CASE 24

Optimization of Machining Conditions by Electrical Power

Abstract: Together with others, we reported research on parameter design using an L_{12} orthogonal array as a study of energy conversion at the initial stage to confirm additivity of measurements and effectiveness of energy evaluation. Test pieces of ferrous and copper materials were used. We obtained good reproducibility of gain using energy evaluation and satisfied quality characteristics as our final goal. However, due to the limited scale of our experiment, we could not investigate the details and left many issues behind in terms of machining efficiency and generality of research.

1. Functional Evaluation by Energy Conversion

To assess machining of stainless steel used for mass production, we conducted a practical experiment using an L_{18} orthogonal array. We surmised that there were certain technical issues because we have not been able to obtain satisfactory reproducibility, even though we have implemented several different analyses after encountering extremely poor reproducibility at first. Considering that there have been some problems with variability of energy during machine idling after referring to the research of Ford, which deals with energy evaluation during idle time, by adding electrical power during idling, we have analyzed the relationships among time, material removed, and electrical power by use of the SN ratio. For electrical power, we calculated the product of time and power as area so as to effectively reflect its variability. For a noise factor, we selected a difference between maximum and minimum electrical power. Using all of them, we computed SN ratios.

2. Generic Function

The objective of machining is to cut a product or part cost-effectively and accurately to realize a target shape. Therefore, machining engineers select optimal conditions by changing conditions of machines and tools used or cutting conditions such as cutting or feeding speeds, and measuring eventual dimensions and roughness of a product or part. In contrast, the objective of machining evaluation by energy is to assess general functions of machines and secure final quality characteristics (machining accuracy or surface roughness).

As an effective evaluation method of cutting, including machine performance, we can pick up a change between electrical power supplied to a machine and power used during cutting. In other words, we assumed that cutting efficiency can be assessed by the relationship between time consumed for cutting and electrical power consumed by a machine. We concluded that unsatisfactory precision of work is caused by inefficient consumption of energy for a target material amount to be removed, due to a factor such as unevenness of material, tool condition, or cutting setup. Generic function 1 is expressed as $y = \beta_1 T$ by the relationship between cutting time, T, and electrical power, y. In this case, the greater the SN ratio and sensitivity, the better. Generic function 2 is expressed as $\sqrt{y} = \beta_2\sqrt{M}$, where the amount removed is M and the power is y. For this, less sensitivity and a higher SN ratio are desirable. Figures 1 and 2 illustrate these relation-

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

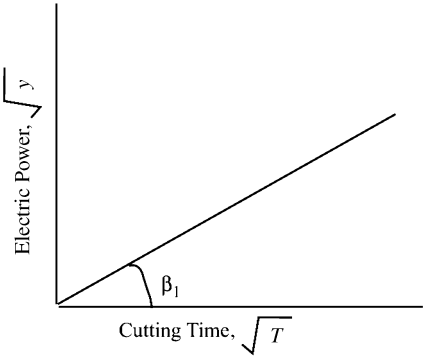

Figure 1
Generic function 1

ships. The reason that we take the square root of both sides of an equation is that in quality engineering, factors are dealt with as energy in decomposing total variation.

3. Measurement and Experimental Procedure

A common manual lathe was used for this experiment. A wattmeter connected to a three-phase distribution board located at a power source for the lathe measured effective power (W) consumed for cutting. Figure 3 depicts the shape of a test piece. Its material is SUS 304. Two grooves were added

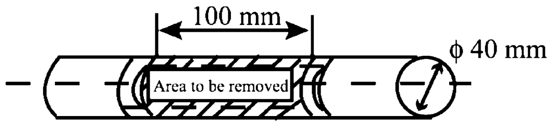

Figure 3
Shape of the test piece

beforehand at the start and end points to clarify them, and the length between them was held constant. Figure 4 outlines the cutting processes. We regarded the electrical power needed to run a lathe after a test piece is chucked on it as idling power. Subsequently, we measured each level of power while cutting the area removed three times. Figure 5 shows a magnified plot of fluctuation in power for cutting run 1. l_{before} indicates a fluctuation of power during idling and h represents a fluctuation while cutting material by feeding a tool. Once cutting is completed, fluctuation goes down to l_{after}. Because l_{before} and l_{after} show power during idling, only h indicates total electrical power that a machine consumes for cutting and idling. Therefore, subtracting l_{before} and l_{after} from h, we can obtain the actual power needed for cutting. Although we do not illustrate plots for other cutting conditions, they also showed great fluctuation. Additionally, the ratio of cutting power to idling power was small; in short, machining efficiency was regarded as poor. Then we concluded that we should evaluate the variability and instability of energy of a machine.

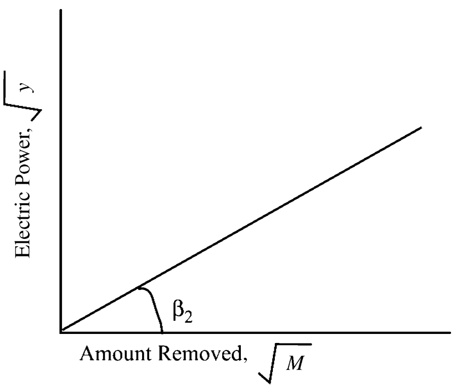

Figure 2
Generic function 2

4. Design of Experiments

For generic function 1, as signal factors we selected each cumulative sum of 12 time intervals into which total time duration from start to finish of cutting was divided equally: T_1, T_2, T_3, ... , and T_{12}. We repeated three times cutting of the area removed. For generic function 2, by cutting the amount removed three times, we measured work for each cutting as a signal factor. Next, considering ease of measurement, we substituted change in the amount removed, M_1, M_2, and M_3, for mass removed per se. For both functions, as the output characteristic we selected the cumulative value of the electrical power, y, for signal at each factor level.

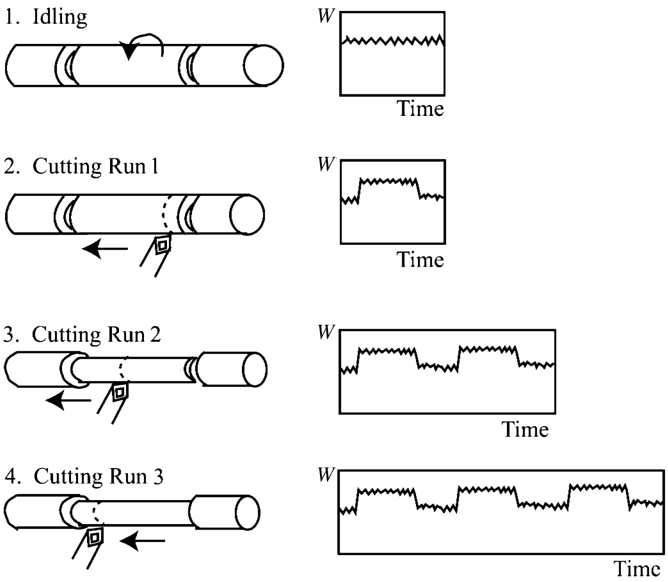

Figure 4
Cutting processes

Assuming that causes for errors affect the variability of power in a direct or indirect manner, we set a difference between maximum and minimum values of electrical power to a noise factor, which should be small. In addition, we selected a minimum value of power y_{min} as N_1 and a maximum y_{max} as N_2. Since the diameter of a test piece becomes smaller as we repeat cutting, a change in electrical power for each cutting run was also chosen as a noise factor.

As control factors, we picked various factors, such as machining setup and tool condition. We confirmed that a revolution during machining does not vary when measured with a tachometer. Control factors are summarized in Table 1.

Electricic Power Measurement Results

When a cumulative value of electrical power is used, its variability is sometimes hidden, due to its accumulation. To solve this problem we substituted a product or area of time and a minimum value W_{min} (or a maximum value W_{max}) for each divided time interval for the simple cumulative value (Figure 6).

For generic function 1, we calculated the maximum and minimum of electrical power, W, for each divide time interval (Figure 7). Table 2 shows a sample of the electrical power measured for cutting run 1. Idling power means before- or after-cutting power. Moreover, by including power during idling, we show the cumulative relationship between time, T, and electrical power, W, in Table 3 and Figure 8, which is a schematic of Table 3. For generic function 2, we computed the electrical power for each time duration from start to finish of cutting (Figure 9). Using electrical power during idling as a standard, we accumulated each area of power (Figure 10), which represent the data of experiment 1 of the L_{18} orthogonal array. The symbol P_0 indicates idling, and P_1, P_2, and P_3 indicate the cutting run number. T, M, and y are point of time, amount removed, and cumulative value of electrical power calculated as area, respectively. In addition, to evaluate the linearity of these data, we plotted Figure 11 for the change of electrical power during idling (Table 4), Figure 12 for the change of electrical power during cutting (Table 5), and for the change in electrical power versus mass removed. As a result, we can see the linearity for each case.

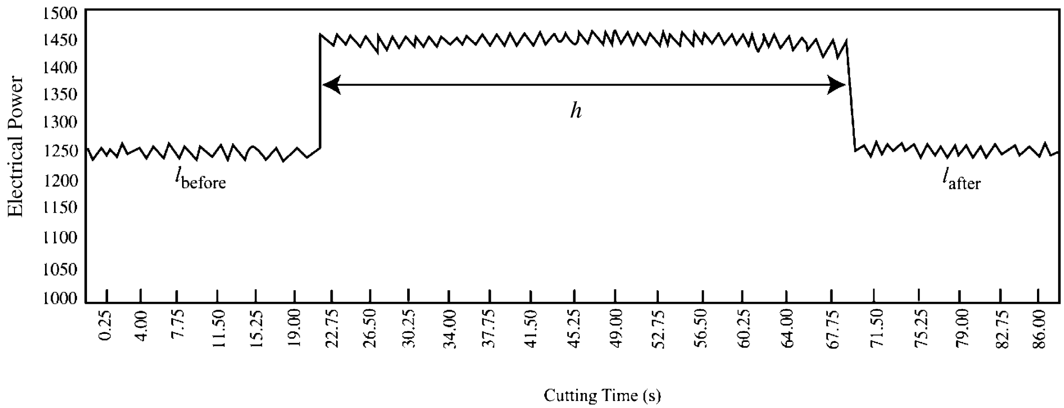

Figure 5
Fluctuation of electrical power at cutting run 1

Based on these results, we describe our calculation process in the following section.

5. SN Ratios and Response Graphs

SN Ratio for Generic Function: Time versus Electrical Power

By calculating the square root of each data point in Table 3, we obtained the converted data in Table 6. We computed $S_{M*\beta}$, which is the effect due to a difference between idling and cutting. For energy consumption, it should be smaller during idling and greater during cutting. By regarding this difference of effect as an effective portion of energy, we calculated the SN ratio.

Total variation:

$$S_T = 125.419^2 + 128.452^2 + \cdots + 349.428^2$$
$$= 4{,}574{,}898.032$$

Linear equations:

Table 1
Control factors and levels

Control Factor		Level 1	Level 2	Level 3
A:	lubricant dilution (%)	Little	Mid	—
B:	depth of cut (mm)	0.5	1.0	2.0
C:	nose angle (deg)	Small	Mid	Large
D:	rake angle (deg)	Small	Mid	Large
E:	side cutting-edge angle (deg)	Small	Mid	Large
F:	tip face type	1	2	3
G:	revolutionary speed (rpm)	Slow	Mid	Fast
H:	feeding speed (mm/rev)	Slow	Mid	Fast

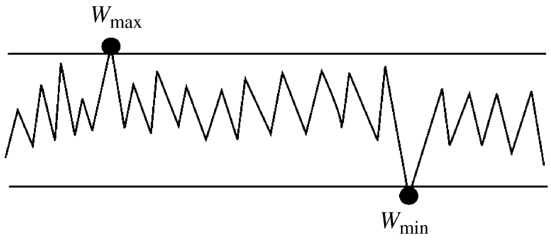

Figure 6
Minimum and maximum values of electrical power

$$L_1 = (3.32)(125.419) + (4.69)(177.370) + \cdots + (8.12)(304.877) = 8692.862$$

$$\vdots$$

$$L_{12} = 9940.218$$

Effective divider:

$$r = 3.32^2 + 4.69^2 + \cdots + 8.12^2 = 230.914$$

Variation of proportional terms:

$$S_\beta = \frac{(L_1 + \cdots + L_{12})^2}{(2)(3)(2)r} = 454{,}651{,}059$$

Variation of differences of proportional terms:

$$S_{N\beta} = \frac{(L_1 + L_3 + \cdots + L_{11})^2 + (L_2 + L_4 + \cdots + L_{12})^2}{(2)3r} - S_\beta = 225.049$$

$$S^*_{M\beta} = \frac{(L_1 + L_2 + \cdots + L_6)^2 + (L_7 + L_8 + \cdots + L_{12})^2}{(3)2r} - S_\beta = 27056211$$

$$S_{P\beta} = \frac{(L_1 + L_2 + L_7 + L_8)^2 + \cdots + (L_5 + L_6 + L_{11} + L_{12})^2}{(2)2r} - S_\beta = 1041.748$$

Error variation:

$$S_e = S_T - S_\beta - S_{N\beta} - S_{M^*\beta} - S_{P\beta} = 64.434$$

Error variance:

$$V_e = \frac{S_e}{67} = 0.962$$

Total error variance:

$$V_N = \frac{S_e + S_{N\beta} + S_{P\beta}}{70} = 19.018$$

SN ratio:

$$\eta = 10 \log \left[\frac{[1/(2)(3r)](S_{M^*\beta} - V_e)}{V_N} \right] = -2.90 \text{ dB}$$

Sensitivity:

$$S = 10 \log \left[\frac{1}{(2)(3r)} (S_\beta - V_e) \right] = 32.15 \text{ dB}$$

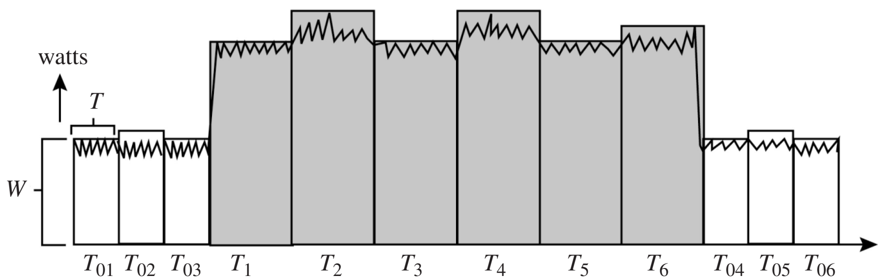

Figure 7
Electrical power for each time interval for cutting run 1 (generic function 1)

Table 2
Measured data for cutting run 1 (W) (generic function 1)

			Time (s)					
			T_{01} 13.00	T_{02} 13.00	T_{03} 13.00	T_{04} 13.00	T_{05} 13.00	T_{06} 13.00
M_1^*: idling	N_1:	W_{min}	1430	1430	1420	1390	1390	1390
	N_2:	W_{max}	1500	1490	1480	1440	1440	1440
M_2^* cutting	N_1:	W_{min}	1960	1950	1950	1950	1940	1940
	N_2:	W_{max}	2030	2020	2010	2010	2000	2010

Table 3
Data of time versus electrical power

				Time					
				T_1 11.00	T_2 22.00	T_3 33.00	T_4 44.00	T_5 55.00	T_6 66.00
M_1^*: idling	P_{01}: cutting 1	N_1	y_{min}	15,730	31,460	47,080	62,370	77,660	92,950
		N_2	y_{max}	16,500	32,899	49,170	65,010	80,850	96,690
	P_{02}: cutting 2	N_1	y_{min}	15,180	30,360	45,650	60,500	75,350	90,200
		N_2	y_{max}	15,620	31,350	46,970	62,040	77,220	92,400
	P_{03}: cutting 3	N_1	y_{min}	14,740	29,840	44,330	58,960	73,590	88,000
		N_2	y_{max}	15,070	30,140	45,320	60,280	75,240	90,200
M_2^*: cutting	P_1: cutting 1	N_1	y_{min}	21,560	43,010	64,460	85,910	107,250	128,590
		N_2	y_{max}	22,330	44,550	66,660	88,770	110,770	132,880
	P_2: cutting 2	N_1	y_{min}	20,680	41,360	61,930	82,390	102,850	23,420
		N_2	y_{max}	21,230	42,350	63,360	84,370	105,270	126,170
	P_3: cutting 3	N_1	y_{min}	19,910	39,930	59,840	79,750	99,550	119,350
		N_2	y_{max}	20,460	40,810	61,160	81,510	101,860	122,100

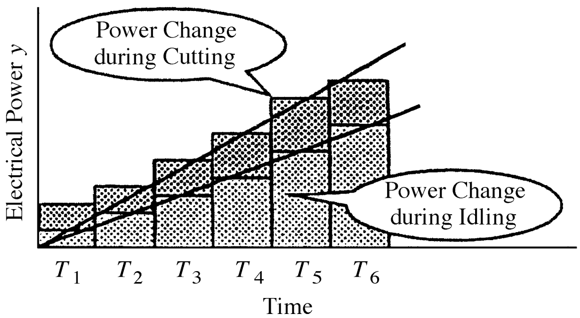

Figure 8
Change in electrical power during idling and cutting (generic function 1)

SN Ratio for Basic Function: Amount Removed versus Electric Power

By calculating the square root of each data point in Table 5, we obtained the converted data in Table 7. Next, using an average value of electrical power as a reference point, we converted the data from Table 7 into the reference-point proportional data in Table 8.

$$S_T = (-10.282^2) + 10.282^2 + \cdots + 389.986^2 = 509{,}577.5952$$

$$L_1 = (13.753)(158.498) + (18.912)(275.875) + \cdots + (22.505)(370.277) = 15{,}730.255$$

$$L_2 = 16{,}811.217$$

$$r = 13.753^2 + 18.912^2 + 22.505^2 = 1053.284$$

$$S_\beta = \frac{(L_1 + L_2)^2}{2r} = 502{,}688.4487$$

$$S_{N\beta} = \frac{L_1^2 + L_2^2}{r} - S_\beta = 554.6836$$

$$S_e = S_T - S_\beta - S_{N\beta} = 6334.4629$$

$$V_e = \frac{S_e}{6} = 1055.7438$$

$$V_N = \frac{S_e + S_{N\beta}}{7} = 984.1638$$

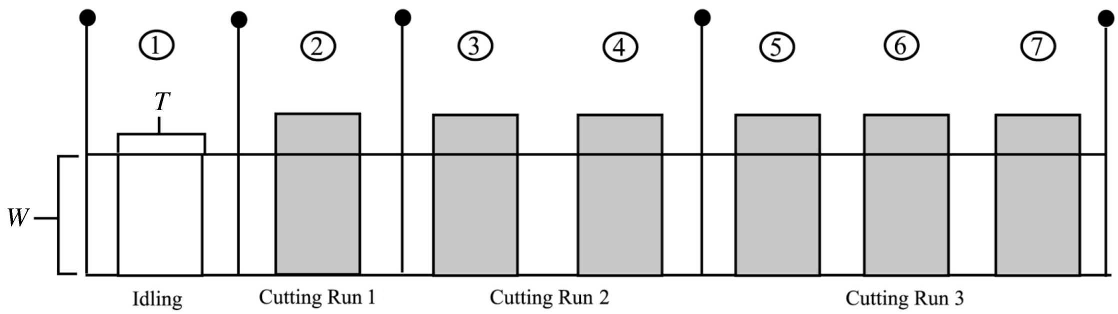

Figure 9
Electrical power for each cutting run, including the idling run (generic function 2)

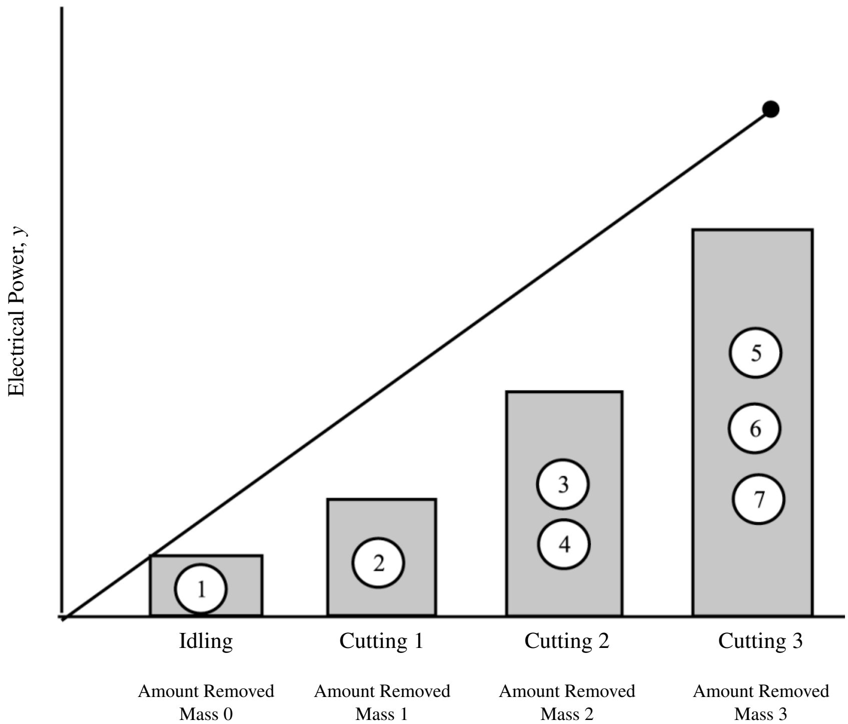

Figure 10
Time change in electrical power for each idling and cutting run (generic function 2)

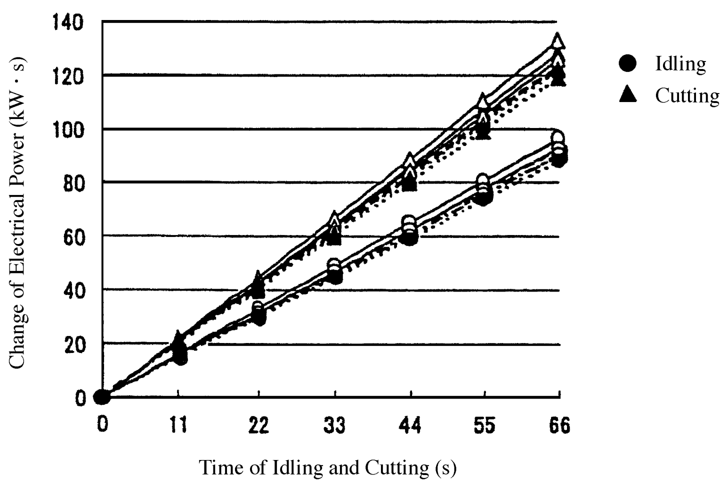

Figure 11
Change in electrical power during idling

Table 4
Measured data for each cutting run (W) (generic function 2)

M: Amount Removed (*g*):			P_0: Idling 0	P_1: Cutting Run 1 189.140	P_2: Cutting Run 2 168.510	P_3: Cutting Run 3 148.830
N_1	W_1	min.	1310	1940	1860	1800
N_2	W_1	max.	1500	2030	1930	1860

SN ratio:

$$\eta = 10 \log \frac{(1/2r)(S_\beta - V_e)}{V_N} = -6.16 \text{ dB}$$

Sensitivity:

$$S = 10 \log \left[\frac{1}{2r} (S_\beta - V_e) \right] = 23.77 \text{ dB}$$

Following these procedures, we computed the SN ratio and sensitivity for other experiments of the L_{18} orthogonal array. Figures 13 and 14 show a comparison of two generic functions for SN ratio and sensitivity, respectively.

6. Confirmatory Experiment and Analysis

While for generic function 1, both the SN ratio and sensitivity should be larger, for generic function 2, the SN ratio should be larger and the sensitivity should be smaller. Looking at each factor effect, we notice that factor *B* depth of cut, factor *G*, of revolution, and factor *H*, feeding speed, have a stronger effect than do other factors. Although a confirmatory experiment should be implemented at optimal and initial configurations for each function, by focusing on a trade-off relationship between generic functions 1 and 2 in our research, we selected $A_1B_1C_1D_2E_1F_2G_3H_3$ as the optimal configuration and $A_2B_3C_2D_2E_2F_2G_1H_1$ as the initial configuration. Table

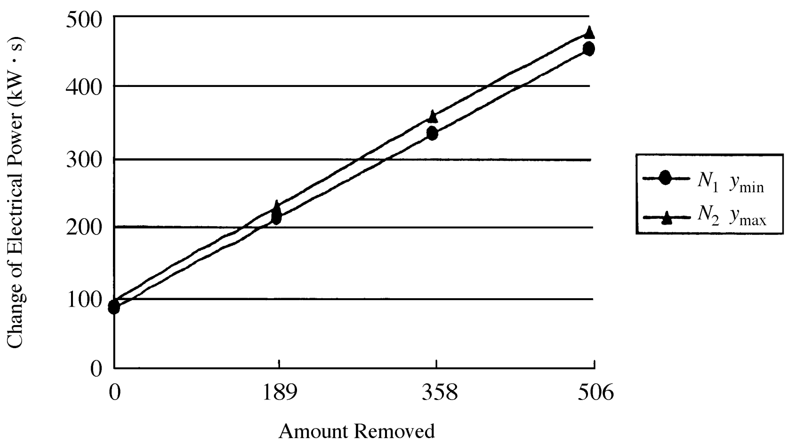

Figure 12
Change in electrical power during cutting

Table 5
Amount removed and electrical power (W) for each cutting run (generic function 2)

M: Amount Removed (*g*):		**P_0: Idling 0**	**P_1: Cutting Run 1 189.140**	**P_2: Cutting Run 2 357.650**	**P_3: Cutting Run 3 506.480**
N_1	y_{min}	86133	213,687.5	335,982.5	454,442.5
N_2	y_{max}	98625	232,097.5	358,995	481,290

9 shows the results. We believe that good reproducibility of gain is obtained.

7. Relationship between Energy Evaluation and Improvement in Dimension and Roughness

If we can obtain improvement effects at the optimal configuration–based energy evaluation, target quality characteristics such as machining dimensions or surface roughness should be improved. The quality of dimension means whether dimension *y* of a test piece is cut for each *P*, the number of cuts, without variability. Therefore, for dimension, the diameter of the test piece for each *P* is measured by a micrometer, and for roughness, average surface roughness is measured by a touch-probe surface roughness measuring instrument. Tables 10 and 11 show the measurement data for dimension and roughness. *J* indicates measurement points in the longitudinal direction of a test piece, *X* and *Y* represent measurement points in the radial direction,

Table 6
Converted data of time versus electrical power (postconversion)

				Time					
				T_1 3.32	**T_2 4.69**	**T_3 5.74**	**T_4 6.63**	**T_5 7.42**	**T_6 8.12**
M_1^*: idling	P_{01}: cutting run 1	N_1	y_{min}	125.419	177.370	216.979	249.740	278.675	304.877
		N_2	y_{max}	128.452	181.356	221.743	254.971	284.341	310.950
	P_{02}: cutting run 2	N_1	y_{min}	123.207	174.241	213.659	245.967	274.500	300.333
		N_2	y_{max}	124.980	177.059	216.726	249.078	277.885	303.974
	P_{03}: cutting run 3	N_1	y_{min}	121.408	171.697	210.547	242.817	271.275	296.648
		N_2	y_{max}	122.760	173.609	212.885	245.520	274.299	300.333
M_2^*: cutting	P_1: cutting run 1	N_1	y_{min}	146.833	207.389	253.5890	293.104	327.490	358.594
		N_2	y_{max}	149.432	211.069	258.186	297.943	332.821	364.527
	P_2: cutting run 2	N_1	y_{min}	143.805	203.372	248.857	287.037	320.702	351.312
		N_2	y_{max}	145.705	205.791	251.714	290.465	324.453	355.204
	P_3: cutting run 3	N_1	y_{min}	141.103	199.825	244.622	282.400	315.515	345.471
		N_2	y_{max}	143.038	202.015	247.305	285.500	319.155	349.428

Table 7
Converted data of amount removed versus electrical power (W) (postconversion)

M: Amount Removed (*g*):		P_0: Idling 0	P_1: Cutting Run 1 13.753	P_2: Cutting Run 2 18.912	P_3: Cutting Run 3 22.506
N_1	y_{min}	293.483	462.263	574.640	674.042
N_2	y_{max}	314.046	481.765	599.162	693.751

Table 8
Data for reference-point proportional equation (W)

M: Amount Removed (*g*):		P_0: Idling 0	P_1: Cutting Run 1 13.753	P_2: Cutting Run 2 18.912	P_3: Cutting Run 3 22.505
N_1	y_{min}	−10.22	158.498	275.875	370.277
N_2	y_{max}	10.282	178.000	295.397	389.986

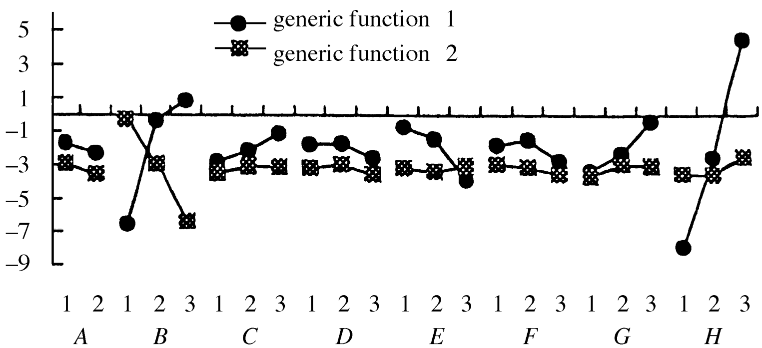

Figure 13
Response graphs of SN ratio of time versus electrical power

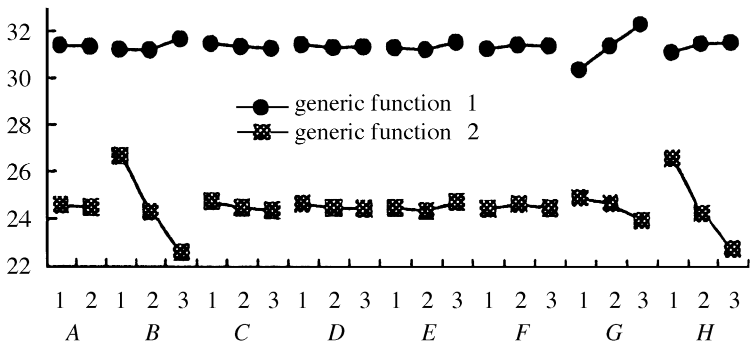

Figure 14
Response graphs of sensitivity of time versus electrical power

Table 9
Results of gain in confirmatory experiments

(a) Time vs. Electrical Power		**Configuration: Optimal**	**Configuration: Initial**	**Gain**
SN ratio	Estimation	2.40	−5.53	7.93
	Confirmation	5.96	−4.92	10.88
Sensitivity	Estimation	32.40	30.36	2.04
	Confirmation	31.96	30.10	1.86

(b) Amount Removed vs. Electrical Power		**Configuration: Optimal**	**Configuration: Initial**	**Gain**
SN ratio	Estimation	0.74	−7.25	7.99
	Confirmation	0.27	−6.93	7.20
Sensitivity	Estimation	24.56	24.97	−0.41
	Confirmation	23.98	24.87	−0.89

R represents repetition of measurement, and N indicates the number of test pieces machined. Table 12 shows the results calculated as a nominal-the-best characteristic. Consequently, we can confirm that we can estimate the final quality and machine products in a stable manner once we improve the cutting process based on energy evaluation.

8. Discussion and Conclusions

The reason that we have not been able to obtain good reproducibility of gain in the research on machining based on energy evaluation is that we have not assessed electrical power during idling (no loading) in a proper manner. As a result of combining

Table 10
Dimensional data at optimal configuration (mm)

			J_1		J_2		J_3		J_4	
			X	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*
N_1	P_1	R_1	30.023	39.025	39.019	39.018	39.015	39.017	39.015	39.014
		R_2	39.031	39.031	39.029	39.029	39.019	39.027	39.030	39.027
	P_2	R_1	38.022	38.023	38.018	38.018	38.015	38.016	38.014	38.014
		R_2	38.020	38.020	38.021	38.019	38.012	38.020	38.022	38.020
	P_3	R_1	37.023	37.023	37.019	37.018	37.015	37.016	37.014	37.014
		R_2	37.023	37.024	37.024	37.022	37.015	37.021	37.025	37.021
N_2	P_1	R_1	39.032	39.025	39.032	39.033	39.027	39.026	39.026	39.025
		R_2	39.013	39.015	39.020	39.019	39.028	39.026	39.026	39.029
	P_2	R_1	38.052	38.045	38.050	38.050	38.045	38.044	38.043	38.043
		R_2	38.020	38.022	38.026	38.024	38.028	38.027	38.027	38.030
	P_3	R_1	37.038	37.027	37.034	37.034	37.029	37.028	37.026	37.026
		R_2	37.024	37.026	37.029	37.026	37.032	37.030	37.033	37.034

Table 11
Roughness data at optimal configuration (μm)

			J_1	J_2	J_3	J_4
N_1	P_1	R_1	2.500	2.460	2.450	2.450
		R_2	2.910	2.950	3.020	2.940
	P_2	R_1	2.500	2.450	2.500	2.530
		R_2	2.930	2.990	3.080	2.940
	P_3	R_1	2.240	2.500	2.480	2.500
		R_2	3.030	3.010	3.100	3.080
N_2	P_1	R_1	3.510	3.580	3.640	3.670
		R_2	1.980	2.030	2.060	2.120
	P_2	R_1	3.560	3.650	3.780	3.820
		R_2	2.211	2.360	2.240	2.780
	P_3	R_1	3.980	4.160	4.140	4.010
		R_2	2.487	2.512	2.604	2.564

Table 12
Gain of the SN ratio of dimension and roughness (dB)

	Configuration			
	Optimal	Initial	Gain	Improvement of Variance
SN ratio of dimension	72.86	60.20	12.66	1/18.45
SN ratio of roughness	13.64	11.98	1.66	1/1.47

data for electrical power with data for each generic function, we have obtained good reproducibility. In addition, we have proven that we can estimate final quality characteristics using the results.

As one of the analyses in this research, by using the difference between idling and cutting and regarding this difference as an effective amount of energy, we have calculated SN ratios. Next, looking at the relationship for $y = \beta_1 M$, β_1 should be greater; conversely, for $y = \beta_2 M$, β_2 should be smaller. The reason is that when $M = (\beta_1/\beta_2)T$, β_1/β_2 should be greater. Indeed, electrical power consumption seems great if β_1 is great; however, electrical power required for the same amount of machining can be smaller if β_2 is small. Thus, we conclude that electrical power during idling should be smaller, whereas that during cutting should be greater. These considerations are applicable to performance evaluation of a robot or other machines that have two functions, one during idling and one during loading.

Since a portion to be removed should be shaved uniformly at each microscopic area with even energy in cutting, we have proved that it reasonable to evaluate proportionality of energy with maximum and minimum values of electric power at each microscopic area.

Reference

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