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Abrasive Wear Resistance of Overlay Composite Alloy with Addition of Carbide Powders*

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Abstract

The overall objective of this project is to provide data showing how carbide powder in addition to base alloy powder can be used effectively to increase hardness of overlay alloy and resistance to abrasive wear. An experimental study was performed to examine combinations of base alloy powders and reinforcing powders. The base alloy powders considered were stainless steel, Ni-base alloy, Co-base alloy and high speed steel powder, while reinforcing powders considered were metal-carbide and ceramic powders. The overlay alloys were produced from base alloy or carbide or ceramic dispersion by plasma transfer arc powder welding.

To assess the wear resistance of overlay alloy a rubber wheel abrasion test was performed on its surface. The weight loss due to wear of overlay alloy with addition of reinforcing powder was lower than that of base overlay alloy only due to the existence of primary carbides and non-fused carbide particles in it. Especially, the abrasive wear resistance of overlay alloy depended on the volume fraction of primary carbides and non-fused carbide particles.

The addition of carbide powder, especially Ti-carbide, to high speed steel powder increases effectively the hardness of overlay alloy, and hence increases resistance to abrasive wear of it.

Key Words: *Plasma transfer arc powder welding, Base alloy powder, Reinforcing powder, Carbide dispersion type overlay alloy, Non-fused carbide particle, Resistance to abrasive wear*

1. Introduction

In general, Co-base alloy, Ni-base alloy powder and these powders mixed with Cr-carbide[1)], W-carbide[1)] and Nb-carbide[2−3)] powder were used for hardfacing overlay alloy on a plasma transfer arc overlaying process (PTA). The PTA method has some merits to give necessary properties to plate surface of popular materials and to produce easily an overlay alloy by the use of different powders.

These overlay alloys were applied on many parts of machines and many kinds of rollers which were required to possess hardenability, resistance to corrosion, resistance to heat and resistance to wear. As for those properties of overlay alloys, for example, resistance to wear at sliding parts of machine, even if the overlay alloys consist of same compositions, the degree of wear resistance differs between sliding wear and abrasive wear. The compositions of overlay alloy may be selected depending on whether the type of wear is abrasive or sliding, but in the materials design for the overlay alloys it is not clear how their compositions decide a wear resistance in use. And combinations of plural powders, morphologies of microstructure, hardness and other properties of overlay alloys were not discussed systematically[4−6)].

The present work was carried out to study the morphologies of microstructures and carbides, to estimate hardness and resistance to abrasive wear under existence of carbide in overlay alloys, and to investigate the effect of mixing combinations of base alloy powders and carbide powders on the resistance to abrasive wear.

2. Experimental procedure

2.1 *Materials*

In this experiment, a commercial SS400 plate was used as substrate plate. Stainless steel, Ni-based alloy, Co-based alloy and high speed steel powders were used as base alloy powders. Ti-carbide, V-carbide, Nb-carbide, W-carbide, Cr-carbide and Mo-carbide, and SiC, Al_2O_3 and Zr_2B powders were used as reinforcing powders for overlay alloys. Table 1 shows their chemical compositions and distributions of powder size.

The mixing ratio of base alloy powder and reinforcing powder was 70:30 mass percentage for carbide powder series and 95:5 mass percentage for ceramic series powder. The mixing powders added with C_2H_5OH and HCP binder were pre-heated at 373K for 7.2 ks and passed through a 50-mesh sifter. Then the

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Table 1 Chemical compositions of substrate and powders used (mass%), and distributions of powder size.

Materials		C	Si	Mn	Ni	Cr	Mo	Fe	Distribution of powder size, mass% +177	+149	+108	+74	-74, µm	Melt. Temp., K
Substrate	SS400 a)	0.14	0.41	0.89	0.01	0.02	0.01	bal.	—					—
Base alloy powders	(A) Stainless steel b)	0.02	0.99	0.12	10.32	18.97	0.02	bal.	—	2.1	41.4	47.0	9.5	—
	(B) Ni-base alloy c)	0.26	3.61	—	bal.	7.66	—	2.36	0.4	6.8	35.2	34.2	23.4	—
	(C) Co-base alloy d)	1.30	1.20	0.70	0.20	30.40	0.01	0.10	0.2	5.2	35.8	33.8	25.0	—
	(D) High speed steel e)	1.92	0.34	0.32	—	6.69	3.8	bal.	—	—	47.7	35.2	17.1	—
		Total C	Free C	Fe	Mo	Si	Al							
Reinforcing powders	Ti-C	19.45	0.08	—	—	—	—	bal./Ti	0.1	5.1	71.2	22.9	0.7	3423
	V-C	17.29	0.14	0.82	—	—	—	bal./V	—	2.8	58.4	37.4	1.4	3123
	Nb-C	11.37	0.01	0.10	—	—	—	bal./Nb	0.1	0.1	22.6	74.1	3.1	3873
	W-C	6.10	0.03	0.05	0.03	—	—	bal./W	—	9.8	67.0	23.0	0.2	3058
	Mo-C	5.91	0.08	—	—	—	—	bal./Mo	—	10.0	9.1	6.0	74.9	2963
	Cr-C	9.98/C	—	0.45	—	0.15	0.29	bal./Cr	—	23.0	—	44.1	32.9	2163
	Si-C	88.4/SiC	—	—	—	—	—	—	21.4	28.0	19.1	13.2	18.3	—
	ZrB_2	0.06/C	19.43/B	0.52/O	0.24/N		—	bal./Zr	0.2	0.2	0.2	0.9	98.5	—
	Al_2O_3	96.3/Al_2O_3	2.2/TiO_2		0.08/Fe_2O_3		0.52/SiO_2		10.7	75.0	13.8	0.4	0.1	—

Others compositions; a) 0.028%P, 0.021%S, 0.02%Cu, b) 0.022%P, 0.005%S, 0.01%Cu, c) 1.62%B, d) 4.70%W bal./Co, e) 0.017%P, 0.002%S, 4.33%W 5.74%Co 5.04%V

powders were heated at 433K for 7.2 ks and passed through a 200-mesh sifter, the size of powder arranged was about 300µm in diameter.

2.2 *Procedure of overlay alloys*

The overlay alloys were produced using PTA apparatus. The mixing powders were put into the hopper and were carried to the plasma arc column in Ar gas flow of 1.33 l/s. The feeding speed was 0.75 g/s.

The conditions of PTA were only a little changed by the combinations of powders, but pre-heating temperatures were 373K-473K, welding currents were 145A-155A and welding voltages were 30V-34V for a series of stainless steel powders (A-series). For series of Ni-based alloy powder (B-series), the conditions were respectively 523K-623K, 130A-150K and 30V-34V. For a series of Co-based alloys (C-series) they were 423K-573K, 130A-160A and 28V-34V. And for a series of high speed steel powders (D-series) they were 473K-573K, 130A-160A and 28V-34V respectively. The welding speed was constant at 1.1 mm/s except for Al_2O_3 of C-series, for which it was 1.50 mm/s. The oscillation width was 20 mm and the oscillation frequency was changed 0.83-1.00 cycles/s

2.3 *Observations of microstructures and measurements of hardness for overlay alloys*

The appearance of surface and existence of surface crack in overlay alloy were inspected by the penetrant test. The microstructures at a cross section perpendicular to overlay alloys were observed by optical microscope and SEM. The component elements were examined by EDX and EPMA. Certain kinds of reinforcing powders were partially melted at the surrounding of carbide called non-fused carbide particles in the overlay alloys. The volume fraction of primary carbides and non-fused carbides were measured by point counting method. The hardness was measured by Rockwell hardness test with C-scale of 1470N load and micro-Vickers hardness test with 9.8N load.

2.4 *Method of abrasion test*

A rubber wheel abrasion test was performed on surface of overlay alloys according to ASTM-G65-81[7]. The specimen dimensions were 20w×45l×20h mm. The plane of abrasion test was located at 2 mm inside from the surface of overlay alloy and was polished with No. 500 emery paper. The specimen was set on the apparatus and imposed with a load of 86.24N applied to a rubber wheel of 250 mm diameter which made 2 revolutions per second. Silica sands of 200µm size were used as abrasive sand and dropped between the specimen and the rubber wheel at a rate of 4.3-5 g/s. The weight loss of specimen by wear was a difference between the weight before the test and the weight after 3000 r.p.s. The abrasion morphologies of specimens after the test were observed by SEM.

3. Results

3.1 *Surface morphologies of overlay alloys*

Most of powders were smoothly carried to the plasma arc column and contributed well in the formation of bead without Mo-carbide and Zr_2B powders which were initially too small. The overlay alloys with SiC and Al_2O_3 powders included many blowholes and the surfaces of overlay alloys were not smooth with an irregular formation of slag on bead.

Transverse cracks were observed on the surface of overlay alloy by penetrant test. The powder combinations of overlay alloys with cracks were Ti-carbide/Ni-based alloy powder and /high speed steel powder, W-carbide/stainless steel powder, /Ni-based alloy powder and /Co-based alloy powder, and SiC/Co-based alloy powder and /high speed steel powder.

3.2 *Microstructures of overlay alloys*

In the case of base alloy powders only, the microstructure consisted of dendritic structure in all base

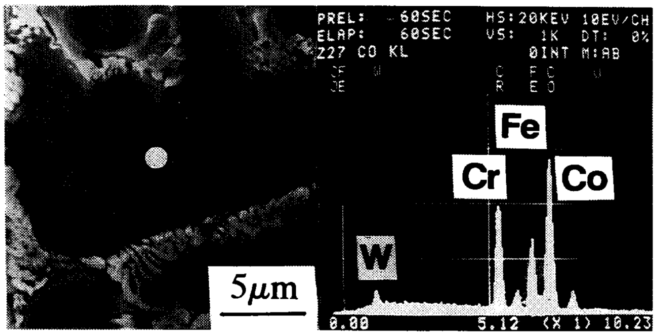

Fig. 1 X-ray analysis of matrix in the base overlay alloy C.

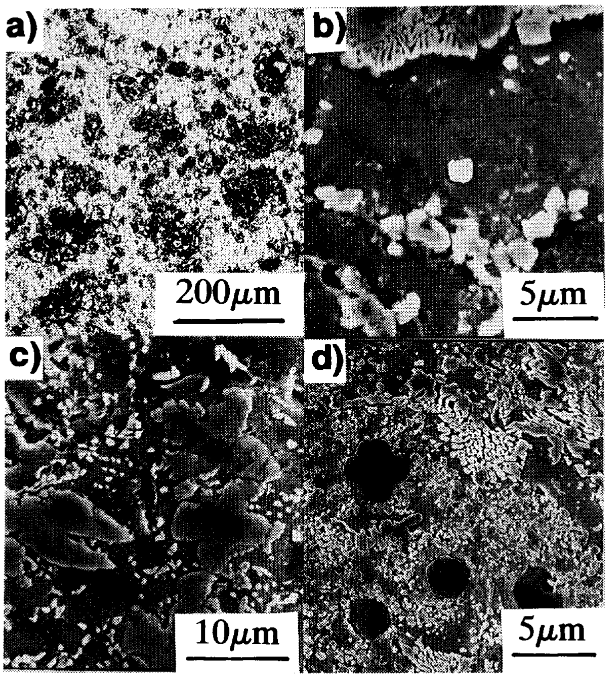

Fig. 2 Shape of carbides in overlay alloy, (a) base alloy powder A/Ti-C, (b) base alloy powder C/Ti-C, (c) base alloy powder A/Nb-C and base alloy powder D/V-C.

overlay alloys. For example, the microstructure of the Co-base overlay alloy consisted of Co solid solution with eutectic carbide as shown in Fig. 1.

In the case of the reinforcing powder mixed into the base alloy powder, the microstructure was as shown in Fig. 2. In overlay alloys mixed with Ti carbide, most of Ti carbide powders remained in the initial shape, but many fine carbide particles existed around a coarse Ti carbide as shown in Fig. 2(a) and (b). Nb and V carbides were observed as primary crystal NbC and VC as shown in Fig. 2(c) and (d). Ti, Nb and V easily form a stable binary carbide like a stable NaCl type cubic, because their standard formation free energies for carbide are relatively low and their carbides do not form a three-dimensional carbide[8-9]. Although melting temperatures of their carbides are high, they melt and form a primary crystal in overlay alloys. In the case of mixed W carbide powder, center of powder was non-fused zone and was surrounded by a partially melted zone which consisted of W and C as shown in Fig. 3(a). In the case of mixed Cr carbide powder, the outside of Cr carbide melted and the melted carbide turned into an acicular shape carbide in a radial manner as shown in Fig. 3(b) and (c). The acicular carbide consisted of complex carbides like $(Fe, Co)_3C$, $(Cr, Fe)_7C_3$ and $(Cr, Fe)_{23}C_6$. The standard formation free energies of W- and Cr-carbide are relatively high, therefore W and Cr do not form a stable binary carbide, their carbide melted from outside and the acicular shape carbide consisted of complex carbide[8-9]. In the case of mixed Mo carbide powder, it melted in matrix because initial size of the powder was too small.

Microstructure of overlay alloys consisted of dendritic structures, primary crystal, acicular carbide and non-fused carbide. Table 2 shows the volume fractions of carbides and non-fused carbides. When Ti-carbide powder was added to based alloy powder, its volume fraction was high and the distribution of its carbide was fine. The V-carbide and Nb-carbide were distributed widely as numerous particles. The distributions of W- and Cr-carbides were nonuniform

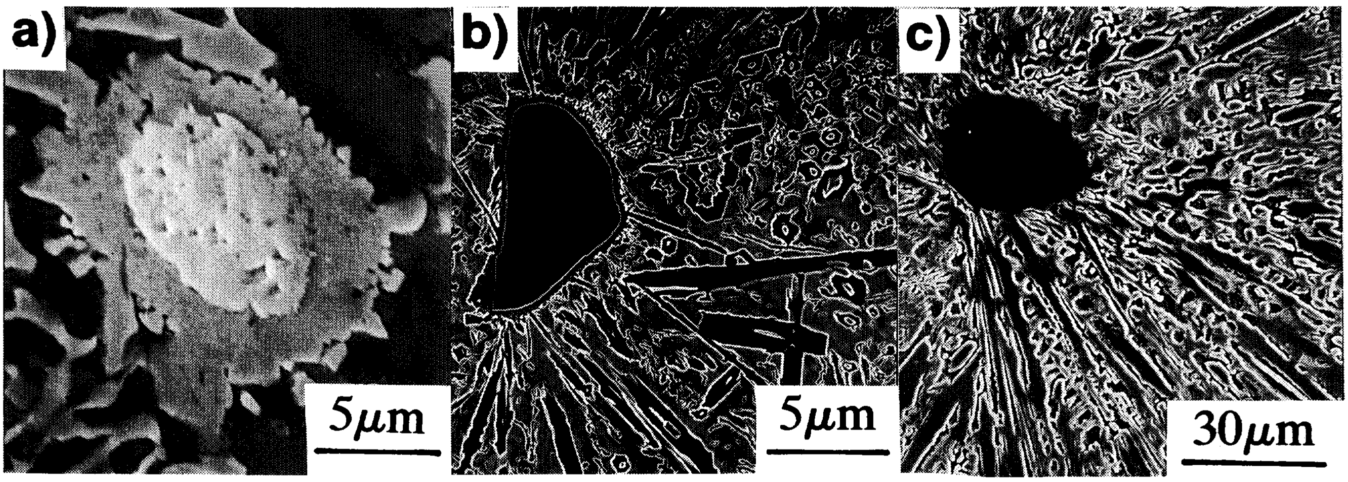

Fig. 3 Fusion of reinforcing powder in overlay alloy, (a) base alloy powder D/W-C, (b) base alloy powder B/Cr-C and (c) base alloy powder D/Cr-C.

Table 2 Volume fraction of carbides and non-fused carbide particles in overlay alloy.

Reinforcing powder	Series A	Series B	Series C	Series D
Ti−C	36.94	40.64	32.95	40.41
V−C	10.82	24.75	22.91	23.52
Nb−C	18.53	16.68	18.80	20.33
W−C	6.41	12.70	5.42	7.06
Mo−C	1.17	4.44	3.36	3.21
Cr−C	5.35	6.09	3.59	1.82

because the carbides were radially surrounded by the acicular shape carbide. The volume fraction of Mo-carbide was lower because the initial size of the powder was too small and the powder melted in matrix.

3.3 *Hardness of overlay alloys*

Hardnesses of above-mentioned structures differed between matrix and carbide depending on the combination of powders. Fig. 4 shows hardness of matrix for overlay alloy.

Hardnesses of matrix for A- and C-series were higher than those of base overlay alloys. Hardnesses of matrix including Ti-carbide and Mo-carbide in B-series, and Ti-carbide in D-series were higher than that of base overlay alloy. It seems that the increase of hardness is caused by melted carbides with reinforcing powders. The additions of the reinforcing powders enhanced the hardness of matrix with the fusion of their powder and its hardness was higher than that of the base overlay alloy. But, when the hardness of base overlay alloys was higher, for example D-series, the addition of reinforcing powder did not effectively increase the hardness of matrix unlike addition of Ti-carbide and Mo-carbide as shown in Fig. 4(d). The addition of SiC, Zr_2B and Al_2O_3 powders did not affect hardness of matrix.

3.4 *Weight loss of overlay alloys by wear*

The wear of overlay alloys was estimated by weight loss as shown in Fig. 5. Comparing the four base alloy powders, the weight loss of Ni-base alloy powder (B-series) was the greatest in quantity, and the order of the weight loss was Co-base alloy powder (C-series), stainless steel powder (A-series) and high speed steel powder (D-series).

When base alloy powder and reinforcing powder were mixed, the weight loss was lower than base overlay alloy only. In the case of same reinforcing powder added to four base alloy powders, the weight losses in A-, B- and C-series were much the same, but the weight loss in D-series exhibited obviously a tendency to decrease.

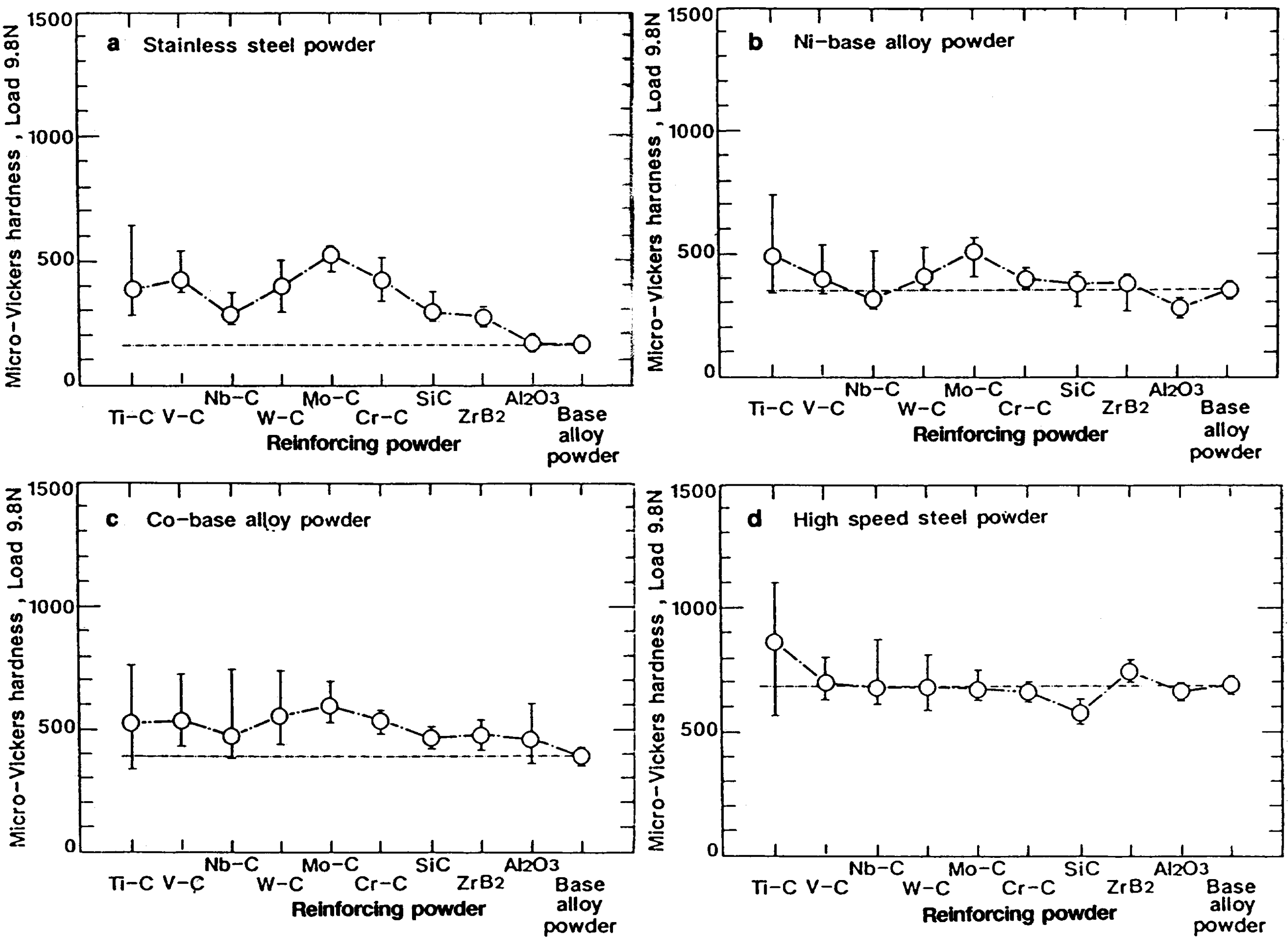

Fig. 4 Vickers hardness of matrix for overlay alloys with base alloy using various reinforcing powders.

The weight losses of overlay alloys with Ti- and V-carbide were lower than others. The order of weight loss was the reinforcing Nb-, W-, Cr- and Mo-carbide powder. The addition of SiC was ineffective for reducing wear loss.

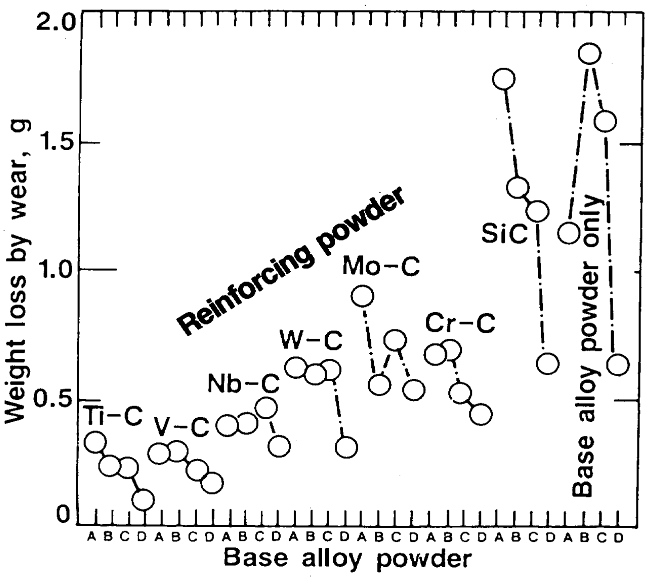

Fig. 5 Result of sand abrasive wear test for overlay alloy with base alloy using various reinforcing powders.

Fig. 6 shows the wear surface of the specimen after wear test. The wear marks were observed on the surface of the base overlay alloys as shown in Fig. 6(a). On the other hand many particles were observed with protrusions on the wear surface of the specimen with reinforcing powders. The particles which projected on wear surface were non fused carbide particles as shown in Fig. 7, and therefore non-fused carbide particles had a resistance to abrasive wear.

4. Discussions

4.1 *Effect of the volume fraction of carbides and non-fused carbide particles on the resistance to abrasive wear*

The morphologies of abrasive wear depend on the mixed reinforcing carbide, the hardness of matrix and the existence of carbide and non-fused carbide particle. Fig. 8 shows the effect of volume fraction of carbide and non-fused carbide particle on weight loss by wear and also shows the test results of abrasive wear about other mixing ratios of Nb- and W-carbide powders to A- and B-base alloy powders. The weight loss decreased with an increasing volume fraction of non-fused carbide. The carbide and non-fused carbide in overlay alloy is effective to improve resistance to

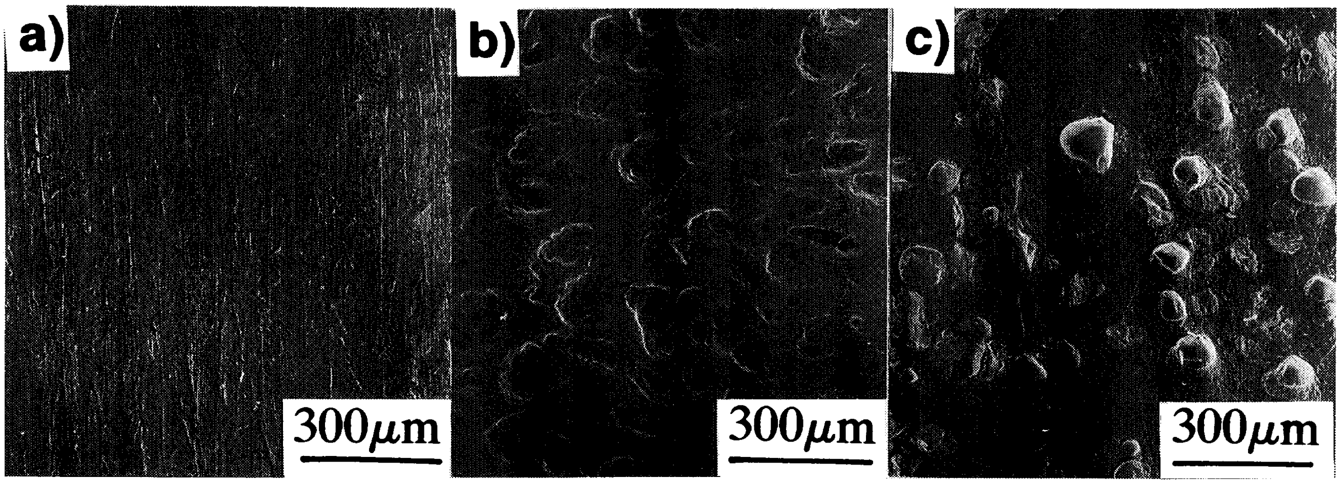

Fig. 6 Wear surface after wear test, (a) base overlay alloy D, (b) base alloy powder D/Ti-C and (c) base alloy powder D/Nb-C.

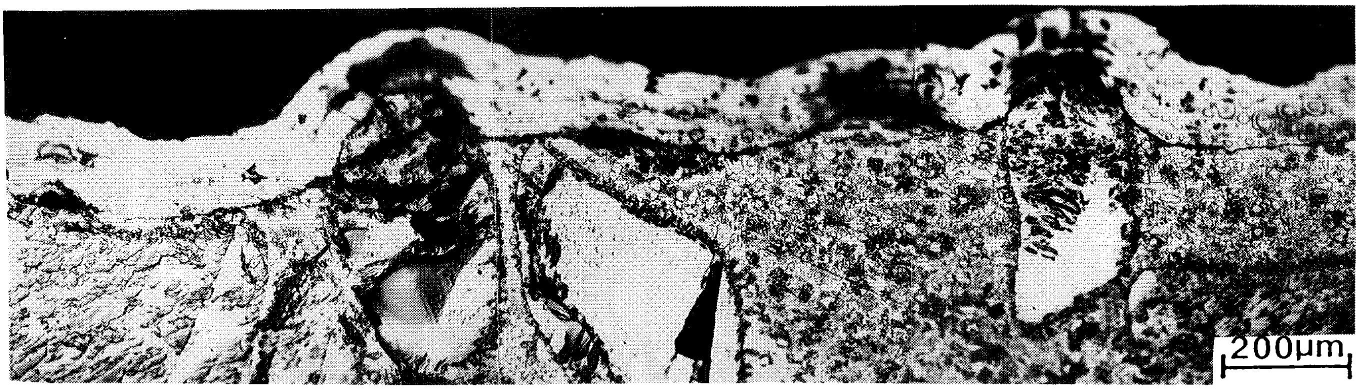

Fig. 7 Cross section of wear surface, (base alloy powder C/V-C).

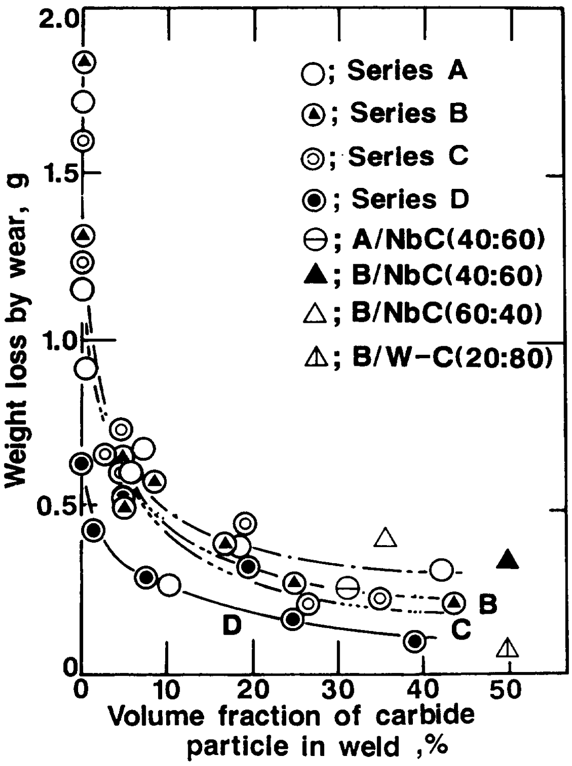

Fig. 8 Effect of volume fraction of carbides and non-fused carbide particles in overlay alloy on weight loss by wear.

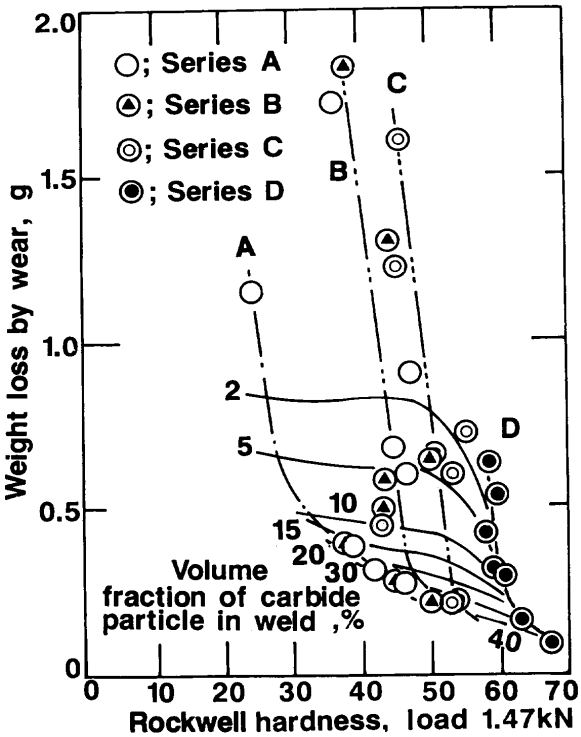

Fig. 9 Relation among weight loss by wear, Rockwell hardness and volume fraction of carbides and non-fused carbide particles in overlay alloys.

abrasive wear.

4.2 *Effect of the hardness on the resistance to abrasive wear*

The microhardnesses of overlay composite alloys differ depending on the matrix and the existence of carbide and non fused carbide. Then, the resistance to abrasive wear was evaluated using Rockwell hardness as macroscopic hardness. Fig. 9 shows the relation among the weight loss by wear, Rockwell hardness and the fraction of carbide and non-fused carbide. In all series of overlay alloys with a reinforcing powder, the weight loss by wear decreased with an increasing hardness and the weight loss was minimum at HRC 68, which is close to the silica sand hardness of HRC 69.5. However, there is a scatter in some experimental points depending on the reinforcing powder used. As for the data of the A-series, B- and C-series, except D-series the weight loss did not necessarily depend on hardness.

4.3 *Effect of the reinforcing powder on the resistance to abrasive wear*

The kinds of base alloy powders, the kinds of the reinforcing powders and the fraction of carbides and non-fused carbide particles affected the weight loss of overlay alloys by abrasive wear.

Comparing the four kinds of base alloy powders, the weight loss of Ni-base alloy powder (B-series) was the greatest in quantity, the order of the weight loss being Co-base alloy powder (C-series), stainless steel powder (A-series) and high speed steel powder (D-series).

The alloy with Ti- and V-carbide suffered less weight loss than the others. The weight loss increased in the order of the reinforcing Nb-, W-, Cr- and Mo-carbide powder. Ti, Nb and V easily form a stable binary carbide like a stable NaCl type cubic. In the case of mixed W carbide powder, the carbide powder formed a non-fused zone at center of powder surrounded by a partially melted zone. In the case of mixed Cr carbide powder, a Cr carbide melted from outside and the melted carbide turned into an acicular shape carbide arranged in a radial manner.

The protrusion of many particles was observed on the wear surface of the specimens with the reinforcing powders. The particles which projected on wear surface were non-fused carbide particles and therefore non-fused carbide particles had a resistance to abrasive wear.

In the case of mixed Mo-carbide powder, it melted in matrix because initial size of the powders before the arrangement was too small, but Mo-carbide effectively increased the hardness of matrix and decreased its wear loss. In the addition of SiC powder, its powder melted in the matrix, but hardness did not decrease and the addition of the powder was ineffective for decreasing the wear loss.

The additions of certain reinforcing powders enhanced the hardness of matrix with the fusion of these powders and its wear resistance was higher than that of the base overlay alloy, but when hardness of base overlay alloys was higher, for example D-series, the addition of reinforcing powder did not effectively increase the hardness of matrix unlike addition of

Ti-carbide and Mo-carbide. The addition of Ti-carbide can be used effectively to increase the hardness, and resistance to abrasive wear.

The carbides and non-fused carbide particles in overlay alloy are effective to improve the resistance to abrasive wear. Therefore, the abrasive wear resistance may be improved through selection of the combinations of base alloy powder and reinforcing powder and may increase the volume fraction of carbide and non-fused carbide particles. Under the wear condition of this work, the suitable combination of those was that of high speed steel powder with Ti-carbide.

5. Conclusions

1. The overlay alloys consisted of matrix, eutectic carbides, primary carbides and non-fused carbide particles.

2. The average hardness of matrix for high speed steel powder was higher than those of other powders used. The hardnesses of the overlay alloys with addition of some reinforcing powders were higher than that of each base overlay alloy only.

3. The weight losses of overlay alloy with addition of reinforcing powder were lower than that of base overlay alloy only, due to the existence of carbides and non-fused carbide particles in it.

4. The abrasive wear resistance of overlay alloys depended on the increase in the volume fraction of carbides and non-fused carbide particles. The carbides and non-fused carbide particles in overlay alloy are effective means to improve the resistance to abrasive wear.

5. The improvement of abrasive wear resistance may be achieved by selecting the combinations of base alloy powder and the reinforcing powder and increasing the volume fraction of carbide and non-fused carbide particles. Under the wear condition of this work, the suitable combination of those was that of high speed steel powder with Ti-carbide.

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