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SUHARA, Toshiro
Research Institute for Applied Mechanics, Kyushu University : Professor

KITAJIMA, Kazunori
Research Institute for Applied Mechanics, Kyushu University : Professor

FUKUDA, Shigehisa
Research Institute for Applied Mechanics, Kyushu University : Research Associate

ITO, Hiroshi
Division of Research and Development, Nippon Tungsten Co., Ltd.

他

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COATING BY WIRE EXPLOSION SPRAYING (II)†
—Structure and Adhesion of Tungsten Coatings on the Mild-Steel and Copper Substrate—

By Toshiro SUHARA*, Kazunori KITAJIMA*, Shigehisa FUKUDA**, Hiroshi ITO*** and Hiroki FUKUNAGA***

The coating method and the characteristics of wire explosion spraying developed in our laboratory are described. The mechanism of adhesion between the coating and substrate in two metal systems, W-mild steel and W-Cu which differ in mutual solubility, is studied.

Metallographic observations using EPMA and soft X-ray confirmed the presence of a solid solution boundary layer in the case of the mild steel substrate, and a critical shearing stress of adhesion measured by our method ranged from 20 to 26 kg/mm^2, which is nearly equal to the shearing strength of the tungsten coating itself of 24 kg/mm^2, and the fracture propagated within the coating itself. In the case of the copper substrate the critical shearing stress of adhesion was 9 to 13 kg/mm^2 which is much weaker than the shearing strength of copper, 28 kg/mm^2, and the fracture propagated along the boundary between the coating and the substrate.

Theoretical considerations attempt to explain the mechanisms of formation of the structures and the adhesion properties.

It is concluded that the high adhesion strengths obtained by this method are attributable to the characteristics of the particles sprayed by wire explosion, i.e., the small size of average 5 μ, the high temperature of near the boiling point of materials, the high impinging velocity of 500~600 m /sec, and furthermore the uniformities of the size, velocity and temperature of the sprayed particles.

1. Introduction

Wire explosion spraying is a new method of metal spraying developed in our laboratory. Systematic studies have been made on the mechanism of wire explosion, the properties of coatings, and problems concerning practical applications.[1)~7)] This paper presents studies on the structure and the strength of the boundary layer between the coatings and the substrates, particularly

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* Professor, Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan.
** Research Associate, Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan.
*** Division of Research and Development, Nippon Tungsten Co., Ltd., Fukuoka, Japan.

comparing the two cases of mutually soluble and insoluble metals of coating and substrate.

First, the techniques of wire explosion spraying [1),2)] and the general properties of spray coatings deposited by this method are described. Second, the results of the metallographic observations of the structure of boundary layer between the coating and the substrate are shown, where the substrate materials used in these experiments were mild steel and copper and the sprayed material was tungsten. Third, some theoretical considerations on the processes of spraying and the mechanism of the formation of boundary layer are made. Fourth, the critical shearing stresses of adhesion of the coating to the substrate are measured by the shearing tests specially designed and the fracture surfaces are observed by EPMA.

Synthesizing the above mentioned results, the relationships between the high adhesive strength and the structures of the coatings and the boundary layer are discussed. Finally the results of the improvement of properties of cemented-carbide coatings by the diffusion and infiltration processes are presented.

2. Description of Wire Explosion Spraying

2-1 Method and applications

When the stored electric energy is instaneously discharged through a metallic wire under suitable circuit conditions, the wire is rapidly gasified and exploded in part, and the rest which has melted is broken into fine particles and spattered by the gas. Wire explosion spraying is a method of metal spraying utilizing such exploding and spattering of the metallic wire of spray materials in the air. Fig. 1 shows the discharge circuit of the equipment of wire explosion spraying.

In order to get the best coating, it is necessary to determine the electric circuit condition and the appropriate location of the wire to the substrate [1)]. Fig. 2 shows the explosion and the spattering of melted particles of tungsten; (a) is the explosion by insufficient electric energy for spraying and (b) is

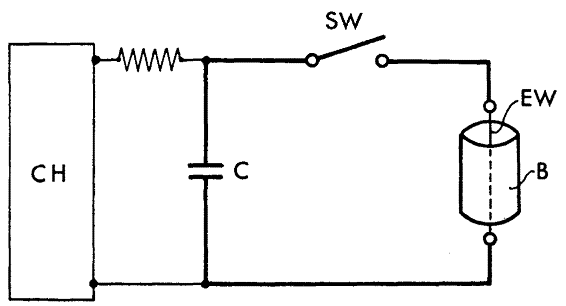
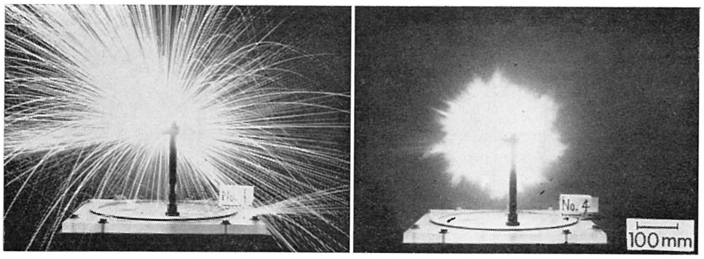


Fig. 1 Discharge circuit of equipment of wire explosion spraying.
CH: charger, C: capacitor, W: wire, S: substrate.



(a) (b)

Fig. 2 Exploding gas and spattered particles of tungsten wire (1$\phi \times 50$ mm).
(a) wire explosion with insufficient electric energy for spraying,
(b) optimum wire explosion for spraying.

the optimum explosion for spraying. In the case of the optimum explosion for spraying, the exploded gas of the wire reaches first, the surface of the substrate excluding the air, and is followed by the impingement of molten particles onto the substrate in the atmosphere of the exploded gas of the wire, so that both the impinging particles and the substrate are scarcely oxidized.

The characteristics of this method are enumerated as follows. First, all metals including refractory metals such as tungsten, molybdenum, etc. can be sprayed. Second, the diameter of the spattered particles is very small. The electron photomicrographs of these particles of the exploded tungsten and molybdenum are shown in Fig. 3. Fig. 4 shows the size distribution of these particles [3]. As shown in these figures, the size of particles can be divided into two groups; one has its average particle diameter of several-hundredth microns and the other several microns. The coating films are mainly composed of the larger particle group and the weight of the film coated on the inner face of a hollow cylinder is about 55～60 % of the original wire. Third, since the wire is gasified in superheated state in the process of electric discharge, the liquid particles spattered are considered to be uniformly heated up to the temperature near the boiling point of the material. Fourth, the particles are spattered with a uniformly high velocity of 500～600 m/sec [1]. For the characteristics of the method mentioned above,

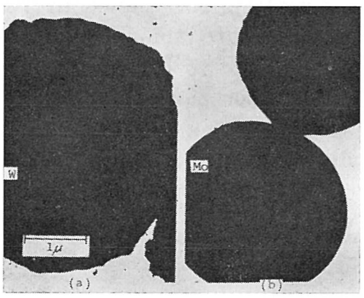


Fig. 3 Electron photomicrographs of sprayed particles.

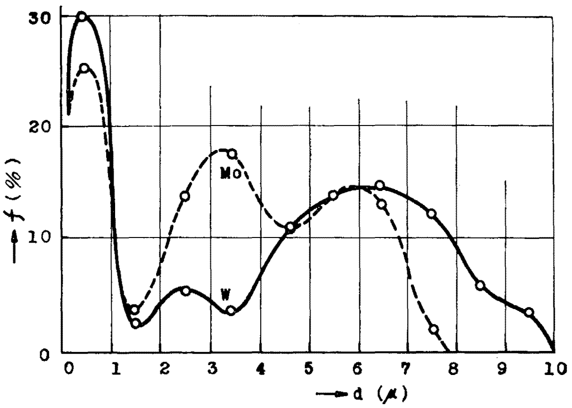


Fig. 4. Particle size distributions of sprayed particles.

the coatings obtained have generally the compact layered structures and the strong adhesive bond with the substrates as will be shown later. Fifth, since the substrate is scarcely affected by the heat of processing, it is possible to coat the surface of glasses and ceramics, as well as metals. Sixth, the advantage of this method lies in the fact that not only the plane surface but also the inner surface of a hollow cylinder, even with a diameter as small as less than 10 mm, can be sprayed. A typical example of this method is to coat the inner faces of aluminum alloy cylinders (40~140 mmϕ) of an internal combustion engine with molybdenum or other low cost materials. Using this method, Kawasaki Heavy Industries Ltd., and Honda R. and D. Co., Ltd. have succeeded in increasing the wear-resistivity and the air cooling efficiency of motor bicycle engines compared with the usual hard-chrome plating or the cast-iron sleeve. Mass production of these engines has now been put into practice in Japan.

2-2. General properties of spray coatings

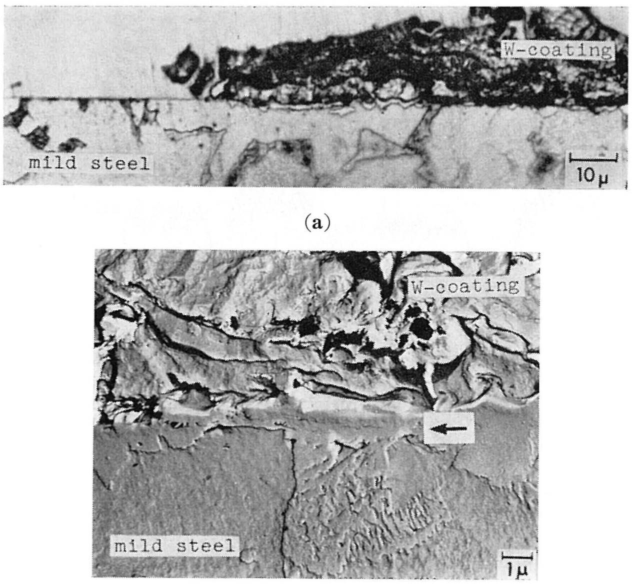
The thickness of coating obtained by a single spraying is from 5 to 15 μ, and by repeating the spraying it can be increased to about 100 μ. The general properties of these coatings are shown in Table 1. As shown in the table, the surfaces of coatings are smooth and the adhesive strength of coatings on the substrates is found to be much higher than those obtained by other methods such as flame or plasma spraying. In addition, the wear resistance of tungsten and molybdenum coatings is high, and the friction coefficients are very small.

3. Experimental Studies on Structures of the Boundary Layers Between Coatings and Substrate

We shall study the structures and properties of coatings obtained by wire explosion spraying, particularly comparing the soluble and insoluble systems of deposit and substrate metals, i.e. tungsten coatings on mild steel and copper.

3-1 Tungsten coating on mild steel substrate

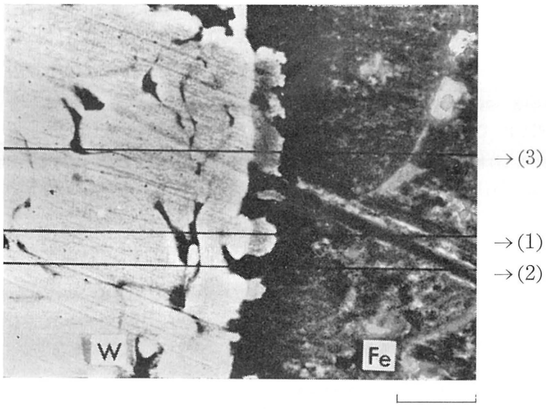
1) Metallographic observations by microscopes. Fig. 5 (a) is an optical photomicrograph of a section of a specimen of mild steel coated with tungsten. The left half of the photograph shows the original surface of the substrate, since this part of the specimen was masked using a thin plastic plate. As clearly shown, the boundary surface between the coating and the substrate has sunk 1~2 μ under the level of the original surface of the substrate. This may suggest that, owing to the high-velocity impingement of the fused tungsten particles, the surface of the mild steel was melted and mixed fluid-mechanically with the fused tungsten. Furthermore, a layer of about one micron in thickness can be observed along the boundary of the deposited metal (indicated by an arrow in Fig. 5 (a)). Fig. 5 (b), the electron photomicrograph of the same part, shows that the grain boundary of the mild steel has disappeared in this layer. This may suggest that the melted zone of the substrate is formed by the heat flow from the deposited material which has already solidified.



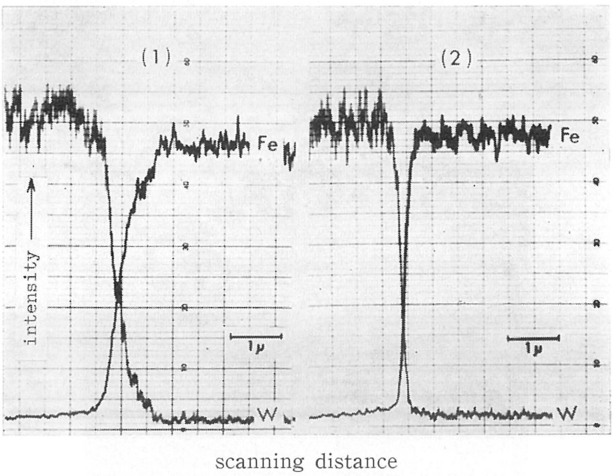
(b)

Fig. 5 Tungsten coating on mild steel: (a) optical photomicrograph, (b) electron photomicrograph of the same specimen showing melted zone of mild steel.

2) Metallographic observations by EPMA. In order to confirm these results, experiments by EPMA were performed. Fig. 6 (a) shows the secondary-electron image of the section of the mild steel specimen coated with tungsten, where the narrow layers of half tone are observed along the boundary of both materials. The breadth of these layers are fairly uniform and is about 1∼1.5 μ. This may be caused by the uniformity of the size, temperature, and velocity of the spattered particles. Furthermore this is considered to be the characteristic of a soluble system in contrast to an



(a)



(b) (c)

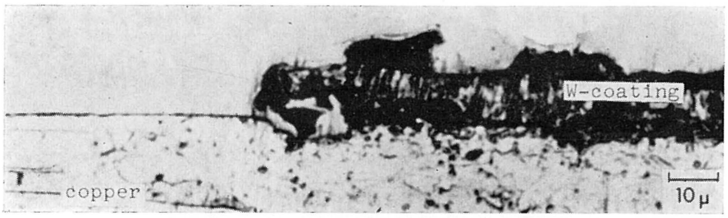
Fig. 6 Obsrevations of the boundary layer between a tungsten coating and a mild steel by EPMA: (a) secondary-electron image, (b) line analysis of an X-ray along line 1 in Fig. 5(a), (c) line analysis of an X-ray along line 2 in Fig. 5(a).

insoluble system as will be shown in the next section. Fig. 6 (b) and Fig. 6 (c) are the results of X-ray analysis along the line 1 and 2 in Fig. 6 (a) respectively. The line 1 traverses the narrow layer but the line 2 does not. In Fig. 6 (b), the characteristic X-ray intensity curves of W and Fe change gradually within a distance of 1~2 μ which indicates the existence of a mixed or welded zone with breadth 1~2 μ. On the other hand, Fig. 6 (c) does not show such clear existence of a boundary layer.

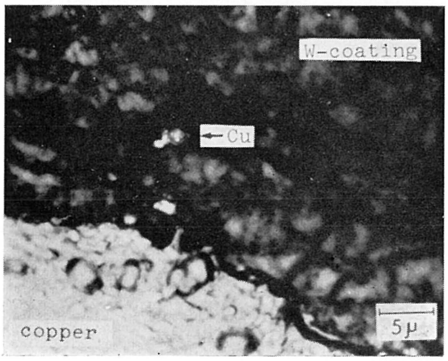
3-2 Tungsten coating on copper substrate

1) Metallographic observations by microscopes. Fig. 7 (a) is an optical photomicrograph of a section of a specimen of the copper substrate coated with tungsten. As in Fig. 5 (a), the left half of the photograph shows the original surface of the substrate. The boundary surface between the coating and the substrate has sunk 3~4 μ under the level of the original surface of the substrate, which is larger than that of mild steel substrates. Furthermore, the boundary line between the coating and the substrate shows an irregular form and solitary islands of copper are frequently observed inside the tungsten coating.

2) Metallographic observation by EPMA. Fig. 8 (a) shows the secondary electron image of the section of the copper specimen coated with tungsten.



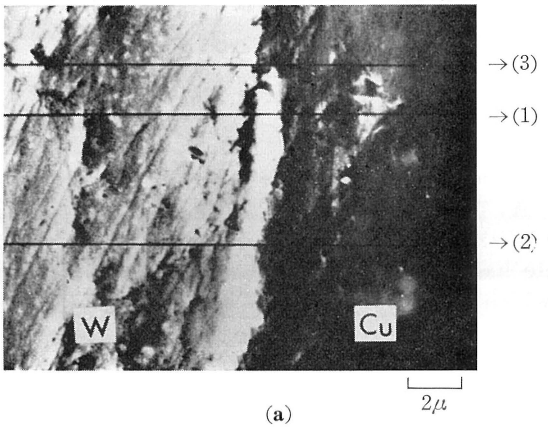
(a)



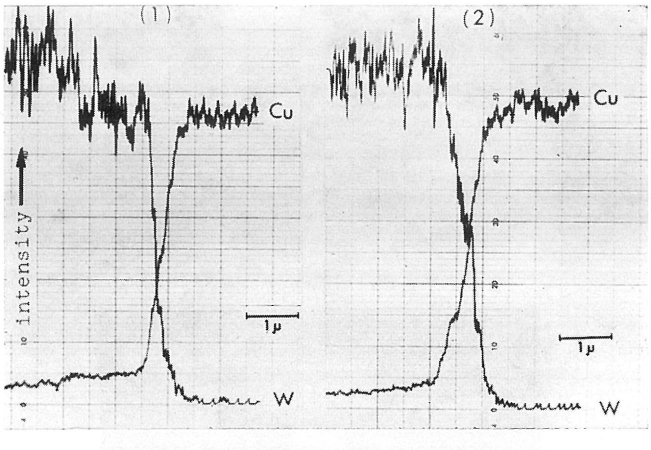
(b)

Fig. 7 Tungsten coating on copper.

Fig. 8 (b) and Fig. 8 (c) are the results of the X-ray analysis along line 1 and 2 respectively in Fig. 8 (a). In these figures, the mixing of a very small amount of copper is observed inside the tungsten coatings but the mixing of tungsten is not observed inside the copper substrate.



(a)



(b) (c)

Fig. 8 Observations of the boundary layer between a tungsten coating and a copper substrate by EPMA, (a) secondary-electron image, (b) line analysis of an X-ray along line 1 in Fig. 8 (a), (c) line analysis of an X-ray along line 2 in Fig. 8(a).

4. Considerations of the Mechanism of Formation of the Boundary Layer between Coating and Substrate

4–1 Impingement of fused tungsten particles

The foregoing experiments show the existence of a fluid-mechanically mixed layer between the coating and the substrate, which may provide an important contribution to the adhesive bonding. In this section, theoretical considerations of the formation of such layers are discussed.

The average diameter of spattered tungsten drops is about five microns as shown in article 2. The cylindrical cloud of these drops, whose thickness is approximately 5 mm, expands with the velocity V of about 500 m/sec. As already mentioned, the temperature of these drops is considered to be near the boiling point of material, and the decrease of temperature by heat radiation during time of flight is calculated to be negligibly small.

The pressure P generated on the surface of the substrate at the instant of impingement of one of the drops is

$$P=\rho V^2 \simeq 500 \text{ kg/mm}^2,$$

where ρ and V are the density and velocity of the drops respectively. This value is sufficient to deform and work-harden the surface of the substrate. The rise in temperature of the drops by the impingement is calculated to be about 270 °C, where the kinetic energy of the particle is assumed to be transformed to heat, so that this effect can be neglected compared with the temperature of the fused tungsten. As the drop impinges onto the substrate, it spreads and solidifies in the form of a circular disc whose average diameter is about ten microns and whose thickness is about one micron as shown in the experiments. The time t required for this process is

$$t=(10\mu/2)/V' \simeq 10^{-8} \text{ sec},$$

where V' is the expanding velocity of the fused tungsten on the surface of the substrate and is assumed to be nearly equal to its impinging velocity, V. On the other hand, the time t' required to complete the impingement of the cloud of drops with 5-mm thickness, is about

$$t' \simeq 5\text{mm}/V \simeq 10^{-5} \text{ sec},$$

and in this time, five layers, on the average, are deposited one on top of the other. Then Reynolds number R of the flow of fused tungsten is estimated in rough approximation as,

$$R=\frac{V'L}{\nu} \simeq 10^{3\sim4},$$

where $V' \simeq 500$ m/sec, L, the depth of the flow, $\simeq 1\mu$, and ν, the kinematic viscosity of liquid tungsten, is assumed to be $5\times10^{-4} \sim 5\times10^{-3}$ cm^2 sec^{-1}

deducing from the available data of other metals. The value of R suggests that this flow is turbulent. In such a case, the surface of the substrate is considered to be melted by heat transfer from the flow of the fused tungsten and mixed by the turbulent flow.

4-2 Melting of substrate and fluid-mechanical mixing of tungsten and substrate

1) Spraying tungsten onto a mild steel substrate

Since the flow of the fused tungsten is considered to be turbulent, the surface of the mild steel melted by this flow is mixed quickly with it. The solidifying temperature of this mixture may decrease to that of the mild steel since both metals are soluble in each other. We estimate, in rough approximation, the thickness of the melted layer of mild steel.

In Fig. 9, d is the depth of flow of liquid tungsten which is assumed to be one micron, X_L is the boundary between the liquid of mixture and the solid part of mild steel at time t. Denoting ΔX_L the increment of X_L in time Δt, the equation of heat flow is

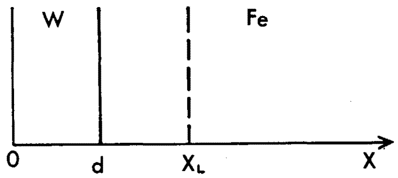


Fig. 9

$$-\lambda_1\left(\frac{\partial T_1}{\partial X}\right)=\frac{1}{\Delta t}\{(L_2\rho_2+C_{v2}\rho_2 T_{M2})\Delta X_L+C_{v2}\rho_2 T_{M2}\cdot\Delta X_2\} \quad . \qquad (1)^*$$

The left-hand side of the equation represents the rate of transfer of heat from the mixture of tungsten and mild steel to the solid mild steel, the right-hand side represents the mean of the heat required to melt the mild steel of thickness ΔX_L and to heat the solid portion of the mild steel with effective thickness ΔX_2 by heat diffusion in time Δt, T_1 and λ_1 are the temperature and thermal conductivity of the melted metal mixture respectively, and T_{M2}, C_{V2}, ρ_2 and L_2 are the melting temperature, the specific heat, the specific density, and the heat of fusion of the mild steel respectively. The last term of right-hand side of the equation can be neglected because ΔX_2 is small compared with ΔX_L as will be shown later. The temperature gradient at the boundary of the melted zone can be estimated as

$$\frac{\partial T_1}{\partial X}\simeq(T_{B1}-T_{M2})/kd \quad , \qquad (2)$$

* see Appendix

where T_{B1} is the initial temperature of the tungsten which is assumed to be equal to the boiling temperature of tungsten, and k is assumed to be 0.1 to 1.0. The former value of k corresponds to the turbulent flow in the earlier stage and the latter to laminar flow in the later stage of the impingement respectively. Using the following values

$$T_{B1} \simeq 5900\ ^\circ\mathrm{C},\quad T_{M2} \simeq 1540\ ^\circ\mathrm{C},$$

$$\lambda_1 \simeq 0.3\ \mathrm{cal/cm \cdot sec \cdot ^\circ C},\quad C_{V2} \simeq 0.11\ \mathrm{cal/g \cdot ^\circ C},$$

$$\rho_2 = 7.86\ \mathrm{g/cm^3},\quad L_2 \simeq 64\ \mathrm{cal/g}\quad ,$$

and assuming $\Delta t \simeq 10^{-8}$ sec, we obtain from Equation (1) and (2),

$$\Delta X_L \simeq 0.73\mu \sim 7.3\mu\quad .$$

The thickness of the melted layer of mild steel can be estimated in another way. Assuming that the tungsten is solidified and cooled to the temperature T_{M2} in time Δt, the equation of the total balance of heat is expressed as

$$\{L_1\rho_1 + C_{V1}\rho_1(T_{B1} - T_{M2})\}d$$
$$= (L_2\rho_2 + C_{V2}\rho_2 T_{M2})\Delta X_L + C_{V2}\rho_2 T_{M2} \cdot \Delta X_2\quad , \tag{3}$$

where C_{V1}, ρ_1 and L_1 are the specific heat, the specific density, and the heat of fusion of tungsten respectively, and ΔX_L is the thickness of the melted mild steel. The second term of the right-hand side of Equation (3) is the amount of heat diffused into the solid portion of the mild steel from the melted zone, and the effective thickness ΔX_2 is defined as the thickness of that portion heated up to a temperature higher than $1/2 \times T_{M2}$. Assuming one-dimensional conduction of heat with a boundary condition of constant temperature T_{M2} at one end and taking $t = 10^{-8}$ sec, we obtain

$$\Delta X_2 \simeq \sqrt{2\lambda_2 \Delta t / C_{V2}\rho_2} \simeq 0.4\mu, \tag{4}$$

Since the boundary between the melted and the solid mild steel moves, the actual value of ΔX_2 is much smaller than this. However, if ΔX_2 in Equation (3) is equal to this value and we put

$$L_1 \simeq 44\ \mathrm{cal/g},\quad C_{V1} \simeq 0.03\ \mathrm{cal/g \cdot ^\circ C},$$

$$\rho_1 \simeq 19.3\ \mathrm{g/cm^3},\quad d \simeq 1\ \mu\quad ,$$

then we obtain

$$\Delta X_L \simeq 1.5\mu\ .$$

Based on the values obtained by these two methods of estimation and the results of experiments reported above, we conclude that the depth of the melted and mixed layer of mild steel due to the impingement of a liquid tungsten drop is about 1∼2 μ, and that this layer is a solid solution of the two materials. On the other hand, the melted layer of the mild steel may spread further by the heat transfered from the already solidified mixed zone which is continuously heated by the successive deposition of liquid tungsten drops.

2) Spraying of tungsten onto a copper substrate

Using Equation (3), the thickness of the melted layer of a copper substrate can be calculated as spraying of tungsten onto a copper substrate

$$\Delta X_L \simeq 2.4 \ \mu \ ,$$

which agrees well with the observation of Fig. 7 (a), where $T_{M2} \simeq 1083$ °C, $C_{V2} \simeq 0.10$ cal/g·°C, $\rho_2 \simeq 8.93$ g/cm³ and$L_2 \simeq 51.0$ cal/g, and ΔX_2 as

$$\Delta X_2 \simeq 1.2 \ \mu \ ,$$

which is much larger than that of the mild steel, where $\lambda_2 \simeq 0.84$ cal/cm·sec·°C.

The process of mixing of liquid tungsten and copper is much different from that of tungsten and mild steel, since both metals are mutually insoluble in the former case and soluble in later. At the instant of impingement, the fused copper is pushed aside by the flow of tungsten and is partly mixed with it, and at the interface with tungsten, it is vapourized, because the boiling temperature of copper is lower than the melting temperature of tungsten. Consequently, the boundary line between the coating and the substrate is jagged and the solitary islands of copper are observed in the tungsten coatings as shown in Fig. 7 (b). Moeover a small quantities of copper is mixed in tungsten as shown in Fig. 8 (b) and Fig. 8 (c).

5. Structure and Adhesive Strength of the Bond between the Coating and the Substrate

In this section the adhesive strength of the coatings to the substrates, is discussed in correlation with the structures of the coatings and boundary layers as described above.

5-1 Tungsten coating on mild steel substrate

In the case of a tungsten coating on mild steel, a zone of solid solution of two materials is produced between the coating and the substrate. Numerous photographs of the secondary electron image, as illustrated in Fig. 6 (a), indicate that about seventy percent of the boundary between them is composed of these zones which have fairly uniform depths of about 1.5 μ and are considered to produce strong bonding between the coating and the substrate.

The two types of tests shown in Fig. 10 (a) and Fig. 10 (b) were adopted in this study to measure the shearing strength of the coating itself and the critical shearing stress of adhesion between the coating and the substrate respectively, since the strengths were too high to be measured by the conventional methods using epoxy resin. The results of these measurements are shown in Table 1. The strengths are much higher than those obtained for coatings deposited by other methods such as plasma and flame spraying. For example, as shown in Table 1, the adhesive strength of the high-carbon steel coating on the mild steel obtained by this method is about five times as great as that obtained by the flame spraying.

Fig. 11 (a) and Fig. 11 (b) show the composition image and W-L_α X-ray image of the shear-fractured surface of the test specimen respectively. It is shown in these figures that the fracture started and propagated inside the coating. This is confirmed by another experimental result that the shear-fracture stress in this case was 20~26 kg/mm^2 which was nearly equal to the general shear-fracture stress (~24 kg/mm^2) of the coating itself as measured by the method shown in Fig. 10 (a).

It may be concluded from these results that the welded zones of tungsten and mild steel form a strong adhesive bond between the coating and the substrate, furthermore the strength of coating itself is much greater than those obtained by the other conventional methods of spraying. Such high strength of coating itself and the strong bond between coating and substrate

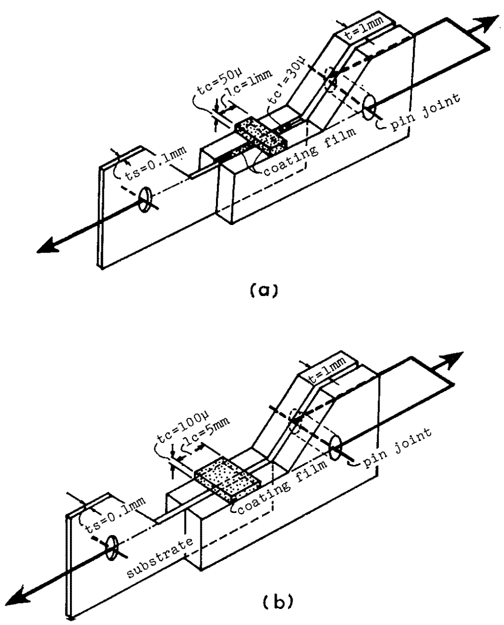


Fig. 10 Test specimen for measuring (a) shearing strength of coating, (b) critical shearing stress of adhesion of coating to substrate. *lc*: breadth of coating, *tc*: thickness of coating *ts*, *t*: thicknesses of test specimens

Table 1. Properties of Coatings by wire Explosion Spraying

	Substrate	Coating material		
		W	Mo	Piano wire
1. Surface roughness (ave. μ)	...	2.2	1.0	4.5
2. Relative density (%)	...	94.6	96.2	93.0
3. Hardness (H_v)	...	550	260	760~950
4. Oxygen content (%)	...	0.92	1.6	...
5. Shearing strength of coating (kg/mm²)	Mild steel	~24.8	~16.0	~42.3
6. Critical shearing stress of adhesion (kg/mm²)	Mild steel	19.6~26.5	16.3~18.8	23.0~26.8 (Flame spraying: 4.88)[4]
	Al	≧9.18	6.2~6.8	5.3~6.0
	Cu	8.6~13.5	6.5~9.0	~0
7. Wear* (Volume ratio) Rotor (dry)	SK-5	0.26	0.33	0.3
Stator	SK-5	1.0	0.87	...
8. Coefficient of friction	SK-5 (dry)	0.05~0.2	0.05~0.2	~0.2

* Volume ratio is 77.2~550 in wear test of SK-5 to SK-5.

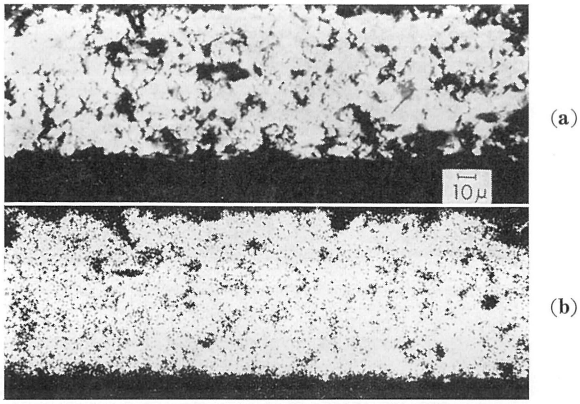
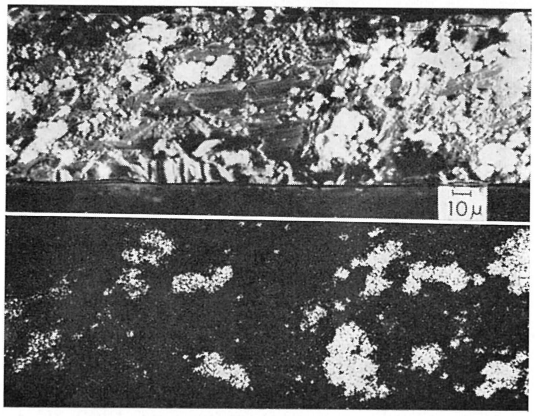


Fig. 11 Shear fractured surface of test specimen of mild steel coated with tungsten: (a) composition image, (b) W-L_α X-ray image by EPMA.

are attributed to the characteristics of the particles sprayed by wire explosion, i.e., the small size, the high temperature and the high impinging velocity and furthermore the uniformities of these characters of the sprayed particles.

5-2 Tungsten coating on copper substrate

Fig. 12 (a) and Fig. 12 (b) show the composition image and W-L_α X-ray image of the shear-fractured surface of the test specimen respectively. They show that the specimen fractured mainly along the boundary between the coating and the substrate in contrast to the case of mild steel. The measured shear-fracture stress is 9～13 kg/mm^2. This value is less than a half of that of a specimen of tungsten brazed with copper at 1600 °C in hydrogen atmosphere which fractured at 28 kg/mm^2 within copper itself. This weakness of the boundary may be attributed to the voids which remain along the boundary between the coating and the substrate. At the time of formation of the coating, a portion of the copper in contact with molten tungsten may be vapourized even after the tungsten has been solidified. This may cause a number of voids to remain in the boundary between the coating and the substrate after cooling.



(a)

(b)

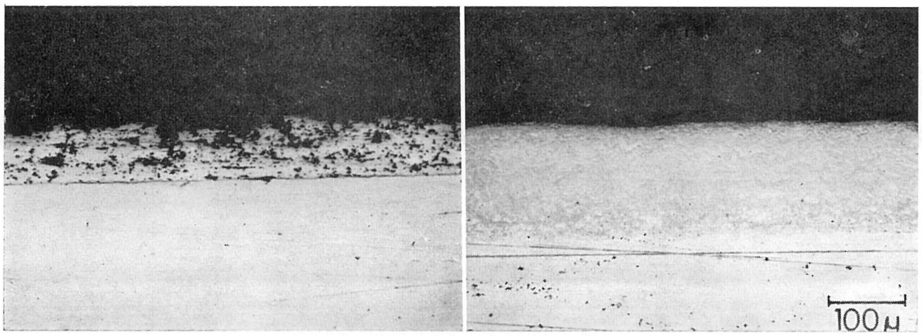
Fig. 12 Shear fractured surface of test specimen of copper coated with tungsten: (a) composition image, (b) W-L_α X-ray image by EPMA.

6. Improvement of Coatings

In general, coatings by wire explosion spraying have smaller porosities and higher strength compared with those obtained by flame plating[5]. However, the cemented carbide (e.g. WC-6.5 %Co) coating had comparatively large porosity and the breaking occurs from coatings [6]. For the purpose of the improvement of above-mentioned properties of these coatings, a diffusion process and a infiltration process were carried out on the coatings after spraying.

6-1 Diffusion process

The Ni-P (8～12 %) alloy was electronless plated on the WC-6.5Co alloy coating sprayed onto a mild steel substrate. Then the coating plated with Ni-P alloy was heated in a hydrogen atmosphere at 1000°C for 1 hr. The Ni-P alloy diffuses very rapidly in tungsten carbide, cobalt and iron[7], so the pores of the coating disappeared completely. The microstructure of the coating by this process is shown in Fig. 13 (b). The mutual diffusion phase with 5~6 μ in width was formed between the coating and the substrate. By this process the hardness of the coating increased from H_V 1050 to H_V 1400 and the adhesive strength increased from 4~7 kg/mm^2 to 15~25 kg/mm^2. Also the wear volume decreased to 1/12 in the wear test.



(a) (b)

Fig. 13 Cemented carbide coating on mild steel
(a) before diffusion treatment of coating,
(b) after Ni-P diffusion treatment.

6-2 Infiltration process

Copper was infiltrated in the WC-Co alloy coating on a high speed steel substrate by heating in a hydrogen atmosphere at 1300 °C for 10 min. The mutual diffusion phase of copper and iron at the boundary between the coating and the substrate was observed by this process. After infiltration, the hardness of the coating increased to about H_V 1700 and the adhesive strength increased to 15~20 kg/mm^2. But the properties of the substrate was not affected by heating, because the heating time in this process is short.

As mentioned-above, the diffusion process of Ni-P and the infiltration process of copper on the cemented carbide coating by wire explosion spraying improved the properties of the coating.

Appendix

The basic equations which describe the processes of melting and mixing of the substrate metal by the fused tungsten flow are as follows

$$\text{(A)} \quad \frac{\partial}{\partial t}(C_{V_2}\rho_2 T_2)=\lambda_2\frac{\partial^2 T_2}{\partial X^2}, \quad X>X_L$$

(B) $-\lambda_1 \frac{\partial T_1}{\partial X} = L_2 \rho_2 \frac{\partial X_L}{\partial t} - \lambda_2 \frac{\partial T_2}{\partial X}, \quad X = X_L$

(C) Equations of the turbulent flow of the mixture of the liquid tungsten and the liquid substrate for $X < X_L$.

Since it is difficult to solve the Equations (A) to (C), we shall approximate the solution by taking the average of Equation (B) with respect to t from 0 to Δt.

The average value of the left hand side of Equation (B) is

$$\overline{-\lambda_1 \frac{\partial T_1}{\partial X}} = \frac{1}{\Delta t} \int_0^{\Delta t} \left(-\lambda_1 \frac{\partial T_1}{\partial X} \right)_{X = X_L} dt,$$

and the average value of the first term of the right-hand side of (B) is $L_2 \rho_2 \cdot \Delta X_L / \Delta t$. Integrating (A) with respect to X,

$$-\left(\lambda_2 \frac{\partial T_2}{\partial X} \right)_{X = X_L} = \int_{XL}^{\infty} \frac{\partial}{\partial t} (C_{V2} \rho_2 T_2) dX$$

$$= \left(\frac{\partial X_L}{\partial t} \right) C_{V2} \rho_2 T_{M2} + \frac{\partial}{\partial t} \int_{XL}^{\infty} C_{V2} \rho_2 T_2 dX,$$

the average value of the second term of right-hand side of (B) is

$$\frac{1}{\Delta t} \int_0^{\Delta t} \left(-\lambda_2 \frac{\partial T_2}{\partial X} \right)_{X = X_L} dt = C_{V2} \rho_2 T_{M2} (\Delta X_L + \Delta X_2)) / \Delta t,$$

where ΔX_L is the thickness of melted layer of the substrate and ΔX_2 is the effective thickness of the heated layer of the substrate of solid part defined as

$$(C_{V2} \rho_2 T_{M2} \Delta X_2)_{t = \Delta t} = \int_{XL(t = \Delta t)}^{\infty} C_{V2} \rho_2 T_2 dX,$$

then we obtain the quation (1).

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