Title	Effect of Spraying Condition on Ceramic Coating Quality in Gas Tunnel Type Plasma Spraying(Physics, Process, Instrument & Measurement)
Author(s)	Kobayashi, Akira; Kurihara, Setsu; Arata, Yoshiaki
Citation	Transactions of JWRI. 1988, 17(2), p. 305-310
Version Type	VoR
URL	https://doi.org/10.18910/4590
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Effect of Spraying Condition on Ceramic Coating Quality in Gas Tunnel Type Plasma Spraying

Akira KOBAYASHI*, Setsu KURIHARA** and Yoshiaki ARATA***

Abstract

The quality of Al_2O_3 coatings formed by a gas tunnel type plasma spraying apparatus was evaluated with respect to hardness and porosity under various spraying conditions. And the proper spraying condition to get preferable quality of Al_2O_3 coatings was decided. The deposit characteristics of Al_2O_3 powder sprayed to a substrate by this type of plasma spraying were also clarified and the relation between the deposit characteristics and the spraying condition was discussed. Estimation by the deposit characteristics was found to be a very effective method for determining the proper spraying conditions under which a good quality coating can be obtained.

KEY WORDS : (Alumina Coating) (Thermal Spraying) (Gas Tunnel) (Spraying conditions) (Critical Spraying Distance) (Estimation of Coating Quality)

1. Introduction

A gas tunnel type plasma jet can be generated in a low pressure region called a "gas tunnel", which is produced along the axis of the plasma jet torch by a special vortex flow. This type of plasma jet has a positive discharge characteristic (volt-ampere characteristic) and a high voltage. Therefore, a high power can be easily obtained[1]. A gas tunnel plasma jet is stable and has a high temperature and high energy density[2,3]. To generate a plasma jet of the same power, a substantially smaller current is required than for a conventional plasma jet. As a result there is less damage to the electrodes.

This type of plasma jet can be easily applied to the production of ceramic coatings. A gas tunnel type plasma spraying apparatus[4] is able to feed the spraying powder from the center electrode of the spraying torch to the plasma. Powder supplied in this way is thoroughly melted as it travels through the long plasma jet and is then sprayed at a high speed. As a result, even at a lower power than a conventional plasma spraying apparatus[5], the Al_2O_3 coating obtained using this apparatus is very hard and has less porosity[6]. And the deposit characteristics of powder sprayed by a gas tunnel type plasma spraying apparatus, with Al_2O_3 powder has been clarified[7].

Few investigation has been made of the relation between the sprayed coating and the deposited particles[8,9]. Therefore, determining the best and/or preferable spraying conditions, including the power input to the torch, the spraying distance, the working gas flow rate and the kind of working gases has often been carried out only empirically. However, it's very important not only to clarify the effect of those conditions on the spraying powder, but also to investigate the relation between the spraying conditions and the sprayed coatings.

In this paper, for the purpose of determining the proper spraying conditions, the quality of Al_2O_3 coatings (hardness, porosity) was experimentally investigated by producing actual coatings at various spraying distances for both low and high inputs to the plasma jet. The deposit characteristics of alumina powder were also discussed by mainly the shape and weight of the Al_2O_3 powder deposited on a substrate through gas tunnel plasma spraying. The relation between some properties of Al_2O_3 coatings and the powder deposit characteristics was investigated, and a method of estimating the proper spraying conditions, especially the spraying distance, was proposed and discussed.

2. Experimental Method

The gas tunnel type plasma spraying torch used in this experiment has been described in detail in a previous report[4]. **Table 1** shows the experimental conditions. Plas-

Table 1 Spraying conditions
(gas divertor nozzle diameter is 12 mm)

Current	200-300A
Voltage	100-200V
Working gas (Ar)	200 l/min
Powder carrier gas (Ar)	10 l/min
Spraying distance	50-300mm

ma spraying was carried out at various inputs to the plasma jet and at various spraying distances.

The composition of coating powder used in this experiment was 99.5% Al_2O_3 with a powder size of 10-40 microns. The shape of the powder is "smashed type", not spherical. The powder was sprayed on blasted SUS304 stainless steel ($2.0^t \times 25 \times 50$) at different spraying distances. The coating produced was examined with regard to Vickers hardness and the porosity of a cross section. The weight load used for hardness measurement was 300 g. The porosity was determined from a picture of its cross section of the coating by means of a point counting method.

In order to inverstigate the state of the sprayed powder deposited on the substrate at a variety of spraying distances, an aluminum plate ($1.0^t \times 50 \times 250$) was positioned so that it tilted 26° from the center axis of the torch. The tilted plate traversed the plasma jet during spraying. This method has the important advantage of allowing the effect of varying the spraying distance on the coating to be observed with only a single pass.

The coating thickness was measured in a radial direction from a cross section of the coating. The weight of sprayed deposit was then measured for each distance, by dividing the testing plate into a series of 10mm sections.

The powder deposited on the plate was observed through an optical microscope.

3. Results and Discussion

3.1 Shape of sprayed powder deposit

The shape of Al_2O_3 powder sprayed vertically onto an aluminum plate has been reported in previous paper[7]. At a short spraying distance (for example $L = 100mm$), the sprayed powder is severely damaged as it collides with the plate at a high temperature and high speed.

At larger spraying distance of $L = 200mm$, very little severely damaged powders can be observed. In contrast, there is a larger number of flat round particles. From these results it can be concluded that after the sprayed powder is melted it become like a sphere due to surface tension as it traverses the distance to the substrate. In addition, sphere-like particles in the deposits can be observed on the aluminum substrate.

In the case of large spraying distance, the temperature of the sprayed powder decreases in flight before it is deposited, resulting in partial solidification and giving the deposited particles a flat round shape. Therefore the porosity of coating is increased and the hardness is decreased, as the spraying distance increases.

In this way, the spraying distance as well as the power imput to the plasma jet is one of the most important spraying conditions for influencing the coating quality.

3.2 Properties of Al_2O_3 coating

Cross sections of Al_2O_3 coating on stainless steel at the spraying distances of $L = 100, 150, 200mm$ are shown in **Fig. 1**, where the power input to the plasma jet is $P = 36kW$. Thus, the thickness of the coating decreases as the spraying distance L increases. The black parts in each coating indicate porosities, which increase in size as the
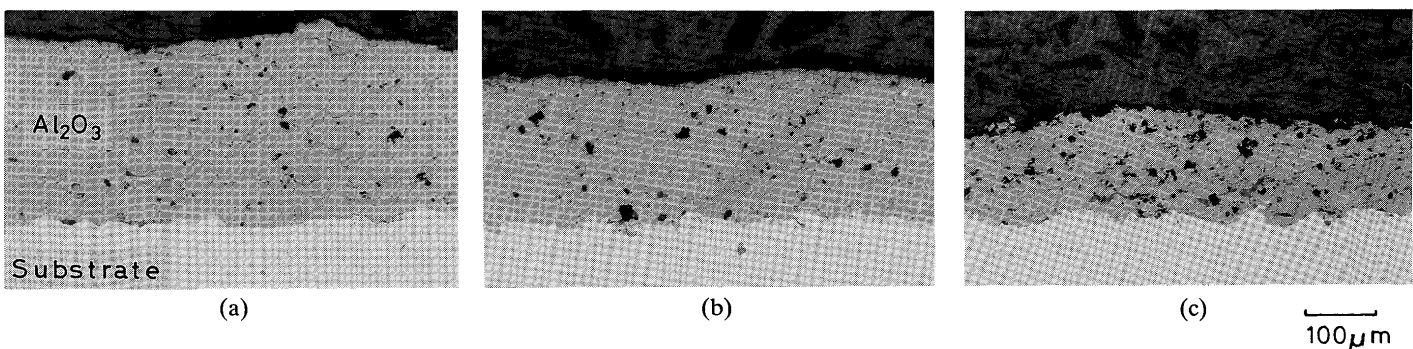

(a)   (b)   (c)
100μm

Fig. 1 Cross section of Al_2O_3 coatings under various spraying
distances at $P = 36kW$.
(a) $L = 100mm$ (b) $L = 150mm$
(c) $L = 200mm$

spraying distance increases.

At smaller spraying distance, for example $L = 100$mm, the deposited powder is thoroughly melted and crushed on the plate. In this case, the sprayed coating consists of severely damaged powders. As a result, a less porous coating can be obtained (as shown in the figure) and there is stronger joining between the coating and substrate.

On the contrary, at $L = 200$mm as shown in Fig. 1 (c), the coating which consists of mainly flat round particles, has much pores.

At the short spraying distance (the substrate is near the plasma jet), the interface of the coating and the substrate sometimes separates. This phenomena is caused due to the difference of the expansion coefficient between the
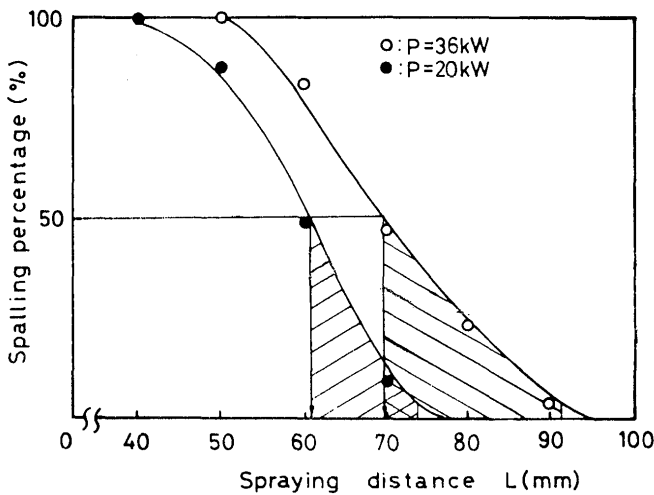

Fig. 2 Spalling percentage of Al₂O₃ coating.

coating (Al₂O₃) and the substrate (SUS 304). **Figure 2** shows the spalling percentage of the Al₂O₃ coating separating from the substrate. In the case of $P = 36$kW, 50% point of spalling percentage is at the spraying distance of $L = 70$mm, and in the case of 20kW, $L = 60$mm. These value of the spraying distance is seemed to be changed by the cooling rate of the testpiece (both substrate and the coating).

The porosity γ (%) was measured from a picture of a cross section of the coating.

The porosity increases as the spraying distance increases, as shown in **Fig. 3** for inputs of both 20kW and 36 kW. In the case of 20kW, the region where the porosity is more than 20% corresponds to a region where round particles were observed.

In the case of $P = 36$kW, the coating is less porous than at of $P = 20$kW, $L = 100$mm. For the same input, even at a spraying distance of $L = 160$mm, the porosity of the coating is as low as that of a coating applied at $P = 20$kW, $L = 100$mm.
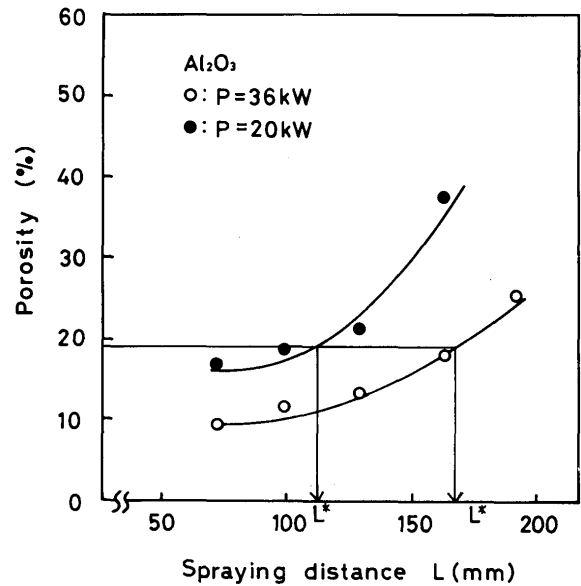

Fig. 3 Dependence of porosity γ of Al₂O₃ coating on spraying distance L.

The results of Vickers hardness H_V measurement of the coatings are shown in **Fig. 4**, for both $P = 20$kW and 36kW. As the spraying distance L increases, the hardness H_V decreases. At a large L there is a substantial increase in porosity and apparently weaker joining between the coating and the substrate as the spraying distance increases. It can be concluded that the state of melting and the shape of the sprayed powder have a strong influence on coating quality.
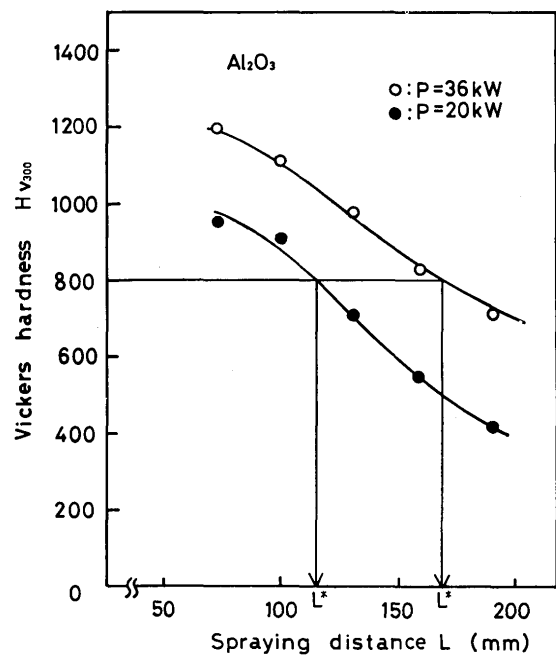

Fig. 4 Dependence of Vickers hardness H_V of Al₂O₃ coating on spraying distance L.

3.3 Proper spraying condition to get preferable quality

For Al_2O_3 coatings, a Vickers hardness of more than $H_V=700$ is considered to be good quality and suitable for practical use. It is thus necessary to determine the critical spraying distance L for obtaining a good coating quality. When we use $H_V=800$ as a preferable value for an Al_2O_3 coating, the critical distance L^* can be easily determined from Fig. 4.

In the case of $P=20kw$, at $L=120mm$, the Vickers hardness is $H_V=800$. For $P=36kW$ the critical distance becomes much larger at $L=170mm$. Taking $L=120mm$ as the critical spraying distance, the porosity γ is about 18% from in the case of $P=20kW$, as shown in Fig. 3. For $P=36kw$, when $L=175mm$ the porosity is $\gamma=18\%$. This value is nearly equal to the critical spraying distance ($L=170mm$) that determined by the Vickers hardness.

Therefore, the required coating quality is thought to be a hardness of $H_V=800$ and a porosity of $\gamma=18\%$. **Table 2** shows the critical spraying distance L^* for obtaining a good quality coating fulfilling these conditions. As shown in this table, L^* is $L^*=120mm$ for the input of 20kW and $L^*=170mm$ for $P=36kW$, respectively.

Table 2 Critical spraying distance L^* for obtaining a high quality coating, H_V : Vickers hardness, γ : Porosity

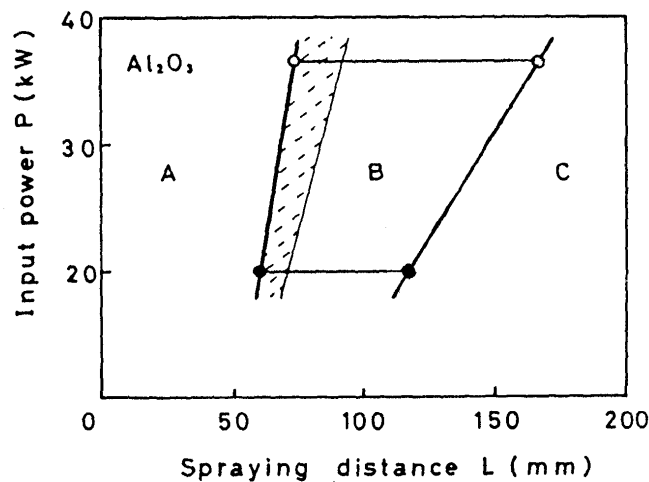| Quality of Al_2O_3 coating		20kW	36kW
Vickers hardness	$H_V=800$	$L^*=120mm$	$L^*=170mm$
Porosity	$\gamma=18\%$		

Fig. 5 Proper spraying condition for obtaining good quality of Al_2O_3 coating.
A : spalling region, B : proper spraying region.
C : bad spraying region.

From above discussion, we can get proper spraying condition with this spraying torch for obtaining good quality Al_2O_3 coating. The result is shown in **Fig. 5** with both the spraying distance and the power input to plasma jet. In this figure, **A** shows a spalling region obtained by using Fig 2, **C** shows the region where bad quality coating is gained, and **B** is preferable region where good quality coating is obtained. The proper region is wider for the spraying distance than that of the conventional plasma spraying apparatus.

3.4 Examination of Al_2O_3 deposits on a tilted plate

The profile of a sprayed Al_2O_3 deposit on a tilted aluminum plate shows the direction of the sprayed powder from torch and the width indicates the radial broadening of the deposited powder. Increasing the power of the plasma jet elongates the deposit distance where the sprayed powder adheres.

These radial distributions of coating thickness are symmetrical to the torch axis, and the width of the deposit is a nearly constant at each spraying distance. As the spraying distance increases, the coating thickness t_c along the center axis decreases. And there exists a spraying distance L^* (t_c) which corresponds to a boundary point where the thickness characteristics change.

The relation between the deposit weight w and spraying distance L for both $P=20kW$ and $P=36kW$ is
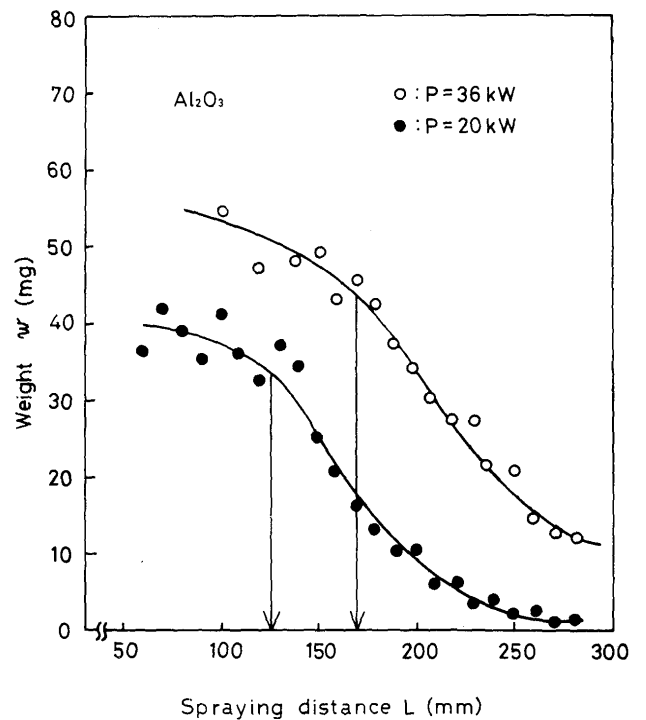

Fig. 6 Relation between weight of deposit w and spraying distance L at $P=20kW$, $36kW$

shown in **Fig. 6.** w was obtained from the weight of the deposit powder deposited on a 1cm-long aluminum plate at each distance.

For each power input, as the spraying distances increases, the weight of the deposited powder decreases, but the decreasing rate is rather small up to a certain distance L^* (w). At $P = 20$kW, the distance is L^* $(w) =$ 125mm and at $P = 36$kW, $L^*(w) = 170$mm. The spraying efficiency is high in the region: $L < L^*$ (w), where good quality coatings can be obtained as shown in Fig. 1(a)(b).

This special spraying distance $L^*(w)$ is nearly equal to the critical spraying distance L^* at each power, so the coating quality can be estimated by means of the value of $L^*(w)$. When $L > L^*(w)$, the weight greatly decreases as L increases. In the case of larger distances of L such as $L > 210$mm at $P = 20$kW, the deposit weight becomes very small. This tendency of the deposit weight with respect to L is related to the change in shape of the deposited powder.

At a short spraying distance, each individual sprayed deposit of Al_2O_3 powder cannot be distinguished and the shape of several powder deposits is not clear. As the increase of the spraying distance, however, individual deposits can be observed with no difficulty. Almost all the deposits on the plate have a tail extending toward the direction of flight. At a large spraying distance, a number of the elliptical particles without a tail appear in addition to the deposits with a tail. It can be inferred that these elliptical deposits correspond to the flat round deposits on the vertical plate.

Figure 7 shows the percentage of crushed particles (damaged particles with a tail) correlated with spraying distance L for both $P = 20$ and $P = 36$kW. In this respect there is a special spraying distance L^* (p) for each input.
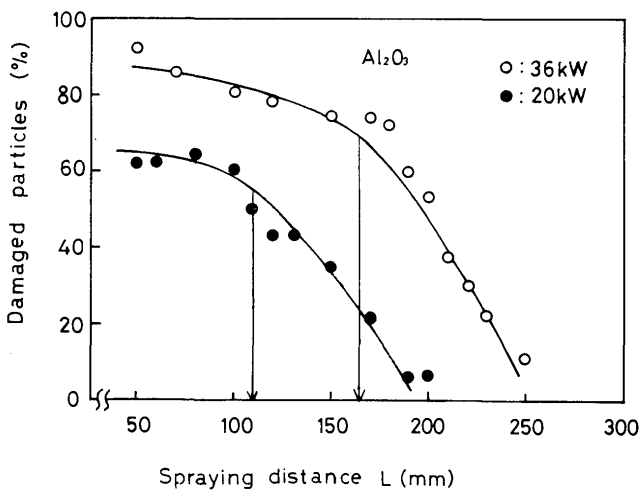
While there is a marked decrease in the percentage of crushed particles at $L > L^*$ (p), there is an increase in elliptical particles with a corresponding degeneration in coating quality.

This tendency for the shape of the deposited powder to a change in the spraying distance can be correlated with the change in weight of the deposited powder, as shown in Fig. 6.

3.5 Estimation of proper spraying distance for obtaining good coating quality

As mentioned earlier, when the spraying distance L is less than the critical spraying distance L^* $(L < L^*)$, the spraying powder is thoroughly melted and collides with the substrate at a high speed and strongly adheres to the surface. As a result, a good quality Al_2O_3 coating with a Vickers hardness of more than 800 and a porosity of less than 18% can be obtained.

The melted state and the shape of the sprayed powder are strongly influence coating quality.

There is a strong relation between the critical spraying distance L^* and the deposit characteristics. The coating thickness t_c, coating weight w and the shape of the deposit powder all have respective boundary points: the difference of a characteristics exists on each side of L^*.

By using those special spraying distance it is possible to estimate the coating quality. **Figure 8** shows the correspondance of both the critical spraying distance L^* and special spraying distances $L^*(t_c)$, $L^*(w)$ and $L^*(p)$ considering with the measuring error. The values display a high correspondence. L^* (w) is particularly suitable for estimating L^* at inputs of both 20 kW and 36 kW.
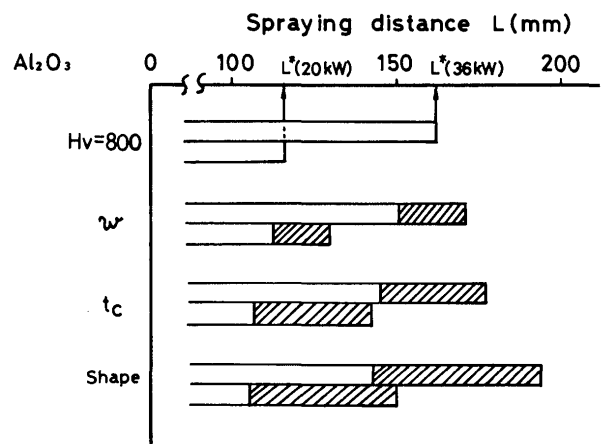
In this way, the deposit characteristics which are deter-

Fig. 7 Percentage of damaged particles against spraying distance.

Fig. 8 Correspodance of the special spraying distances to the critical spraying distances L^*, w shows the method by the deposit weight ; t_c : by coating thickness ; Shape : from the shape of deposit powder.

mined at one time using a tilted plate lead to a critical spraying distance L^* at any plasma jet input. Thus, by this method, the coating can be easily estimated since a good quality coating can be obtained when $L < L^*(w)$.

4. Conclusion

Al_2O_3 coating quality is strongly influenced by the spraying conditions and the characteristics of the sprayed powder in gas tunnel type plasma spraying. The characteristics of Al_2O_3 powder deposited on a substrate were therefore discussed to clarify their relation to coating quality indicators such as the Vickers hardness and porosity in order to determine the proper spraying conditions.

The proper spraying condition for good quality of Al_2O_3 coating was determined by means of examining its hardness, porosity and the spalling state of the coating. This gas tunnel type plasma spraying has larger critical spraying distance L^* necessary for obtaining good coating quality than the conventional type plasma spraying.

By means of studying on the deposit characteristecs, special spraying distances $L^*(t)$, $L^*(w)$ and $L^*(p)$ were able to be defined. The value $L^*(w)$ corresponds well with the critical spraying distance L^* necessary for obtaining good coating quality. Therefore, this method of examining the weight of the deposited powder is convenient for estimating the proper spraying conditions.

References

1) Y. Arata, A. Kobayashi ; J. High Temp. Soc., Vol.11 No.3 (1985) pp.124-131 (in Japanese)

2) Y. Arata, A. Kobayashi and Y. Habara ; Trans. JWRI, Vol.14 No.2 (1985) pp.235-239

3) Y. Arata, A. Kobayashi and Y. Habara ; Jpn. J. Appl. Phys., Vol.25 (1986) pp.1967-1701

4) Y. Arata, A. Kobayashi, Y. Habara and S. Jing ; Trans. JWRI Vol.15 No.2 (1986) pp.227-231

5) Japan Institute of Thermal Spraying ; "Thermal Spraying Handbook" Shin-Gijutsu Kaihatsu Center (1987) (in Japanese)

6) Y. Arata, A. Kobayashi and Y. Habara ; J. High Temp. Soc., Vol.13 No.3 (1987) pp.116-124 (in Japanese)

7) Y. Arata, Y. Habara and A. Kobayashi ; JWRI Vol.16 No.1 (1987) pp.31-36

8) J. M. Houben ; "Thermal Spray Coatings", American Society for Metals (1985) pp.1-19

9) J. Madejski ; J. Heat Mass Transfer, Vol.19 (1976) pp.1009-1013