Transactions of the Japan Welding Society, Vol. 15, No. 2, October 1984

Relation Between Arc Spraying Condition and Adhesive Strength of Sprayed Coating*
— Study on Arc Spraying (Report 1) —

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Abstract

The relationship between arc spraying conditions and the adhesive strength of sprayed coating is investigated. The suitable condition of arc spraying is obtained through arc stability test, measurementof the adhesive strength and observation of fused particle with a high speed camera.

Main results of the study are summarized as follows:

(1) *Three different areas on arc stability of spraying are recognized dependent on negative and positive wire feed speed that is stable, self-regulation and unstable arc areas.*

(2) *The maximum adhesive strength of sprayed coating is obtained under the spraying condition of boundary between the stable and the self-regulation arc areas.*

(3) *The adhesive strength increases with an increasing size of fused particle in stainless steel arc spraying.*
The fused particles are spheres of various diameters.
The fused particles are cooled within 1/8000 second after bombardment on the substrate.

1. Introduction

Arc spraying is a method of surface treatment. In this method, an electric arc is employed as the heat source to melt various metallic materials. The fused metal is sprayed on steel plate or other objects, using compressed air to form a coating on the surface. This method has been evaluated to give better workability and a relatively high quality coating, compared with the flame spray method or plasma spray method.[1)-4)] Thus its scope of application has been increasing. However, few papers are published on fundamental discussion of relation between arc spraying and coating performance, such as sprayed coating adhesive strength, porosity, etc.

In this study, the authors employed a DC arc spraying equipment with separate control at positive wire and negative wire feed speed. The authors used aluminium and two kinds of stainless steels as the spraying materials. The relationships of spraying conditions such as arc voltage, arc current, positive and negative wire feed speeds, with the arc stability and the adhesive strength of the sprayed coating were studied. The arc spraying condition has thus been investigated and verified.

In addition, the shape and bombardment condition of fused particles on the substrate were photographed under various spraying conditions using a high-speed 16 mm cine-camera to examine their relationship to adhesive strength.

2. Experimentation Method

2.1 *Thermal spraying equipment*

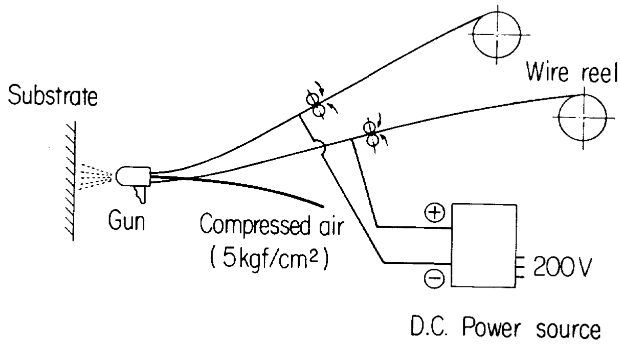

Fig. 1 Scheme of arc spraying equipment

Figure 1 illustrates the scheme of arc spraying equipment used for the experiment. This equipment uses DC power source of constant voltage characteristic, and is capable of controlling the positive wire and negative wire feed speeds separately. In this experiment, the spray gun was mounted on a self-running type platform car, and spraying was done at a spraying distance of (l) with a spraying gun moving speed of (vs). The compressed air pressure for spraying was maintained constant at 5 kgf/cm^2 in each phase of the experiment.

2.2 *Spraying materials and substrate*

The spraying materials used for the experiment were three kinds of metal wires as shown in Table 1. Wires having a diameter of 1.6 mm were employed. A mild steel sheet of $4.5\times500\times300$ mm size with grid-blasted surface of about 50 μmRz roughness was used as the substrate. The spraying was done within four hours after blasting.

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Table 1 Spraying materials

Material	Composition
Aluminium (Al)	Pure Al (over 99.7%)
Stainless steel (SUS 308)	10~12% Ni, 19~21% Cr
Stainless steel (SUS420)	12~14% Cr

2.3 *Evaluation method of arc stability, and adhesive strength test method*

For arc stability, the arc voltage and arc current at the time of spraying were recorded by a pen-recorder, and evaluation was made as in the classification shown in Table 2, from the variable condition of the arc voltage and arc current.

Figure 2 shows the measuring method for the adhesive strength of the sprayed coating. The spraying gun was mounted on a self-running type platform car and spraying was done on the mild steel plate to attain a coating thickness of 250–300 μm, while maintaining a constant spraying distance (l) and constant spraying gun moving speed (vs). Several 40×50 mm sized specimens were cut from the sprayed mild steel plate, and a columnar jig, having a diameter of 25 mm, was bonded onto the sprayed surface of each specimen with epoxy resin adhesive agent. After the adhesive agent had cured, cutting was made in the sprayed coating along the circumference of the columnar jig. Then the specimen and the columnar jig were pulled until they fractured, by means of an Instron type tension tester moving vertically at a speed of 3 mm/min. All of the fractures occurred in the boundary of the sprayed coating and the steel plate. The fracture stress was calculated as the adhesive strength of sprayed coating.

Table 2 Judgement of arc stability

Judgement	Fluctuation of arc current and arc voltage	Classification
○	Little	Stable arc
△	Much	Self-regulation arc[5]
×	Short or Non fuse	Unstable arc or Imcomplete wire fusion

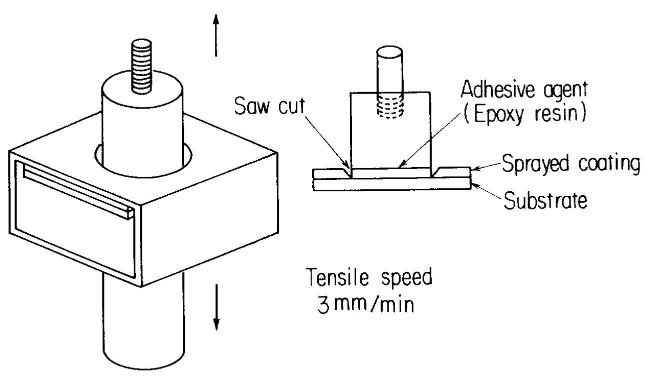

Fig. 2 Method of adhesion test

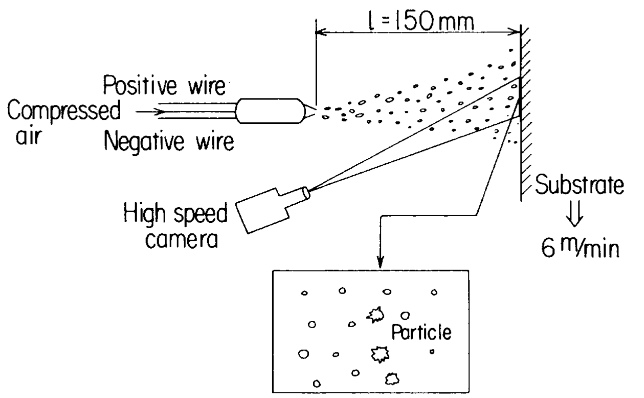

Fig. 3 Illustration of filming technique of spraying particles with high speed camera

2.4 *High-speed motion photography of fused particles*

For the stainless steel (SUS 308), the shape and bombardment condition of the fused particles under various spraying conditions were photographed by a high-speed 16 mm cine camera (about 8,000 frames/second). Figure 3 illustrates the filming method. In this case, in order that the bombardment of fused particles might be always made on a new surface, the steel plate was moved at a speed of about 6 m/min.

3. Experimental Results and Discussion

With three kinds of spraying materials, the arc stability and adhesive strength tests were conducted. The results of the tests and discussion on aluminium spraying and stainless steel spraying (in that order) are as follows:

3.1 *Aluminium spraying*

Figure 4 shows the evaluation of arc stability as classified in Table 2, when the arc voltage (V) was

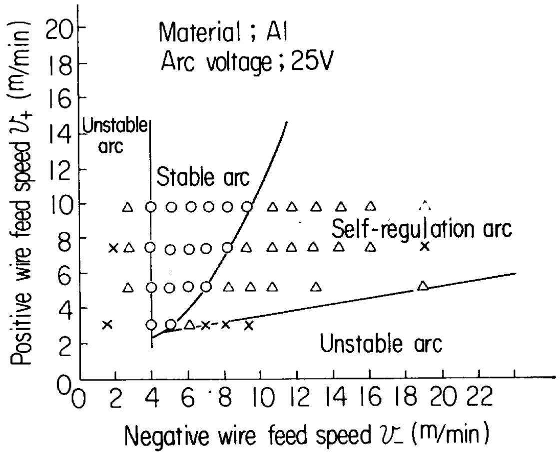

Fig. 4 Relation between wire feed speed and arc stability

kept constant at 25 V, and when positive wire feed speed (v_+) and negative wire feed speed (v_-) were varied.

There is a stable arc area when (v_+) is slightly made larger than (v_-). In this case, the stable arc area is a region where practical spraying is expected to be performed. An almost identical trend was observed when the arc voltage was changed to 30 V and 35 V. However, it was recognized that the arc stability in the stable arc area becomes slightly lower at 30 V or 35 V when compared to 25 V.

Figure 5 shows the sprayed coating adhesive strength test result, when the spraying distance (l), spray gun moving speed (vs), and positive wire feed speed (v_+) were kept constant at 10 cm (distance between the top end of spray gun and the surface of steel plate), 6 m/min, and 8 m/min respectively, while varying (V) from 25 to 30 and 35 V and negative wire feed speed (v_-) from 3 to 16 m/min to perform the spraying. It was found that the maximum adhesive strength of the sprayed coating was obtained at $v_-=8$ m/min against $v_+=8$ m/min. Discussion on the spraying condition which enabled the attainment of the maximum adhesion strength follows.

Figure 6 shows the relationship between the wire feed speed ratio (v_-/v_+), the adhesive strength, and the arc current (I) (from the data in Fig. 5). From this figure, it is known that the wire feed speed ratio which gives the maximum adhesive strength at arc voltages of 25, 30 and 35 V, almost agrees with the wire feed speed ratio at which the current change in arc current (I) shows a turning point. When plotting the spraying condition needed to obtain the maximum adhesive strength on the graph (Fig. 4) which shows the arc stability, the relationship is expressed by a dotted line in Fig. 7. Namely, it can be said that the spraying conditions needed to obtain the maximum adhesive strength are near the borderline between the stable arc area and the self-regulation arc area. Even though Figure 7 shows an example when the arc voltage (V) is 25 V, it has been confirmed that exactly the same trend is seen when (V) is 30 V or 35 V.

From the above, the spraying condition needed to obtain the maximum adhesive strength to the sprayed coating can be determined by investigating the relationship between the wire feed speed ratio and the arc current (I), and the condition for a turning in the relationship curve can be understood.

3.2 *Stainless steel spraying*

Figure 8 illustrates arc stability spraying conditions and the determination of maximum adhesive strength of the sprayed coating with SUS 308. The arc stability was evaluated using the criterion detailed in

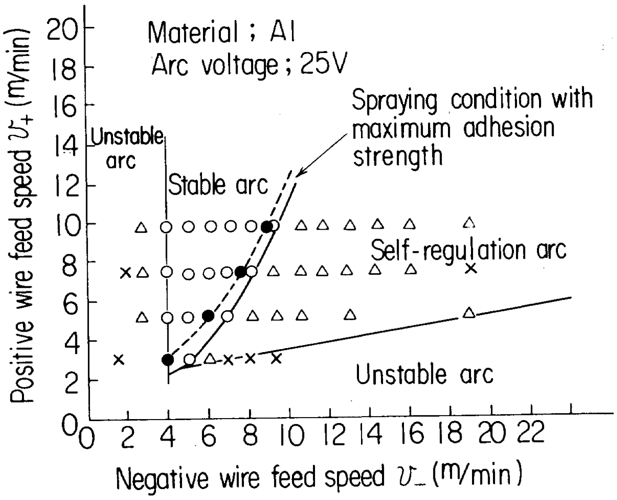

Fig. 7 Relation between wire feed speed and arc stability

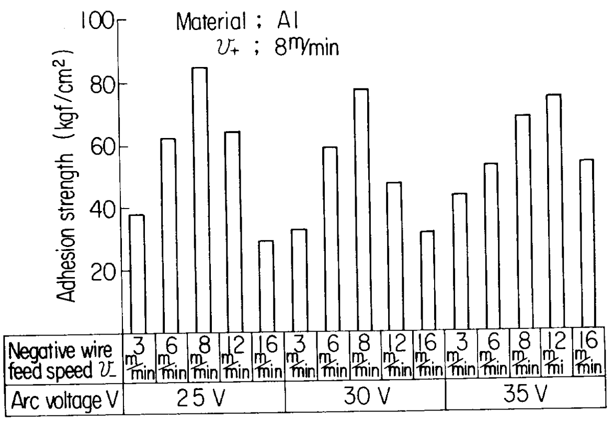

Fig. 5 Relation between wire feed speed and adhesion strength

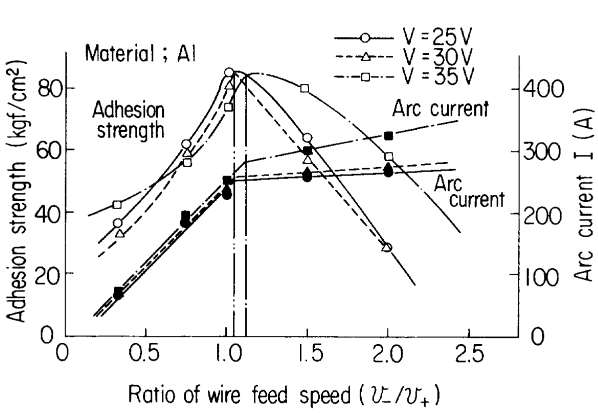

Fig. 6 Ratio of wire feed speed versus adhesion strength and arc current

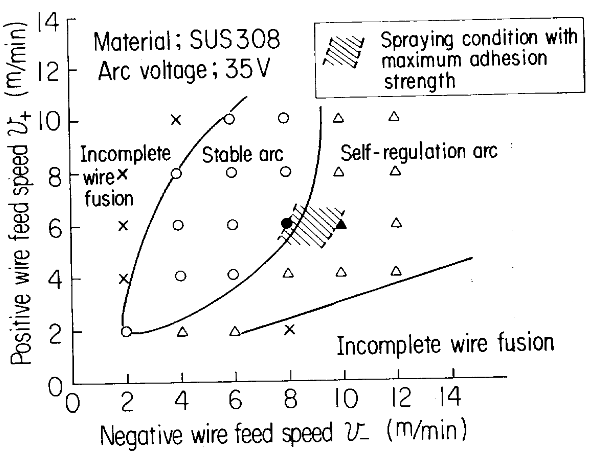

Fig. 8 Relation between wire feed speed and arc stability

Table 2, by changing the positive wire feed speed (v_+) and negative wire feed speed (v_-). The stable arc area is in the region where (v_+) and (v_-) are virtually equal. The test was made on the adhesive strength of sprayed coating by changing (v_-) in 5 conditions, namely, 4, 6, 8, 10 and 12 m/min, while maintaining (v_+) constant at 6 m/min. It has been found that the optimum conditions to obtain the maximum adhesive strength are (v_+)=6 m/min, and (v_-)=8~10 m/min. It can be said that, as with aluminium spraying, the spraying condition needed to obtain the maximum adhesive strength exists near the borderline between the stable arc area and the self-regulation arc area. Even though Figure 8 shows such a case with an arc voltage (V) of 35 V, it has also been confirmed that nearly the same trend is obtained when (V) is 30, 40 or 45 V.

Figure 9 shows arc stable spraying condition and the determination of maximum adhesive strength of sprayed coating with SUS 420. As with SUS 308 material, the stable arc area is where (v_+) and (v_-) are nearly equal. The spraying conditions to obtain the maximum adhesive strength are, as with aluminium and SUS 308 material, on the borderline between the stable arc area and the self-regulation arc area.

However, with SUS 308 and SUS 420 materials, a turning point in the relationship curve, such as observed in the relationship of the wire feed speed ratio (v_-/v_+) with arc current (I) for aluminium, was not observed. Therefore, the spraying conditions needed to obtain the maximum adhesive strength cannot be simply determined from the relationship curve of wire feed speed ratio (v_-/v_+) and arc current (I).

From the above-mentioned experimental results, the following can be said. For the spraying of aluminium and two kinds of stainless steels, the spraying conditions to obtain the maximum adhesive strength are on the borderline between the stable arc area and the self-regulation arc area. Therefore, adequate spraying conditions can be estimated easily by investigating the arc stability. In the case of aluminium spraying, the spraying conditions needed to obtain the maximum adhesive strength can be obtained exactly, by investigating the relationship between the wire feed speed ratio (v_-/v_+) and the arc current (I) and knowing the condition for the turning point in its relative curve.

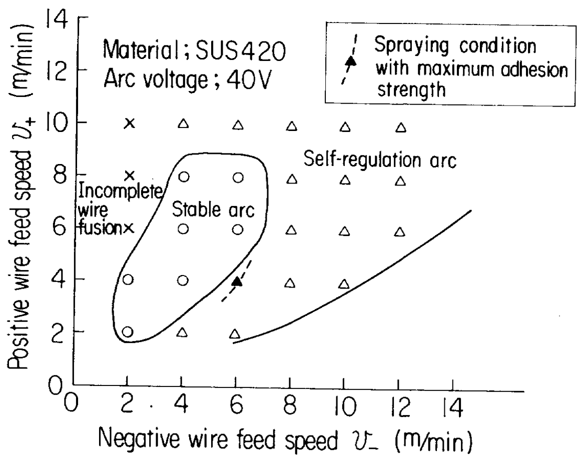

Fig. 9 Relation between wire feed speed and arc stability

4. Discussions from the Viewpoint of Shape, and Bombardment Conditions of Fused Particles

It has been found from the results of experiments so far described that the adhesion of the coating is greatly affected by spraying conditions. Therefore, the shape and bombardment conditions of fused particles were examined by means of high-speed cine-camera, in order to study their influence on the adhesive strength.

Figure 10 shows pictures of the bombardment of fused particles sprayed onto the steel plate at the time of SUS 308 spraying with arc voltage (V)=30 V, (v_+)=6 m/min, and (v_-)=6 m/min. The numbers on top of the pictures show the six frames in their correct sequence. The time between two frames is about 1/8000 second. As can be seen, the fused particles are almost completely spherical in shape. Various sized particles are found. The particle with an arrow mark which has bombarded the substrate at that instance in frame ① can not be seen in frame ②. This indicates that the bombarding particle is cooled instantaneously. Thus the cooling time must be within about 1/8000 secound.

In Figure 11, four representative frames of bombardment of fused particles at the time of SUS 308 spraying under various spraying conditions are traced. It can be seen that the particle size varies when (V) or (v_+) is changed. Thus the particle sizes under various spraying conditions can be compared and there is a method to compare the particle sizes by using Zauter average particle size. Since there was a proportional relationship between the Zauter average particle size and the maximum particle size (D_{max}) [6)-7)], in this study the maximum particle size (D_{max}) under each spraying condition was used as the representative value of the particles.

Figure 12 shows maximum particle size values (D_{max}) under various spraying conditions divided by the maximum particle size ($D_{0,max}$) with spraying conditions of (V)=30 V, (v_+)=6 m/min, and (v_-)=6 m/min. From Figure 12, it is clear that the particle size becomes larger when (V) is increased from 30 V to 40 V, and when (v_+) is decreased from 6 m/min to 4 m/min. On the contrary, the particle size becomes smaller when (v_+) increases from 6 m/min to 8 m/min. Figure 12 also shows the adhesion strength of sprayed coating (F) when steel plate is sprayed under various spraying conditions. In this connection, the relationship between the adhesive strength of the sprayed coating (F) and the maximum particle size ratio ($D_{max}/D_{0,max}$) is discussed below.

Figure 13 shows the relationship between the maximum particle size ratio ($D_{max}/D_{0,max}$) and the adhesive strength of the sprayed coating. As the particle size becomes larger, the adhesive strength increases. Namely, in SUS 308 spraying, adhesive

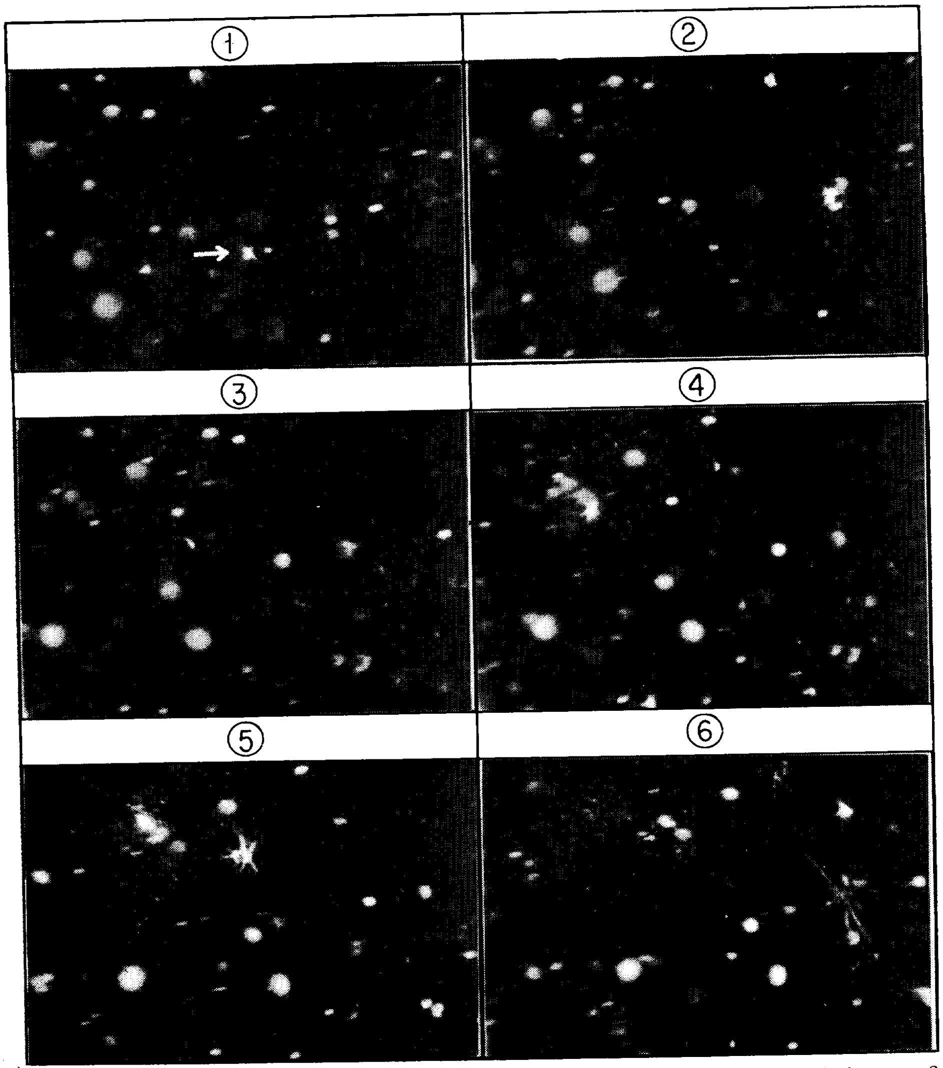

Fig. 10 High speed motion pictures of spraying particles (SUS308, V=30V, v_+=6 m/min, v_-=6 m/min)

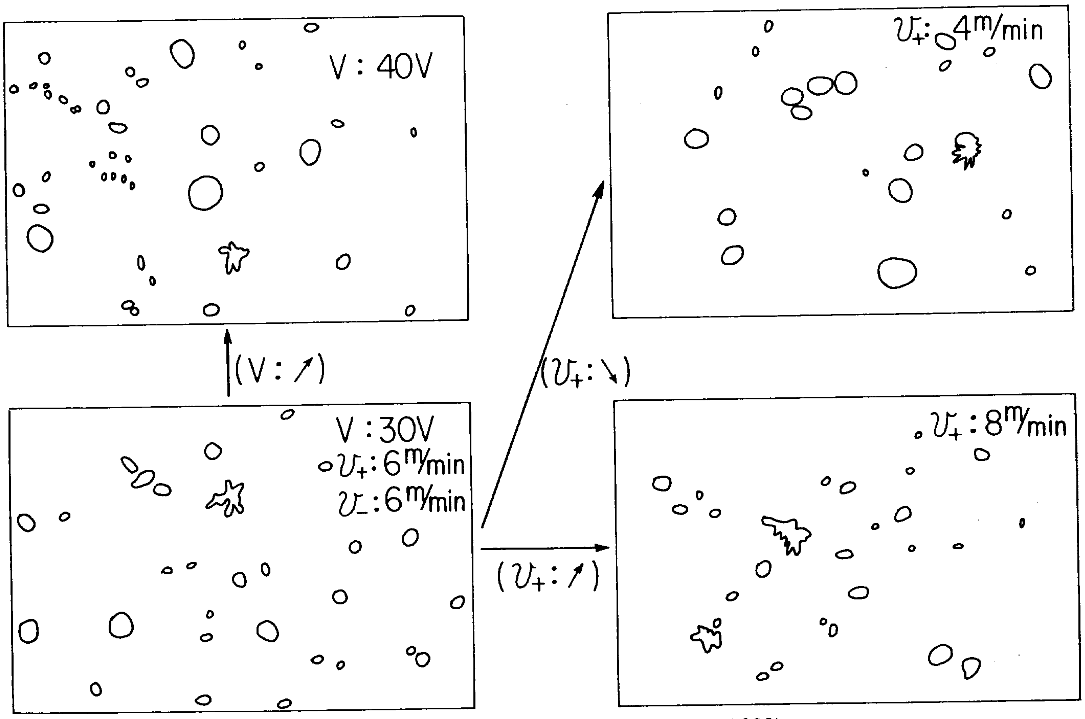

Fig. 11 Shape of spraying particles (SUS308)

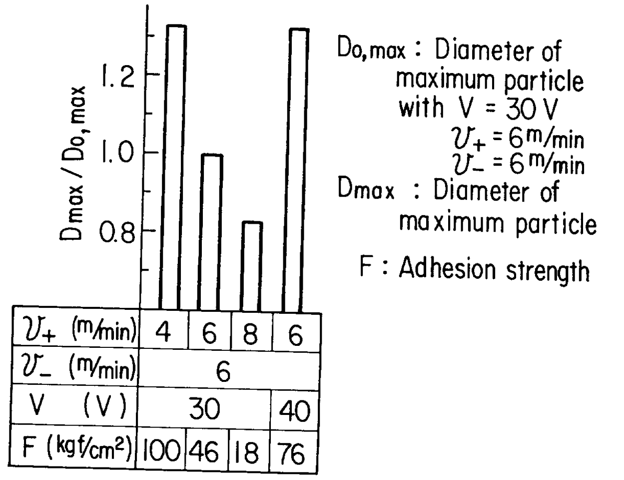

Fig. 12 Ratio of maximum diameter of spraying particles versus spraying condition and ahdesion strength (SUS308)

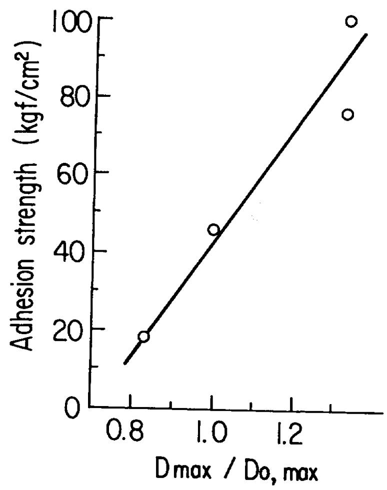

Fig. 13 Relation between adhesion strength and ratio of maximum diameter of spraying particle (SUS308)

strength of the sprayed coating is largely influenced by such spraying conditions as arc voltage and wire feed speed. This is caused by the change in size of fused particles in the spraying conditions. In these spraying conditions in which there is high adhesive strength, the sizes of fused particles become large. As to the reason for the increase in the adhesive strength when the sizes of fused particles become larger, the following has been considered.

As the sizes of fused particles become larger, the amount of oxidation on the surface of particles is reduced, and the cooling during fused particles flight is small. Thus the temperature of the larger particles before hitting the substrate is high. Also when the particle size is larger, the bombardment energy per fused particle is increased, which contributes to the increase in adhesive strength.

Through observation of the shape and bombardment of fused particles in SUS 308 spraying, using a high-speed cine-camera as explained above, the following was observed.

In SUS 308 spraying with spraying conditions designed for high adhesive strength of the sprayed coating, the size of fused particles is increased. The fused particles are almost completely spherical in shape, and the particle sizes spread over a considerably wide range. The fused particles are cooled instantaneously within about 1/8000 second after bombardment of the steel plate.

5. Conclusions

In this study, using aluminium and two kinds of stainless steels as spraying materials and a DC arc spraying equipment, the relationship of spraying conditions such as the arc voltage, arc current, positive and negative wire feed speeds, with the arc stability (or obtained adhesive strength of sprayed coating) was studied, and adequate spraying conditions were investigated and verified. Also the shape and cooling time at bombardment with fused particles under various spraying conditions were observed by means of a high-speed 16 mm cine-camera to verify the relationship between the spraying conditions and the adhesive strength of sprayed coating.

The conclusions thus obtained are summarized as follows:

(1) The arc stability is classified into three regions, namely stable arc area, self-regulation arc area, and unstable arc area caused by the positive and negative wire feeding speeds.

(2) The spraying conditions required to obtain the maximum adhesive strength of sprayed coating come near the borderline between the stable arc area and the self-regulation arc area, with aluminium and two kinds of stainless steel spraying materials. Therefore, adequate spraying conditions can be estimated easily by investigating the arc stability. In aluminium spraying, the spraying conditions needed to obtain the maximum adhesive strength, can be obtained exactly by investigating the relationship between the wire feed speed ratio (v_-/v_+) and the arc current, and by knowing the turning point of the arc current.

(3) In stainless steel (SUS 308) spraying, to attain high adhesive strength of the sprayed coating, the sizes of fused particles must be increased. The fused particles are almost completely spherical in shape. The particle sizes spread over a considerably wide range. The fused particles are cooled instantaneously within about 1/8000 second after bombardment of the steel plate.

Acknowledgment

The authors wish to express their appreciation to Dr. Takuro Kobayashi, Prof. Emeritus of Tohoku University for his guidance, and Mr. Kenji Maehara of Hitachi Zosen Corporation Technical Research Institute for his advice and assistance.

References

1) M. Seki and K. Ishikawa; "Application and Problem of Thermal Spraying", Journal of the Japan Society of Mechanical Engineers, Vol. 82 (1979), No. 724, 270–275 (in

Japanese)
2) S. Uchida; "Spraying for Materials", Journal of the Materials Science Society of Japan, Vol. 15 (1978), No. 1, 29–35 (in Japanese)
3) K. Ishikawa and M. Seki; "Protective Coating for High Temperature Thechnology by Thermal Spraying", Corrosion Engineering, Vol. 26 (1977), No. 6, 313–326 (in Japanese)
4) K. Akimoto; "Investigation of arc sprayed coating", The Journal of the Thermal Spraying Society of Japan, Vol. 16 (1979), No. 1, 17–24 (in Japanese)
5) K. Ando and M. Hasegawa; "Welding Arc Phenomenon", 343–350, Sanpo
6) T. Kurebayashi; "Atomization of Liquids by means of a Rotating Nozzle", Transation of the Japan Society of Mechanical Engineers, Vol. 25 (1959), No. 160, 1259–1275
7) T. Sakai and M. Yamada; "Effects of Additives on Atomization Characteristics of Residual Fuel Oil", Journal of the Chemical Society of Japan, Vol. 65 (1962), No. 11, 1761–1766