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METALLIC SPRAY BY WIRE EXPLOSION

By

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Recently various techniques of the metallic coating have been developed, as exemplified in flame spray coating, plasma-jet spray coating, etc. In this report a new method of coating is presented, where the surface of materials is coated by means of electric-explosion of metallic wire in the air or in the inert gas of normal pressure. By the instantaneous discharge of electric energy into the metallic wire under the proper circuit conditions, the wire is exploded partly and the rest of the melted parts is broken into fine particles and spattered. These particles impinge against the surface of material with the velocity of 1~3 Machs. The characteristics of this method are as follows. Though the proceses are carried out in the air, the oxidation of the coated layer and base material is hardly visible because the impingements of the small particles of melted metal take place in the exploded gas of the wire. The roughness of the coated surface is less than 5 μ, the porosity is less than 10 %, and the adhesive force of the coated layer to the base material is more than 200 kg/cm^2. Another advantage of this method is that it is suitable for coating the inner surface of cylindrical and spherical objects. This report gives the mechanisms of the phenomena, outline of method and properties of coatings.

1. Introduction

There are various methods in the treatment of metallic surface, such as chemical treating, electroytic plating, vapour condensation, anode oxidation, glass lining and metallic spray. Metallic spray is a method in which melted or semi-melted particles are scattered at high speed and plated on the surface of substances. Various equipments devised for this method are an arc metallizing gun, a resistance heat metallizing gun, a high frequency metallizing gun, a plasma flame spray gun, a gas metallizing gun and so on [1].

The present report is related to the newly developed metallic spraying method by means of wire explosion[2]. The process involves the explosion of a portion of wire of spray material in atmosphere or in an inert gas of normal atmospheric pressure by a heavy electric discharge and the impingements, by

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the above explosive pressure, of the atomized particles of remained melted parts of wire with very high speed against the surface of substance to be coated.

This report will deal with the mechanisms of the above phenomena, the outline of method and such properties of coating layer as surface roughness, hardness, component, structure and adhesion strength.

2. Equipment of Spray Coating

The equipment of spray coating used in our laboratory is divided into two parts of an electric discharge and a spray. The circuit diagram of discharge part is shown in Fig. 1. The maximum capacity of the capacitor is 200 μF, the maximum charged voltage is 30 kV and ringing frequency of circuit is about 22 kc. As shown in Fig. 2, a spray apparatus consists of two electrodes of copper tubes and a spray wire (metallic conductor) is exploded between the tops of two electrodes. After one explosion completes, the wire is put through imediately from right tube to left and the next explosion can be ignited, and so on.

3. Mechanism of Spray Coating and Condition of Electric Discharge.

3-1 Partial explosion of wire and optimum condition of discharge

If comparatively low energy is supplied to the wire during the electric discharge, the wire only melts itself without exploding. Whereas it is exploded completely with the supply of sufficiently high energy. When the intermediate energy is supplied, however, wire explodes in part, sending the remained melted part spattering in fine particles. These features are illustrated in Fig. 3 which shows photographs of the partial explosions and the spatterings of melted particles of tungsten wires when charged energy is varied. Fig. 4 a and 4 b show high speed photographs of the partial explosion of lead and tungsten wire respectively. The flushed parts in the photographs are the exploding gas and dark parts are the cloud of fine particles. The circular ring enclosing the exploding gas in Fig. 4 b is the shock wave in the air.

In order to obtain the best coating layer, it is necessary to take optimum values of masses, optimum velocities and optimum temperatures of the fine particles. These physical quantities depend on charged voltage V, capacity C, ringing frequency f, length l, sectional area s and material of wire.

In this report the optimum relations among these quantities are given from the results of a number of experiments. One of the results are shown in Fig. 5, where η is ratio of the total weight of spattered fine particles to the original weight of wire, which is measured by using the method of exploding the wire in a closed chamber and trapping the flying metal particles. The energy density $(CV^2/2sl)$ corresponding to η of $0.5\sim0.6$ generally gives the optimum spray coating.

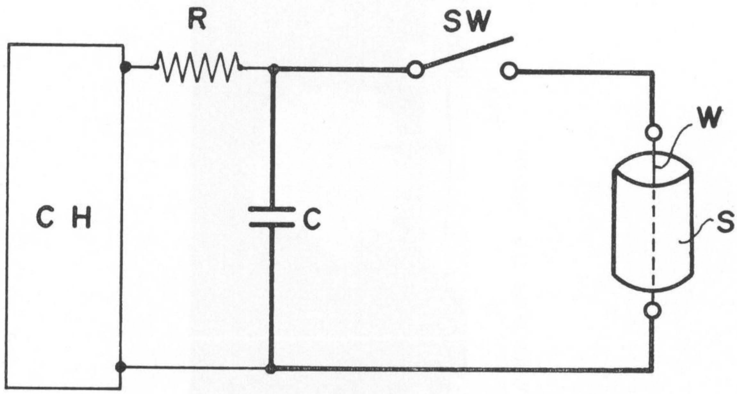

Fig. 1 Circuit diagram of discharge apparatus.

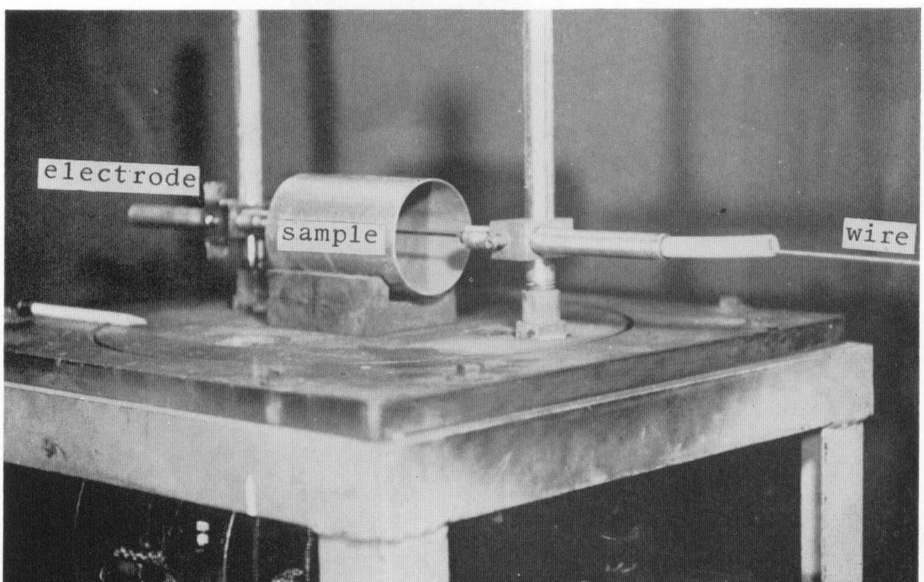

Fig. 2 Spray apparatus (75ϕ cylinder).

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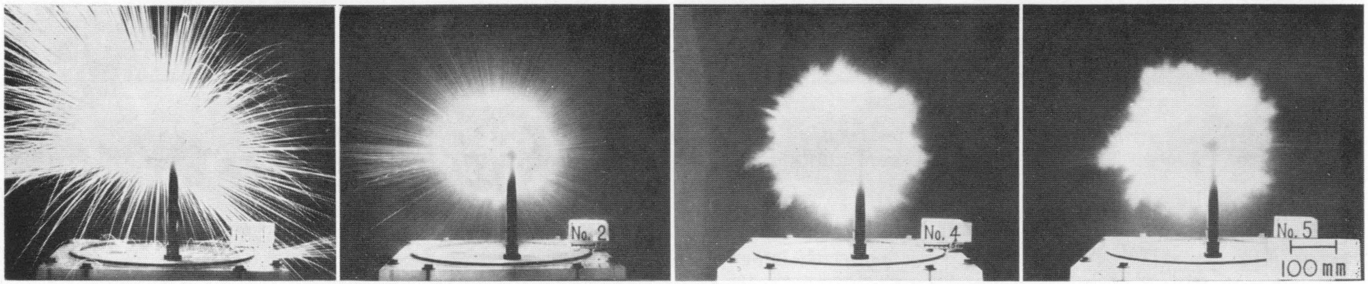
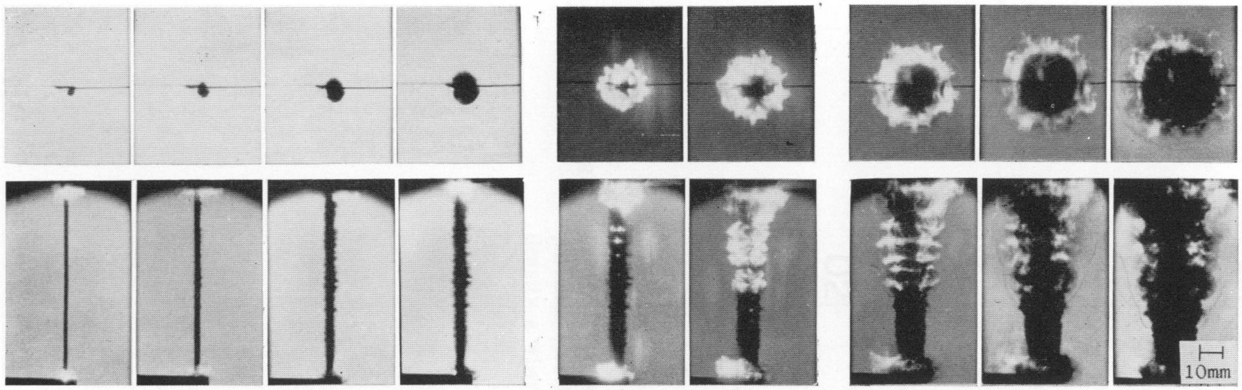


A 2 kJ B 3 kJ C 5 kJ D 6 kJ

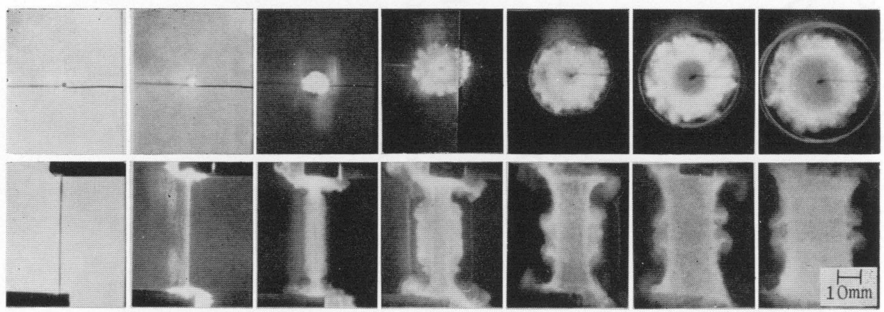
Fig. 3 Photographs of exploding gas and spattering melted particles of tungsten wire ($1\phi \times 50$mm). Energy discharged is denoted under each photograph.



1 2 3 4 5 6 7 8 9

Fig. 4a High speed photographs (200,000 Frames/sec) of exploding lead wire ($2mm^2 \times 80mm$) in the case of optimum spraying. Upper is axial view and lower is side view.

1 ～ 4 : melting and expanding
5 ～ 6 : exploding
7 ～ 9 : jetting of melted metal particles.



1 2 3 4 5 6 7

Fig. 4b High speed photographs (200,000 Frames/sec) of exploding tungsten wire ($0.79mm^2 \times 50mm$) in the case of optimum spraying. Upper is axial view and lower is side view.

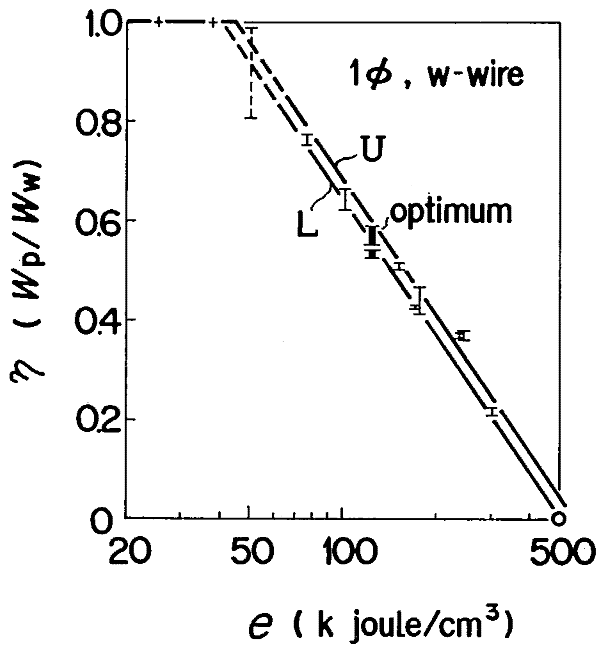


Fig. 5 Relation between ratio η of total weight W_p of spattered particles to original weight W_w of wire and nominal energy density e where $e = CV^2/2sl$.

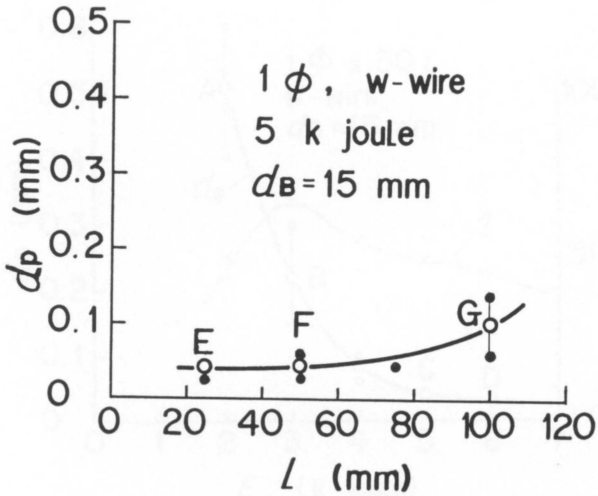
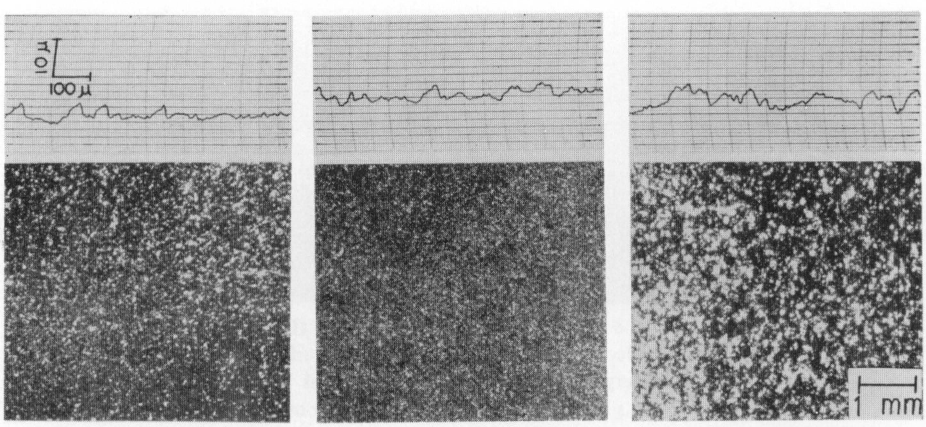


Fig. 6a Relation between grain size d_p of coating surface and length l of wire. d_B is distance between wire and base metal.



E l = 25 mm F 50 mm G 100 mm

Fig. 6b Photographs and roughness of surfaces of coatings. Length of wire is denoted under each photographs. E, F and G correspond to those in Fig. 6a.

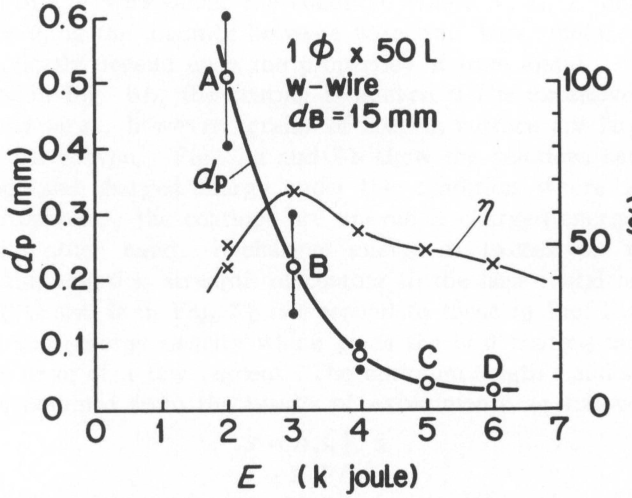
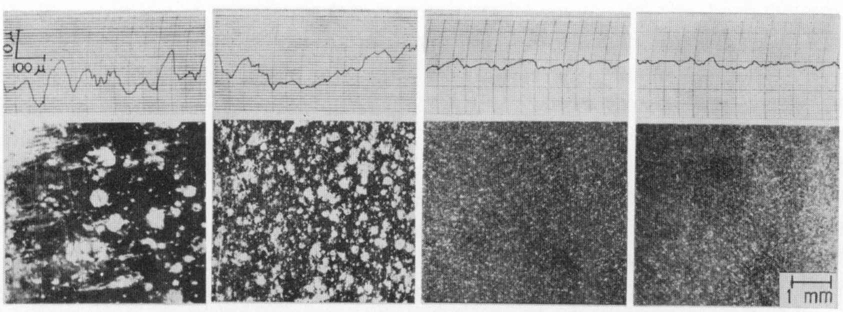


Fig. 7a Relation between grain size d_p of coating surface and energy discharged. d_B is distance between wire and base metal.



A 2 kJ **B** 3 kJ **C** 5 kJ **D** 6 kJ

Fig. 7b Photographs and roughness of surfaces of coatings. Energy discharged is denoted under each photographs. A, B, C and D correspond to those in Fig. 7a and Fig. 3.

Fig. 6a and 6 b show the relation between grain size d_p of coating surface and length l of wire under the condition where V, C, f, and s are constants, where d_B is the distance between wire and base metal. Grain size does not practically depend upon the properties of base metal.

As shown in Fig. 6 b, the coating is uneven if l is excessively small. If l is excessively large, however, grains of coating surface are large and their distributions are uneven. Fig. 7 a and 7 b show the relations between grain size of surface and charged energy under the condition where s and l are constants. Apparently the coatings are uneven if charged energy is insufficient. On the other hand, if charged energy is excessive, the striation appears and the adhesion strength of coating to the base metal is low. Photographs A, B, C and D in Fig. 7 b correspond to those in Fig. 3 respectively.

The optimum energy density which gives the best coating must be determined within error of a few percent. The optimum length l and sectional area s of wire are obtained from the results of experiments as follow [3],

$$s = K_1 C V f^{\frac{2}{3}} \qquad (1)$$

$$l = K_2 V f^{-\frac{2}{3}} \qquad (2)$$

where s is measured in mm², l in mm, C farad, V in volt and f in cycle/sec. K_1 and K_2 are the constants depending only upon the properties of material of wire.

3-2 Spattering velocity of melted particles and location of base metal.

The velocities, masses and temperatures of melted particles at the time of impingement to base metal, which greatly influence the properties of coating, depend on the relative distance and relative angle of the wire to the base metal. When the distance between wire and base metal is excessively small, the surface of base metal are roughened because of the high velocities and high temperatures of the melted particles and exploding gases. Moreover, the base metal may be deformed by the strong shock wave in the air produced by explosion of wire. When the distance is excessively large, the velocities and temperatures of particles decrease and the adhesive force of coating to the base metal is weakened. Flying velocity of metal particles, expanding velocity of gas and shock wave measured by high speed photography in the case of tungsten wire explosion, are shown in Fig. 8 Furthermore, the particles are rapidly oxidized when the distance between the wire and the bese metal is larger than a certain value. These oxidation occures according to the following mechanism. The expanding velocity of the exploding gas decreases suddenly at the distance r_C(50～60 mm from the wire in Fig. 8) and then the melted particles fly out from the gas of wire to the air and oxidized. The distance between wire and base metal must therefore be less than r_C. In the case of the optimum location of base metal, the processes of coating are carried out as follows. In the first place, the exploded gas of wire reachs to the surface of base metal excluding air. Then the impingements of the fine particles to the base metal are followed in the atmosphere of exploded gas of wire. For this reason, both of the particles and base metal are scarcely

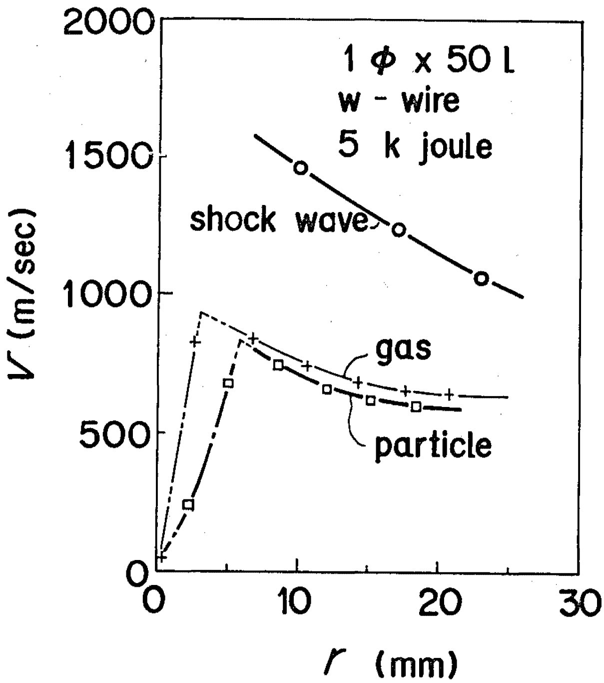


Fig. 8 Expanding velocities of cloud of metal particles, exploding gas and shock wave.

oxidized. From the results of experiments, the optimum distance r_B between the center line of wire and the base metal is expressed as

$$r_B \doteqdot 30\, r_0 \qquad (r_0 \text{ is radius of wire}) \qquad (3)$$

The optimum angle of impingement of particles to the base metal is ninety degrees and at the angle less than forty-five degrees, it becomes difficult for the particles to stick to the base metal. In order to conquer this inexpediency, it is useful to utilize the interction between particles and reflected shock wave or reflected gas from walls placed appropriately near the base metal. By this interaction, some groups of the particles impinge to the base metal at the angle of almost ninety degrees. By these methods, it is easy to obtain the uniform thickness of coating, even on a the flat plane, or to control the direction of spraying. The mechanism and details of this method will be reported in the other paper. Since the time necessitated to complete coating of one layer is about one hundred micro seconds, the base metal is scarceiy affected by the heat of processing.

4. Properties of Spray Coatings [4)5)]

1) Surface roughness

Roughness was measured on the average roughness *H*a and the root mean square average roughness R. M. S.. Table 1 shows *H*a and R. M. S. of spray

Table. 1 Surface roughness of spray coating.

Spray materials / Roughness	W	Mo	Ta	Ti	WC•Co alloy
$Ha(\mu)$	2.2	1.0	0.95	5.1	1.7
R. M. S. (μ)	2.3	1.0	1.0	5.3	1.9

coating of W, Mo, Ta, Ti, cemented carbide and stainless stee 0.95 ~ 5.1 μ and R. M. S. 1.0 ~ 5.3 μ are very smooth compa other spray method. As it is clear from the electron microscc phs, the particles of spray coatings are smaller than that of a spray.

2) Hardness

Table 2 shows hardness of spray coatings of W, Mo, Ta, T

Table. 2 Vicker's hardness of spray coating.

Materials / Hardness	W	Mo	Ta	Ti
Spray coating	550	260	280	240
Normal	450~500	200~250	125	160~250

nted carbide. All materials except cemented carbide show hig than original materials. The hardness of spray coating is redu ted carbide, which means that the density of spray coating is i tered compacts. This however doesn't mean that it is because of $WC \rightarrow W_2C$.

3) Adhesion strength

The steel rod with sectional area of 100 mm² was used as tension test. The sprayed specimen is inserted between two st araldite adhered. Tension test was carried out in the vertical spray coating and the adhesion strength is defined as stress wh

Table. 3 Adhesion strength of spray coating.

Base materials / Spray materials	Adhesion strength (kg/cm²) Fe	Brass	
W	>301	>358	
Mo	>226	>200	
Ta	>336	>231	
Ti	>200	>300	
WC•Co alloy	>270	>213	
SUS-27	>250	>197	

ting is taken off from base metals. The spray was carried out six times on W, Mo, Ta, Ti, cemented carbide and stainless steel respectively, and spray coatings with 20~50 μ thickness were obtained. Table 3 shows these adhesion strength. It is found in general that adhesion strength is large for brass base, and small for Cu base.

4) Components of spray coating

According to X-ray diffraction results of cemented carbide spray coatings by wire explosion, WC was decomposed to W_2C and C because of the unstableness of WC at a high temperature above 2600 °C. The carbon contents of spray coatings are about 0.3 % less than those before spray. This is mainly resulted from oxidation, then the decrease of C contents can be made smaller by improving atmospheres and spray methods.

5) Structures of spray coatings

Fig. 9 shows electron microscopic photographs of surface state of spray coating in some materials. Atomized particles including fine particles of less than 1 μ in size was sprayed. Ti on an average does not include small particles. Sectional photograph of Fig. 10 shows the compactness of spray coatings. W and Mo are fairly compacts. By the water displacement method, the theoretical densities of W and Mo were determined as 93 % and 91 % respectively.

Fig. 11 is the electron microscopic photographs of adhesion boundary. The interlockings of adhesion boundaries are sufficient, and spray coating show dense structures. The diffusion state is not obvious, but the boundary part adheres tightly.

6) Ferroxyl tests

Fig. 12a and 12b show the result of a ferroxyl test. There are very fine pin holes as compared with electrolytic Ni plating.

7) Samples of spray coatings

Fig. 13 shows some samples of spray coatings by wire explosion.

5. Conclusion

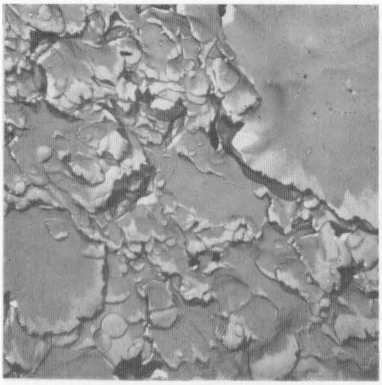
The general characteristics of spray coatings by wire explosion.

(1) By heavy electric discharge, wire of spray metal is exploded partly and the remained melted parts are spattered in fine particles at velocity of few Machs. These fine particles impinge to the base metal to be coated. Accordingly, it becomes unnecessary to depend on particular mediums which are used in other methods to melt and spatter the metals.

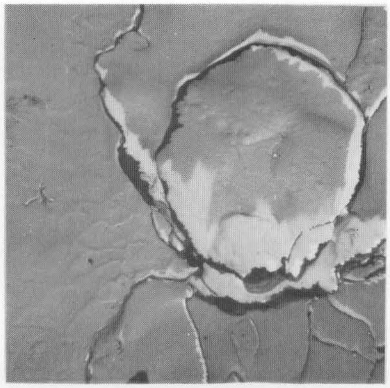
(2) Since the spattering of melted particles can be controlled precisely, reproducibility of coating is high.

(3) Spattered particles fly in the exploded gas of wire and both particles and base metals are scarcely oxidized.

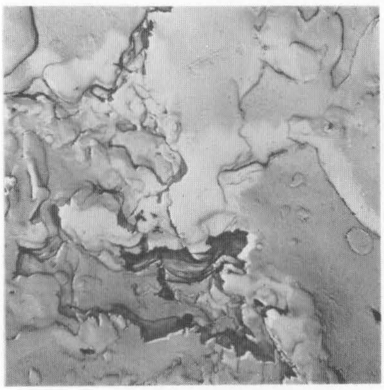
(4) Since velocity and temperature of spattered particles are high, the adhesive force of coating to base metal is large.



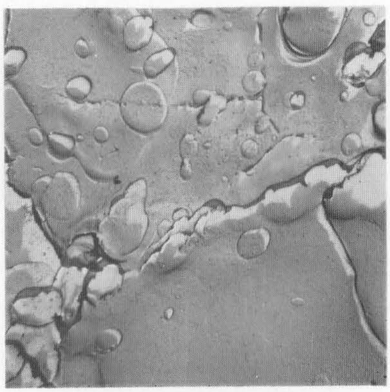
(a) W



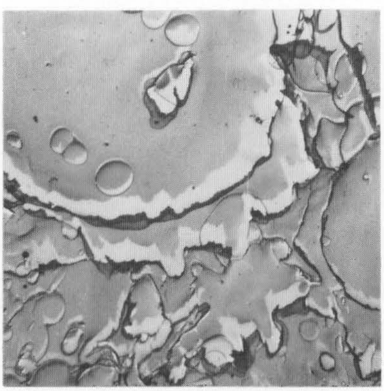
(d) Ti



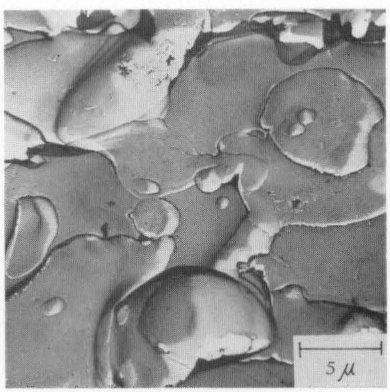
(b) Mo



(c) WC•Co alloy



(e) Ta



(f) SUS-27

Fig. 9 Surface appearance of various spray coatings.

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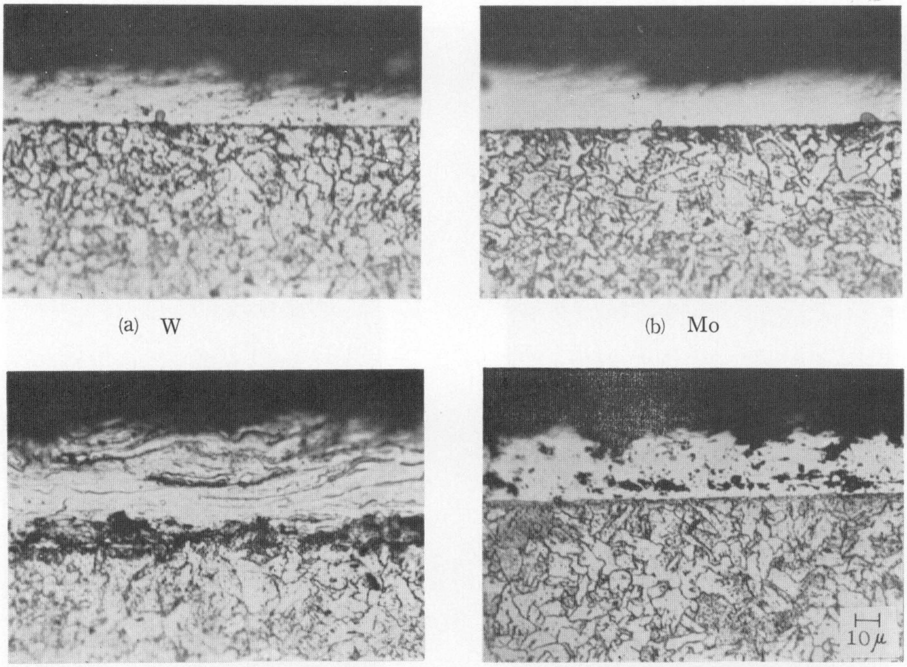
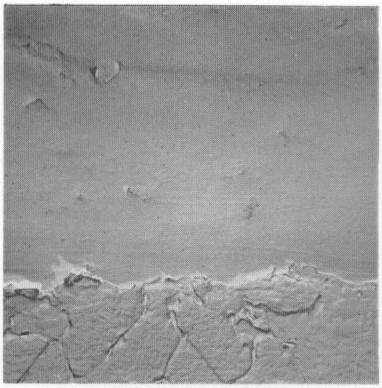


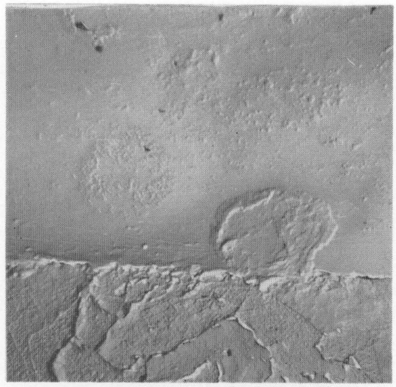
(a) W (b) Mo

(c) Ti (d) WC–Co alloy

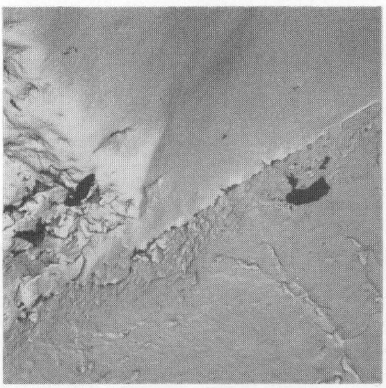
Fig. 10 Section photographs of various spray coatings.



(a) W

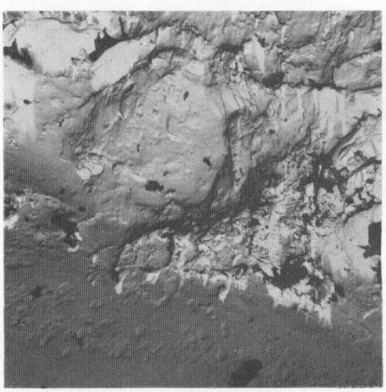


(b) Mo

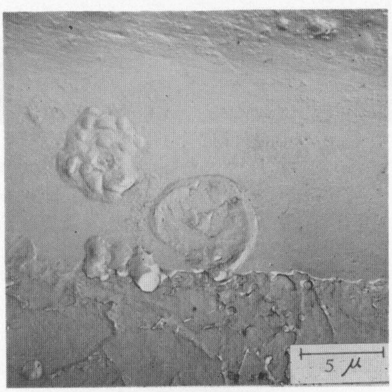


(c) Ta

(d) Ti

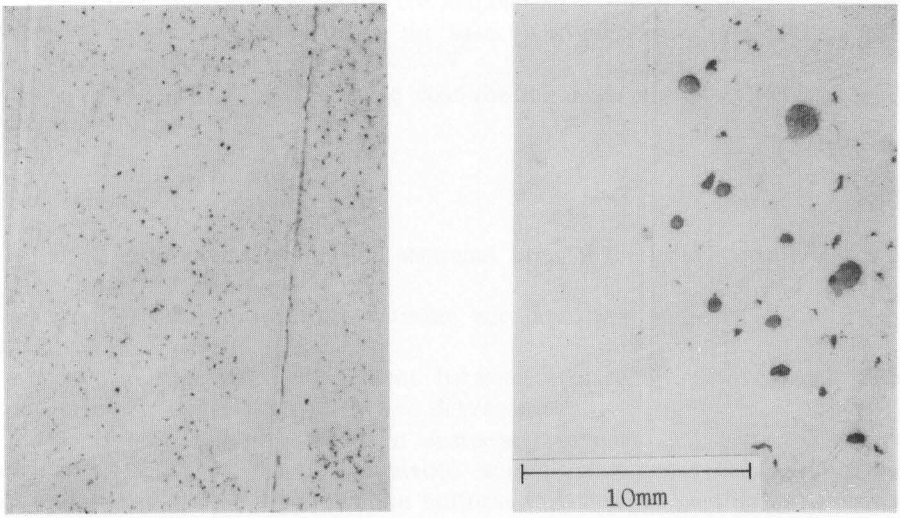


(e) WC–Co alloy



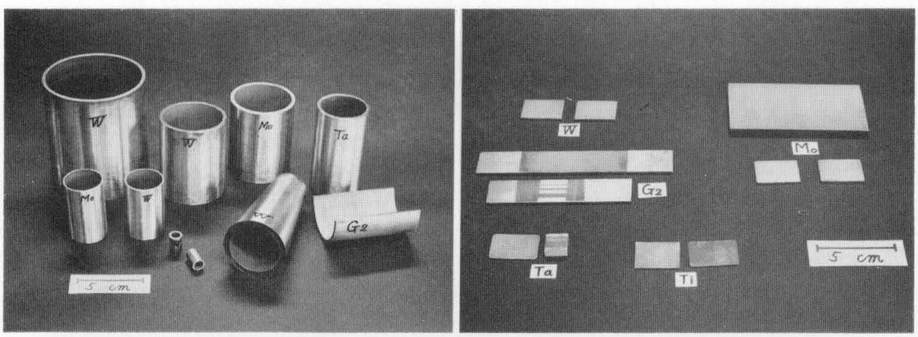
(f) SUS–27

Fig. 11 Microstructure of boundary between spray coating and base metal.



(a) (b)

Fig. 12 Results of ferroxyl test.
(a) Wire explosion spray of nickel.
(b) Electrolytic nickel plating.



(a) (b)

Fig. 13 Samples of spray coating by wire explosion.
(a) Inner surfaces of cylinder of copper, brass and mild steel are coated by W, Mo, Ta and WC•Co.
(b) Surfaces of flat plates of copper, brass, stainless steel and ceramic are coated by W, Mo, Ta, Ti and WC•Co.

(5) Since the time necessary for completing a coating of one layer is about one hundred micro seconds, the base metal is scarcely affected by the heat of processing.

(6) This method is suitable to coat the inner surface of cylindrical and spherical objects,

The methods of spray coatings.

(1) The optimum length and sectional area of exploding wire are given by equations (1) and (2).

(2) The optimum distance between wire and base metal is given by equation (3).

(3) The angle of impingement between spattering particles and base metal must be larger than forty-five degrees.

(4) If the interaction between spattered particles and reflected shock wave or reflected gas from walls placed appropriately near the base metal are utilized, it is easy to obtain the uniform thickness of coating layer even on the flat plane or to control the direction of spraying.

The properties of spray coatings.

(1) The surface of spray coating is smooth and R. M. S. is $1\sim5\,\mu$. It gives a small value as compared with R. M. S. $75\sim125\,\mu$ in plasma flame spray[6].

(2) The hardness of spray coating of cemented carbides is lower than that of original materials. In other cases, however, the hardness of spray coatings is higher.

(3) The components of cemented carbides (WC·Co system) in spray coating are mainly consisted of W_2C and Co. The carbon percent in steel decreases about 30 % after spray.

(4) The adhesion strength is generally high, but it varies according to the combinations of spray metals and base metals. In the case of Cu as base material, the adhesion strength is not so high. In the case of mild steel and brass it is sufficient, more than 200 kg/cm^2.

(5) By an optical microscopic photograph and electron microscopic photograph, the spray coatings are seen to be comparatively compact, and adhesion state are good.

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