

1. Introduction

Conventional machining evaluations are typically performed using a method based on such quality characteristics as the machined surface roughness and dimensions, tool flank wear, and device cutting resistance, for which experiments are conducted by sequentially combining various parameters or by cross multiplication to optimize the machining conditions. When employing such methods, even if the level of a certain parameter is changed in a direction that is thought would yield favorable results, often the results are not as good as had been expected due to the interaction between parameters. In addition, while the experimental design method may employ statistical methods such that the contribution ratio of each parameter relative to the quality characteristics is expressed quantitatively, it is sometimes difficult to obtain the optimum machining conditions as a reduced dispersion.

In recent years, parameter design using the Taguchi method has been proposed. This method differs from the conventional sequential experimental method and the experimental design method. Examples of using this method to optimize the high speed milling conditions for titanium materials and the endmill cutting conditions for quenched steel have been previously reported⁽¹⁾⁽²⁾. However, there are no reported examples of this method being applied to the cutting of nickel-based super alloys (difficult-to-machine materials), which are generally processed by casting and grinding.

We therefore attempted to optimize the machining conditions for cutting nickel-based super alloys (difficult-to-machine materials) with a milling machine by applying the Taguchi parameter design method.

2. Experimental Design

2.1. Fundamental Function

Evaluating machining according to the Taguchi method consists primarily of two methods; namely, a method in which the evaluation is based on transcription of the machining dimensions, and a method in which the evaluation is based on the machining energy. There has been considerable research conducted recently on the latter method involving evaluations based on the energy consumed in machining. This method uses the energy input and output as determined by the amount of electrical power supplied to the machine and the actual amount of electrical power used by the machine for machining⁽³⁾⁽⁴⁾. However, it has been reported that when the energy consumption of the cutting machine was actually measured, as the electrical power during machining is relatively small in comparison with the power consumed during idling, the difference between the two could not be measured⁽⁵⁾.

Therefore, in this study, an evaluation method was applied based on transcription which works on the principle that the function of cutting is to cut a preset removal volume.

2.2. Signal Factor and Evaluation Characteristic

The fundamental function of cutting is to cut and remove a preset removal volume according to the settings mode. Ideally, the settings and amount removed are in a proportional relationship such that, if the settings are doubled, then the amount removed is doubled, and if the settings are tripled, then the amount removed is tripled. If the input (signal factor) is taken as M (preset removal volume), and the output (evaluation characteristic) is taken as y (the actual material removed, or “machined mass”), then the ideal

* Wako Research Center

** Saitama Plant, Honda Motor Co. Ltd.

relationship between the two is the following proportional expression:

$$y = \beta M \quad (1)$$

However, in actual cases of metal cutting, the following complex equation results due to the effects of various errors that cannot be controlled ($X_1, X_2, \dots, X_n$):

$$y = f(M, X_1, X_2, \dots, X_n) \quad (2)$$

However, even if the correlation between each effect and characteristic value can be determined by resolving this complex relationship, it is not actually possible to obtain an optimum solution, including a reduction of the dispersion.

The Taguchi method is a form of optimization for bringing the functional relationship expressed in equation (2) closer to the proportional relationship of equation (1). With the conventional experimental design method, quality characteristics are used directly as the characteristic values for analysis. However, with the Taguchi method, experimental analysis is performed using the characteristic value of the SN ratio that is converted to the ratio of the signal and dispersion from signal factor M and evaluation characteristic y .

In this experiment, the relationship between signal factor M and evaluation characteristic y is expressed by the following proportional expression:

$$y^{1/2} = \beta M^{1/2} \quad (3)$$

Three levels of signal factors were set (preset removal volume). Although the actual material removed increases in proportion to the increase in preset removal volume, there are some conditions that prevent machining from continuing due to breakage of the tool and so forth. In such cases, the value for the final machined surface was substituted for the actual material removed to facilitate data processing (Fig. 1). This was done to identify those conditions that would result in longer tool life and higher machining accuracy.

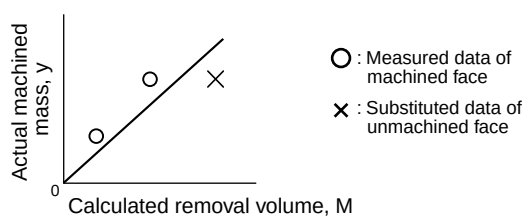


Fig.1 Schematic of ideal function

2.3. Noise Factors

Although the conditions can be selected, including dispersion reduction, to optimize the cutting conditions as well as the machining and production conditions, at the experimental design stage, there are many cases in which optimization is not possible due to unpredictable and not completely understood error factors. With the Taguchi method, consideration is given to which realistic conditions need to be selected, including these error factors. These unknown elements are incorporated into the experiment as noise factors.

In this experiment, it was decided to find realistic

conditions with respect to the following two points from the viewpoint of machining efficiency:

- (1) Being able to cut accurately, regardless of the cutting direction (up-cutting or down-cutting)
- (2) Being able to cut accurately regardless of the overhang (short or long).

Integration of these two points yielded the following noise factors:

N1 (easy cutting): short overhang - down-cutting, the error acts in the positive direction of cutting

N2 (difficult cutting): Long overhang - up-cutting, the error acts in the negative direction of cutting

2.4. Control Factors

Control factors refer to each of the parameters that can be controlled during cutting. In the case of milling, there are numerous parameters such as the tool specifications (material, coating, clearance angle, included angle, tip radius, tool diameter, etc.), feed per tooth, cutting speed, rotational speed and cutting direction. With the Taguchi method, an L18 orthogonal array, which is less susceptible to the effects of parameter interaction, is typically used when designing the experiment. In this case, although a maximum of eight parameters can be assigned, each parameter must be able to be independently controlled. Five parameters were selected for this experiment consisting of the tool manufacturers, feed

Table 1 Control factors and levels

Factor		Level		
		1	2	3
A	Tool maker	1	2	
B	Error			
C	Feed per tooth	Low	Middle	High
D	Cutting speed	Low	Middle	High
E	Width of cut	Low	Middle	High
F	Depth of cut	Low	Middle	High
G	Error			
H	Error			

Table 2 L18

Exp. No.	Control factors								Noise	
	A	B	C	D	E	F	G	H	N1	N2
1	1		Low	Low	Low	Low				
2	1		Middle	Middle	Middle	Middle				
3	1		High	High	High	High				
4	1		Low	Low	Middle	Middle				
5	1		Middle	Middle	High	High				
6	1		High	High	Low	Low				
7	1		Low	Middle	Low	High				
8	1		Middle	High	Middle	Low				
9	1		High	Low	High	Middle				
10	2		Low	High	High	Middle				
11	2		Middle	Low	Low	High				
12	2		High	Middle	Middle	Low				
13	2		Low	Middle	High	Low				
14	2		Middle	High	Low	Middle				
15	2		High	Low	Middle	High				
16	2		Low	High	Middle	High				
17	2		Middle	Low	High	Low				
18	2		High	Middle	Low	Middle				

per tooth, cutting speed, width of cut and depth of cut. With respect to the level values for each parameter, the tool manufacturers were assigned the two levels of 1 and 2, while the other four parameters were set the three levels of low, medium and high. These were allocated as shown in Table 1. An array (L18 orthogonal array) that arranges the levels of each parameter in the form of 18 sets of experimental conditions is shown in Table 2.

2.5. Fixed Conditions

The following were used as fixed conditions:

- tool holder
- tool type (diameter, number of teeth)
- cutting fluid (fluid type, amount of fluid, etc.).

3. Experimental Results

3.1. Examination of the Data

Cutting was performed according to the combinations in the L18 orthogonal array. According to the Taguchi method, the larger the difference in the data for each experiment (difference in SN ratio), the higher the accuracy that can be evaluated. As an example of this, photographs of the test pieces after machining in experiments No. 5 and 13 are shown in Figs. 2 and 3. In addition, the data are shown in Tables 3 and 4, while graphic representations of those data are shown in Figs. 4 and 5.

It is clear from the photographs that, although machining could be performed to the third level (the third machined

Table 3 Data of No. 5

M (mm ³)		y (g)	
		N1	N2
1	1289.217	11.10	10.49
2	2578.434	22.10	20.97
3	3867.651	33.08	20.97

Table 4 Data of No. 13

M (mm ³)		y (g)	
		N1	N2
1	1285.806	10.97	10.89
2	2571.612	22.01	21.84
3	3857.419	32.95	32.79

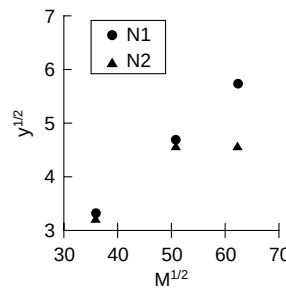


Fig.4 Exp. result (No.5)

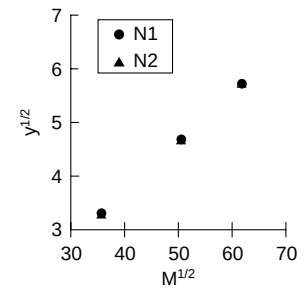


Fig.5 Exp. result (No.13)

surface) of the signal factor at noise factor N1 (easy cutting) in experiment No. 5, in the case of N2 (difficult cutting), further machining was not possible from part of the way through the second level (the second surface). In experiment No. 13, although tool marks remained on the third surface at N2, machining could be performed to the third surface for both N1 and N2.

3.2. Calculation of the SN Ratio

An example of calculating the SN ratio is indicated for the results of experiment No. 5. In addition to showing the data obtained by taking the square root ($\sqrt{\quad}$) of the signal factor and evaluation characteristic, the sum of the squares was analyzed using those results.

Table 5 Data of No. 5

M ^{1/2}		y ^{1/2}	
		N1	N2
1	35.905 7	3.331 7	3.238 9
2	50.778 3	4.701 1	4.579 5
3	62.190 4	5.751 5	4.579 5

- Total sum of squares

$$S_T = 3.3317^2 + 4.7011^2 + \dots + 4.5795^2 + 4.5795^2 = 118.7138 \quad (f=6) \quad (4)$$

- Linear expressions

$$L1 = 35.9057 \times 3.3317 + 50.7783 \times 4.7011 + 62.1904 \times 5.7515 = 716.0273 \quad (5)$$

$$L2 = 633.6328 \quad (6)$$

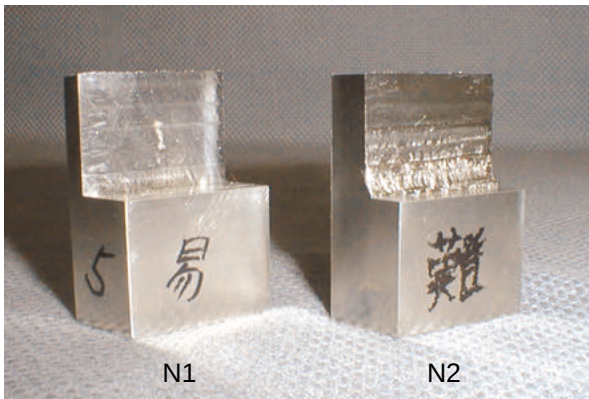


Fig.2 Machined test pieces (No. 5)

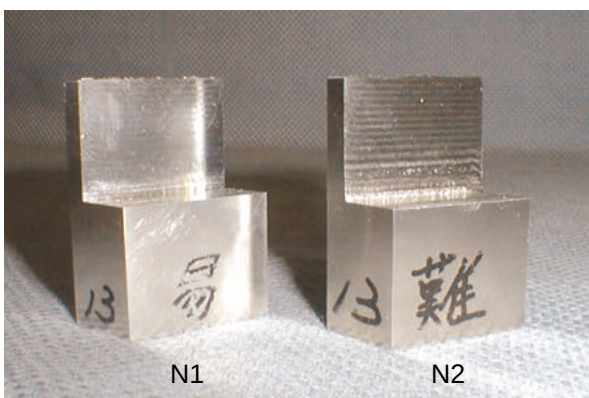


Fig.3 Machined test pieces (No. 13)

- Sum of squares of the primary effect of the signal factor

$$S_{\beta} = (L1 + L2)^2 / 2r \\ = 117.744 \ 8 \ (f=1) \quad (7)$$

where,

$$r = 35.905 \ 7^2 + 50.778 \ 3^2 + 62.190 \ 4^2 \\ = 7 \ 735.301 \ 3 \quad (8)$$

- Sum of squares of the noise factor

$$S_N = S_{N \times \beta} \\ = (716.027 \ 3^2 + 633.632 \ 8^2) / r - 117.744 \ 8 \\ = 0.438 \ 8 \ (f=1) \quad (9)$$

- Sum of squares of the error

$$S_e = S_T - S_{\beta} - S_N \\ = 0.530 \ 2 \ (f=4) \quad (10)$$

- Sum of squares of the error, including the effect of the noise factor

$$S_{N'} = S_{N+e} = S_T - S_{\beta} \\ = 0.969 \ 0 \ (f=5) \quad (11)$$

The results of the foregoing calculations are summarized in the variance results analysis shown in Table 6. Based on the variance analysis, SN ratio η and sensitivity S could be obtained from the following equations.

$$\text{SN ratio: } \eta = 10 \log \frac{\frac{1}{2r} (S_{\beta} - V_e)}{V_{N'}} = -14.06 \text{db} \quad (12)$$

$$\text{Sensitivity: } S = 10 \log \frac{1}{2r} (S_{\beta} - V_e) = -21.19 \text{db} \quad (13)$$

The results from a similar calculation of the SN ratio and the sensitivity from the data for each of the experiments

Table 6 Analysis of variance (No.5)

	Factor	F	Sum of squares	Variance
Primary effect	β	1	117.744 8	117.744 8
Noise factor	$N \times \beta$	1	0.438 8	0.438 8
Error	e	4	0.530 2	0.132 5
	N'	5	0.969 0	0.193 8
Total	T	6	118.713 8	

are shown in Table 7.

Next, the variance analysis (SN ratio) for each control factor according to the calculated results for the SN ratio and sensitivity is shown in Table 8. In addition, the factor effect diagram between the SN ratio and sensitivity is shown in Fig. 6 and 7.

Table 7 SN ratio & S (sensitivity) for each experiment

Exp. No.	SN ratio (db)	Sensitivity (db)
1	11.52	- 20.73
2	16.83	- 20.70
3	- 22.19	- 22.28
4	9.85	- 20.70
5	- 14.06	- 21.19
6	19.86	- 20.70
7	13.38	- 20.73
8	17.86	- 20.69
9	- 13.98	- 21.16
10	- 13.41	- 21.12
11	22.78	- 20.67
12	- 13.71	- 21.13
13	20.74	- 20.70
14	17.11	- 20.68
15	14.58	- 20.68
16	7.85	- 20.72
17	12.46	- 20.71
18	20.96	- 20.68
Average	7.13	- 20.89

Table 8 Analysis of variance – SN ratio

Factor	F	S	V	ρ
A Tool maker	1	140.546 3	140.546 3	3.6%
C Feed per tooth	2	391.876 0	195.928 0	10.2%
D Cutting speed	2	76.083 6	38.041 8	2.0%
E Width of cut	2	1570.217 3	785.108 7	40.7%
F Depth of cut	2	186.696 2	93.348 1	4.8%
e Error	8	1488.005 9	186.000 7	38.6%
Total	17	3853.425 3	226.672 1	

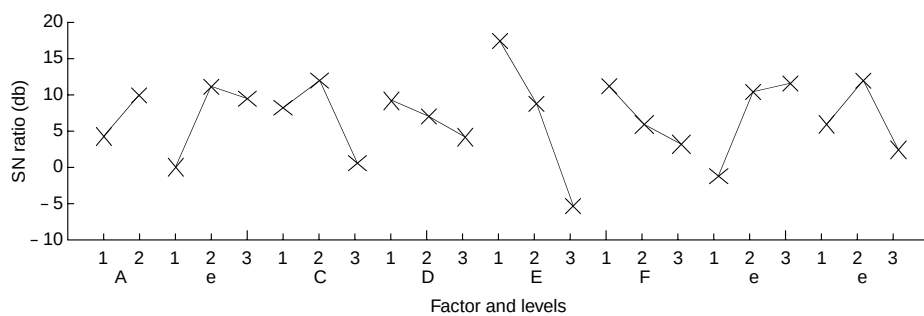


Fig.6 Factor effect diagram of the SN ratio

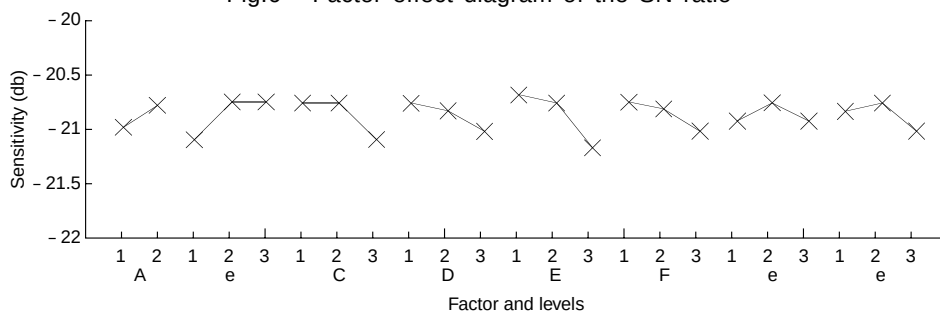


Fig.7 Factor effect diagram of the Sensitivity

According to the Taguchi method, in a factor effect diagram of the SN ratio, the larger the difference between the levels of a factor, the higher the contribution ratio relative to the evaluated characteristic of that factor. In addition, the larger the SN ratio of a level, the greater the degree of agreement with the goal (the improvement of transcription) of that level.

Sensitivity S calculated from equation (13) can be expressed by equation (14) using linear slope b from the fundamental function (Fig. 1). In this experiment, β theoretically expresses the density of the portion removed by cutting.

$$\text{Sensitivity: } S = 10 \log \beta^2 \quad (14)$$

Since the density of the nickel-based super alloy used in this study was $8.53 \times 10^{-3} \text{ g/mm}^3$, ideal sensitivity S calculated by equation (14) becomes -20.69 db. If the value of sensitivity S is small, the density of the portion removed by cutting is also small. In other words, this means that the preset cutting volume was not removed.

Since the trends for each level was the same for both the SN ratio and sensitivity based on Figs. 6 and 7, it is believed that the sensitivity could be improved by selecting a level having a high SN ratio.

In this experiment, as is clear from Table 8, the contribution ratio of the width of cut demonstrated the highest value at 40.7%. Although the large effect of the width of cut demonstrated a similar trend in previous machining experiments, the contribution ratio in this present experiment could be quantitatively determined with the other factors. On the other hand, since the contribution ratio of the error was also 38.6%, this indicated that it is at a level that could not be ignored in comparison with the control factor.

4. Estimation of the Optimal Conditions

4.1. Estimation of the Optimal Conditions

In order to estimate the optimal conditions, a level was selected at which the SN ratio reached a maximum for each control factor based on the factor effect diagram of the SN ratio shown in Fig. 6, and this was compared with the current conditions as shown in Table 9. The current conditions were set using the results of sequential combinations based on each type of machining experiment, and coincidentally agreed with those of current experiment No. 2.

Table 9 Optimal and current conditions

Factor		Optimal condition	Current condition
A	Tool maker	2	1
C	Feed per tooth	Middle	Middle
D	Cutting speed	Low	Middle
E	Width of cut	Low	Middle
F	Depth of cut	Low	Middle

Since the only control factor that exhibited the same level for the optimal conditions and current conditions was the feed per tooth, and the levels were different for the other four factors, the extent to which an improvement in transcription could be expected was quantitatively estimated.

4.2. Estimation of the SN Ratio under Optimal Conditions

The SN ratio was estimated under optimal and current conditions from the SN ratios at each level of all the control factors to determine the gain. The comparative results are shown in Table 10.

Table 10 Estimation of average value (db)

	Optimal condition	Current condition	Gain
SN ratio	32.15	12.33	19.82
Sensitivity	- 20.25	- 20.67	0.42

According to the estimated results for machining performed under optimal conditions, the SN ratio was 32.15 db, indicating that a gain of approximately 20 db could be expected in comparison with the 12.33 db figure under current conditions. On the other hand, the SN ratio based on the results of experiment No. 2, which was equivalent to the current conditions, was 16.83 db, resulting in a difference of 4.50 db between this value and the estimated value of 12.33 db. This is believed to have been due to error factors not grasped conventionally, as was shown in the previously mentioned table for the control factor analysis of variance (Table 8). A confirmation experiment was then conducted to clarify the manner in which the gain would be affected in the case of machining under the estimated optimal conditions.

5. Confirmation Experiment Results and Discussion

The confirmation experiment was conducted under the optimal and current machining conditions (Table 9) as determined by the Taguchi parameter design method as previously described. The results of calculating the SN ratio and sensitivity are shown in Table 11.

Table 11 Confirmed result (db)

	Optimal condition	Current condition	Gain
SN ratio	18.48	10.50	7.98
Sensitivity	- 20.67	- 20.70	0.03

In the case of machining under the optimal conditions, the gain of the SN ratio in comparison with that under the current conditions was 7.98 db. As is shown in the following calculations, this indicates that dispersion of the transcription of machining can be reduced by roughly 60% in terms of the standard deviation.

When the slope is represented by β and the dispersion (standard deviation) is represented by σ , the SN ratio calculated by equation (12) can be represented by equation (15).

$$\text{SN ratio: } \eta = 10 \log \left(\frac{\beta}{\sigma} \right)^2 \quad (15)$$

Accordingly, the following results were determined when the SN ratio under optimum conditions is represented by $\eta_{(opt)}$, the slope by $\beta_{(opt)}$, and the dispersion by $\sigma_{(opt)}$, while the SN ratio under current conditions is represented by $\eta_{(cur)}$, the slope by $\beta_{(cur)}$ and the dispersion by $\sigma_{(cur)}$.

$$h_{(opt)} - h_{(cur)} = 10 \log \left(\frac{\beta_{(opt)}}{\sigma_{(opt)}} \right)^2 - 10 \log \left(\frac{\beta_{(cur)}}{\sigma_{(cur)}} \right)^2 = 7.98 \text{ db} \quad (16)$$

In addition, the following results hold true since $\beta_{(opt)} \doteq \beta_{(cur)}$ from Table 11.

$$\eta_{(opt)} - \eta_{(cur)} = 10 \log \left(\frac{\sigma_{(cur)}}{\sigma_{(opt)}} \right)^2 = 7.98 \quad (17)$$

$$\therefore \left(\frac{\sigma_{(cur)}}{\sigma_{(opt)}} \right)^2 = 10^{0.798} = 6.281 \quad (18)$$

$$\therefore \frac{\sigma_{(cur)}}{\sigma_{(opt)}} = 2.506 \quad (19)$$

Accordingly,

$$\sigma_{(opt)} \doteq 0.4 \sigma_{(cur)} \quad (20)$$

On the other hand, a gain of only 7.98 db could be obtained in the confirmation experiment, corresponding to roughly half that of the 19.82 db gain for the SN ratio indicated by the estimated results. In addition, according to the results of the confirmation experiment, the SN ratio under current conditions was 10.50 db, indicating a considerable difference from the 16.83 db figure for the SN ratio in the case of the preliminary experiment. Thus, problems remain with respect to the reproducibility of the experiment itself.

In this study, the machining transcription, which compares the preset removal volume with the actual removed volume, was selected for the evaluation characteristic. In this case, although the SN ratios are equal if the actual machined mass as the evaluation characteristic is the same, even under different machining of conditions, when considering an evaluation of the entire machining system, there is the possibility that the effects of the parameters, including the error, were not fully understood.

For example, in the case of a machine whose spindle rotational speed is set by feedback control, the rotational speed is kept constant by increasing the electrical power when the cutting resistance increases and the spindle rotational speed momentarily decreases. As a result, even if the evaluation characteristic in the form of transcription were to be the same, the amount of energy used for machining (the amount of power consumed) would increase. This surplus energy would then end up being converted into heat, vibration or noise, and this could generate dispersion.

Thus, instead of just considering the machined mass, it is believed to be necessary in the future to further add the amount of power consumed and other factors relevant to the entire machining system to the evaluation characteristics in order to improve the optimization of machining conditions and the accuracy of gain estimation.

6. Conclusions

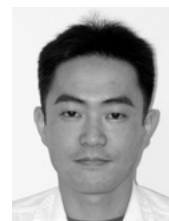
The Taguchi parameter design method was used to optimize the endmill cutting conditions for nickel-based super alloys with the following results:

- (1) The dispersion of machining transcription could be reduced by about 60% when machining was performed under the optimal conditions.
- (2) It is necessary to review the evaluation characteristic based on the complete machining system in order to further improve the accuracy of conditions selection.

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■ authors ■



Sachio KAJIURA



Yasuhiko JINBU



Kazuya KUWABARA