CASE 30

Development of Functional Material by Plasma Spraying

Abstract: New materials composed of metal and ceramic have many interesting and useful properties in the mechanical, electrical, and chemical fields. Recently, a great deal of attention has been paid to the potential utilization of these properties. In this study, the forming process for such material was researched using low-pressure plasma spraying equipment, including two independent metal and ceramic powder supplying devices and a plasma jet flame. Using quality engineering approaches, the generic function of plasma spraying was used for evaluation. After optimization, metal and ceramic materials can be sprayed under the same conditions. Also, it is possible to produce a sprayed deposit layer and metal/ceramic mixing ratio for both dispersed-type and inclined-type products.

1. Introduction

Major technical problems in developing a functional material by plasma spraying were as follows:

1. The conditions for spraying metal are different from those for ceramic because they have extremely different heat characteristics.
2. Metal and ceramics are so different in specific gravity that they cannot comingle.

To tackle these issues, by utilizing two separate powder supply systems connected to a single decompressed plasma thermal spraying device, and by supplying metal and ceramics simultaneously to a plasma heat source, we created conditions that can develop a compound thin film.

2. Generic Function and Measurement Characteristic

Since we wanted to spray two materials that possess different properties, such as heat characteristics or specific gravity, in the first place we considered it important to create conditions where thin-film coating of any material can be achieved. Therefore, we regarded it as a generic function that when we greatly altered a mixture ratio of metal and ceramics and threw them into the same plasma jet, the film amount formed (thickness and weight), y, would be proportional to the number of reciprocal spraying motions, M, and at the same time, the film creation speed, β, would be high. That is, the generic function is $y = \beta M$. Figure 1 shows our experimental device.

When thermal spraying, we used a atmospherically controlled chamber, moving a powder-supplied thermal spraying gun horizontally and moving test pieces vertically until the spray count reaches the predetermined number. As a signal factor, we chose the number of reciprocal motions of a test piece and set each of its three levels to 1, 3, and 5 times. In addition, as a noise factor, we picked the supply ratio of metal powder (nickel) and ceramics powder (alumina) and took two levels of 7:3 and 3:7 in volume. The powder supply amount was kept con-

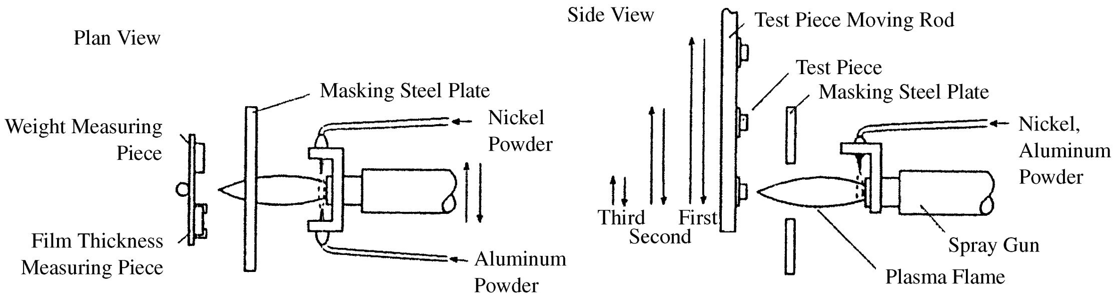

Figure 1
Experimental device

stant at 30 g/min. Finally, we selected two different characteristics, film thickness and film weight. Table 1 summarizes all signal factor noise factors and characteristics chosen in this experiment. See Table and Figure 2 for the thicknesses to be measured, where I_1, I_2, and I_3 and J_1, J_2, and J_3 indicate measurement positions.

3. SN Ratio and Sensitivity

Tables 2 and 3 illustrate the results of thickness and weight measurements. Assuming that the number of reciprocal sprays (signal factor M) and thickness and weight of a thin film (y) are expressed by the zero-point proportional equation ($y = \beta M$), we proceeded with our analysis based on the dynamic SN ratio.

Thickness Experiment

Total variation:

$$S_T = 78^2 + 80^2 + \cdots + 269^2 = 3{,}081{,}538 \qquad (f = 54) \tag{1}$$

Effective divider:

$$r = 1^2 + 3^2 + 5^2 = 35 \tag{2}$$

Linear equations:

$$L_1 = (1)(714) + (3)(2336) + (5)(3575) = 25{,}597$$

$$L_2 = 17{,}667 \tag{3}$$

Variation of proportional terms:

$$S_\beta = \frac{(L_1 + L_2)^2}{(9)(2r)} = 2{,}971{,}069.3 \qquad (f = 1) \tag{4}$$

Variation of differences of proportional terms:

Table 1
Factors and characteristics

Factor	Level 1	Level 2	Level 3
Signal factor			
Number of reciprocating sprays	1	3	5
Noise factor			
Compound ratio (in volume) Ni vs. alumina	7:3	3:7	—
Characteristic	Thickness Weight		—

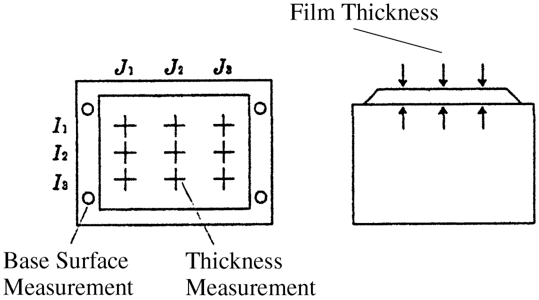

Figure 2
Thicknesses to be measured

$$S_{N\beta} = \frac{L_1^2 + L_2^2}{9r} - S_\beta = 99{,}817.30 \qquad (f = 1) \qquad (5)$$

Error variation:

$$S_e = S_T - S_\beta - S_{N\beta} = 10{,}651.34 \qquad (f = 52) \qquad (6)$$

Error variance:

$$V_e = \frac{S_e}{52} = 204.83 \qquad (7)$$

Total error variance:

$$V_N = \frac{S_{N\beta} + S_e}{1 + 52} = 2084.31 \qquad (8)$$

SN ratio:

$$\eta = \frac{[1/(9)(2r)](S_\beta - V_e)}{V_N} = 2.26 \quad (3.55 \text{ dB}) \qquad (9)$$

Sensitivity:

$$S = \frac{1}{(9)(2r)}(S_\beta - V_e) = 4715.66 \quad (36.74 \text{ dB}) \qquad (10)$$

Weight Experiment

Total variation:

$$S_T = 0.363^2 + 1.0292^2 + \cdots + 1.1260^2 = 59{,}201{,}730 \qquad (f = 6) \qquad (11)$$

Linear equations:

$$L_1 = (1)(0.3630) + (3)(1.0292) + (5)(1.7196) = 12.0486$$

$$L_2 = 7.8716 \qquad (12)$$

Variation of proportional terms:

$$S_\beta = \frac{(L_1 + L_2)^2}{2r} = 5.6687766 \qquad (f = 1) \qquad (13)$$

Variation of differences of proportional terms:

$$S_{N\beta} = \frac{L_1^2 + L_2^2}{r} - S_\beta = 0.2492475 \qquad (f = 1) \qquad (14)$$

Error variation:

$$S_e = S_T - S_\beta - S_{N\beta} = 0.0021488 \qquad (f = 4) \qquad (15)$$

Error variance:

Table 2
Data for 16 of the L_{18} orthogonal array (μm)

		M_1 (First Round Trip)				M_2 (Third Round Trip)				M_3 (Fifth Round Trip)			
		J_1	J_2	J_3	Total	J_1	J_2	J_3	Total	J_1	J_2	J_3	Total
N_1	I_1	78	80	79	237	282	272	274	828	434	419	401	1254
	I_2	75	81	81	237	270	263	257	790	408	400	385	1193
	I_3	78	82	80	240	240	241	237	718	385	375	368	1128
	Total	231	243	240	714	792	776	768	2336	1227	1194	1154	3575
N_2	I_1	48	47	51	146	174	167	160	501	293	292	273	858
	I_2	56	53	52	161	175	178	172	525	294	281	282	857
	I_3	51	49	47	147	160	160	155	475	288	270	269	827
	Total	155	149	150	454	509	505	487	1501	875	843	824	2542

Table 3
Data for experiment 16 of the L_{18} orthogonal array (g)

	M_1 (First Round Trip)	M_2 (Third Round Trip)	M_3 (Fifth Round Trip)
N_1	0.3630	1.0292	1.7196
N_2	0.1842	0.6858	1.1260

$$V_e = \frac{S_e}{4} = 0.0005372 \quad (16)$$

Total error variance:

$$V_N = \frac{S_{N\beta} + S_e}{1 + 4} = 0.0502792 \quad (17)$$

SN ratio:

$$\eta = \frac{(1/2r)(S_\beta - V_e)}{V_N} = 1.6105014 \ (2.07 \text{ dB}) \quad (18)$$

Sensitivity:

$$S = \frac{1}{2r}(S_\beta - V_e) = 0.0809748 \quad (-10.92 \text{ dB}) \quad (19)$$

4. Optimal Conditions and Confirmatory Experiment

Table 4 illustrates control factors for this study. Additionally, Figures 3 and 4 show response graphs of thickness and weight.

To confirm the reproducibility of our experimental results, we performed a confirmatory experiment on a combination of the optimal and worst conditions. In selecting the conditions, we used a combination of SN ratios for weight experiments because both thickness and weight experiments have almost identical tendencies of factor effects; moreover, the large-effect levels in the thickness experiments were consistent with those in the weight experiments. The results are shown in Table 5, which indicates that both estimation and confirma-

Table 4
Control factors and levels

	Level		
Control Factor	1	2	3
A: secondary gas type	Hydrogen	Helium	—
B: electric power (kW)	25	35	45
C: current/voltage (A/V)	12	15	18
D: decompression degree (torr)	50	200	400
E: spraying distance (relative proportion to standard frame length)	0.8	1	1.2
F: moving speed of spray gun (m/min)	6	13	24
G: average particle diameter of metal powder (μm)	6	30	60
H: average particle diameter of ceramics powder (relative proportion to *G*)	0.1	0.5	1

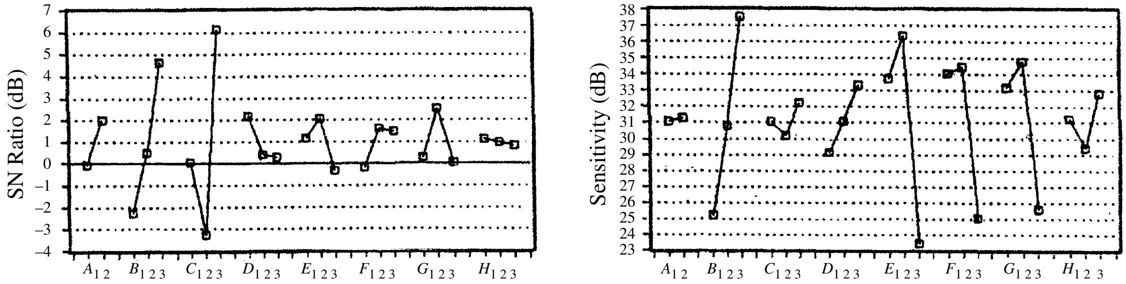

Figure 3
Response graphs of thickness experiment

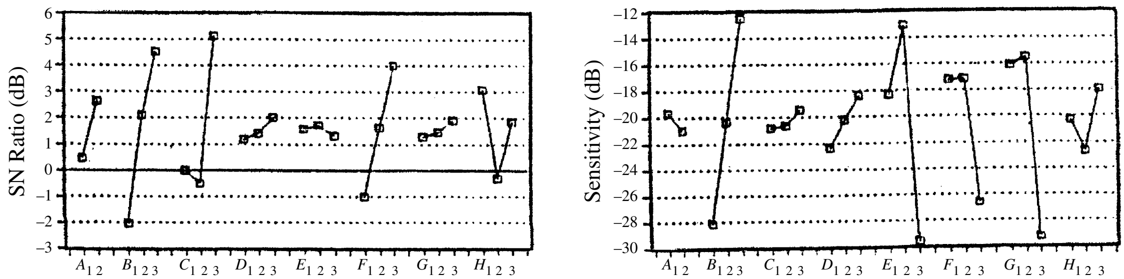

Figure 4
Response graphs of weight experiment

Table 5
Estimation and confirmatory experiment results

		Configuration		
		Optimal	Worst	Gain
Thickness	Estimation	9.83	−6.49	16.32
	Confirmation	12.70	−3.04	15.74
Weight	Estimation	12.16	−8.48	20.64
	Confirmation	15.12	−1.61	16.73

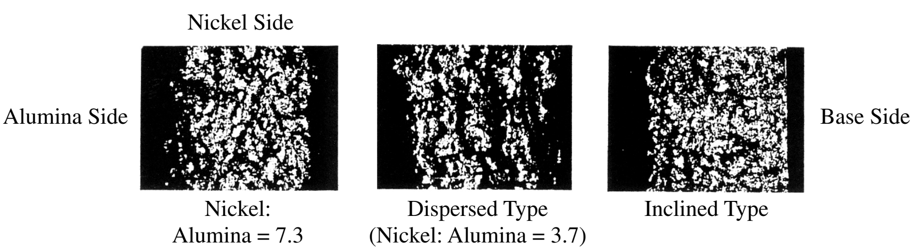

Figure 5
Dispersed and inclined films

tion are fairly consistent and that good reproducibility exists.

Optimal condition: $A_2B_3C_3D_3E_2F_3G_2H_1$

Worst condition: $A_1B_1C_2D_1E_3F_1G_3H_2$

By taking advantage of the optimal plasma-spraying condition obtained in this experiment, we formed both dispersed and inclined plasma-sprayed thin films whose sectional structures (of only thin films) are shown in Figure 5. The right-hand side indicates a base, and the white and dark portions show nickel and alumina, respectively. Based on these, we can see that nickel and alumina are distributed evenly even though their supply ratios are different, and that the distribution rate is close to the supply ratio. On the other hand, for the inclined thermal-sprayed thin film, we gradually alter the supply ratio from the nickel-abundant state to the alumina-abundant state, from right to left in the figure. These results enabled us to deal with metal and ceramics under the same conditions and to develop compounded functional materials by plasma spraying.

Reference

Kazumoto Fujita, Takayoshi Matsumaga, and Satoshi Horibe, 1994. Development of functional materials by spraying process. *Quality Engineering*, Vol. 2, No. 1, pp. 22–29.

This case study is contributed by Kazutomo Fujita.