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Corrosion and wear behaviors of ferrous powder thermal spray coatings on aluminum alloy

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Abstract

Atmospheric plasma spray coating was performed on a cast AA383 Aluminum alloy plate, and this process formed a 170-μm thick spray coating layer by using tentative Fe–C powders with nickel added (up to 14 mass%) or without supplementary nickel. Hardness test, microstructure observation, corrosion and wear tests in engine oil with or without sulfuric acid water solutions added were performed as well. The corrosion performance was dependent upon the nickel content. On the contrary, the wear resistance testing under two engine oil lubrication conditions (with or without sulfuric acid water solution) showed the different tendency instead.

Keywords: Plasma; Thermal spraying; Corrosion; Wear; Diesel engine

1. Introduction

In order to achieve more weight reduction for automobile diesel engine, aluminum cylinder block without cast iron liner treatment (liner-less) is expected to put into practical use soon. Yet, diesel fuel's impurity 'sulfur' element and corrosive attack possibility, such as sulfuric acid generated to the liner surface is higher than gasoline fuel [1,2]. For that reason, wear and corrosion resistances on the inner surface of cylinder-bore are required in order to perform those liner-less aluminum cylinder blocks effectively. For the time being, coating technologies for cylinder-bores have been investigated from the material and method point of view [3–5]. This research is intended to accomplish both performances—wear and corrosion resistances—using plasma thermal spray technology.

2. Experimental details

2.1. Material

One substrate of AA383 Al–11.9 mass% Si–2.4 mass% Cu–0.8 mass% Fe–0.8 mass% Zn–0.3 mass% Mn–0.3 mass% Mg alloys casting was used for cylinder block. As for the spray material, five types of ferrous powders Fe–C–Ni–Cr–Cu–V–B alloys (Ni-1 to Ni-5) with nickel content from 4 to 14 mass% (other elements are fixed) were used in our experiment. Three types of cast iron powders: Fe–C–Si–Cr–Sn alloys (G-1) for cylinder block, Fe–C–Si–B alloy (G-2) for liner material, and Fe–C–Si–Mo–B alloy (G-3) for liner materials were also used for our experiment. The chemical compositions of these tentative powders are shown in Table 1.

2.2. Spray conditions

Atmospheric plasma spraying (APS) was utilized in our experiment. Before the spraying process, blast treatment was performed on aluminum alloy substrate with alumina particle size 710–850 μm. Test pieces were prepared in rectangular parallelepiped shape with size $17\times15\times70$ mm^3. The 170-μm thick-coated layers were obtained after the coating process, and also the spray conditions are described below.

(a) Spray distance: 50 mm (selected from the coating point of inner surface cylinder-bore), (b) current: 400 A, (c) voltage: 50 V, (d) traverse speed: 15 m/min, (e) traverse pitch: 6 mm, (f) pass number: 3.

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Table 1
Chemical compositions of test powders

Powder	Chemical composition (mass%)												
	C	Si	Mn	P	S	Cu	Ni	Cr	V	Mo	Sn	B	Fe
Ni-1	2.95	1.81	0.08	0.004	0.004	3.96	4.04	1.49	0.75	–	–	0.074	Balance
Ni-2	2.98	1.95	0.04	0.003	0.004	3.96	6.42	1.44	0.74	–	–	0.078	Balance
Ni-3	2.84	2.12	0.08	0.004	0.004	3.96	8.83	1.49	0.73	–	–	0.078	Balance
Ni-4	2.95	2.01	0.03	0.004	0.003	3.99	11.21	1.42	0.75	–	–	0.077	Balance
Ni-5	2.93	2.00	0.05	0.003	0.004	3.93	13.59	1.45	0.75	–	–	0.076	Balance
G-1	3.11	2.16	0.68	0.013	0.005	0.75	0.04	0.41	–	–	0.12	–	Balance
G-2	3.26	1.83	0.75	0.036	0.007	0.02	0.02	0.04	–	–	–	0.082	Balance
G-3	3.39	2.04	0.74	0.038	0.008	0.02	0.02	0.04	–	0.63	–	0.045	Balance

2.3. Corrosion testing

Corrosion resistances of coatings were evaluated after the test piece was dipped in 20 mass% sulfuric acid water solutions for 95-h. In order to evaluate only the coating surface, test piece was located into a special jig with sealing rubber to prevent sulfuric acid water solution from penetrating into the aluminum substrate part. During the test, weight of test piece was measured at each appointed checking time.

2.4. Wear testing

Wear resistances of coatings were examined by using one reciprocation motion type testing equipment under two wet conditions—engine oil mixed with or without sulfuric acid water solution (3.6 vol.%). Chromium-plated pin with coating thickness 50–150 μm was used as a counterpart. Wear test was performed at 240-rpm cycle time, 50 mm per stroke, and 98 N load condition. Test pattern is 10-h wear test followed by 14-h stop/hold and then 10-h wear test again, so the actually total wear testing time is 20 h. The maximum wear depth was measured using 'Talysurf S5C' picture image analyzing method by scanning the surface of the test pieces with 2 μm radius of stylus tip.

3. Results and discussion

3.1. Microstructure observation

No crack was found in coating and no abrasion was observed at the interface between coating and substrate in all of the coatings, and the cross-section of typical Ni-3 coating was shown in Fig. 1. Transmission electron microscopy (TEM) revealed that coating structures of Ni-1 to Ni-5 consist of austenite (γ-Fe) with fine cellular structures, fine grain structure, and twin structure. The typical cellular structures of Ni-4 and Ni-5 were shown in Fig. 2. From this figure, it is believed that the Ni-5 structure is finer than Ni-4, and also no compound like carbide has been observed in each structure.

3.2. Corrosion resistance

Corrosion test results of 95-h dipping in 20 mass% sulfuric acid water solutions is shown in Fig. 3. Those Ni containing alloys (Ni-1 to Ni-5) show superior corrosion resistance than Fe–C alloys (G-1 to G-3). It

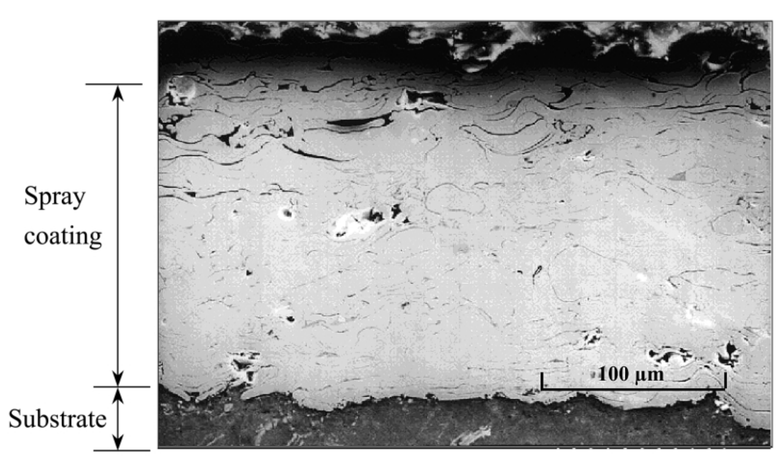

Fig. 1. Cross-section of spray coating: powder Ni-3 (Fe–2.8 C–2.1 Si–4.0 Cu–8.8 Ni–1.5 Cr–0.73 V–0.08 B).

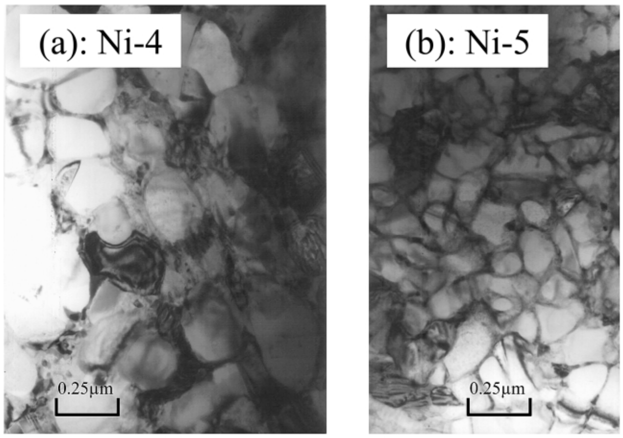

Fig. 2. Typical TEM microstructures of spray coatings (magnification: ×60 000).

is proved that corrosion resistances depend on the nickel content and increase with rising the nickel content of powders. Basically, the Fe–C material (the coatings of liner material powders) without nickel (G-1 to G-3) melted completely within 10 h. Therefore, these alloys show lower level of corrosion resistance.

3.3. Wear resistance

Fig. 4 shows the summary test results of wear test. The maximum wear depths of spray coating and counter pins are compared. The upper and lower data show the wear results at engine oil lubricant conditions mixed with sulfuric acid water solution or without, respectively. In general, wear resistance degraded as nickel content increased in both coatings and counter pins, also the maximum wear depth was increased along with mixed sulfuric acid water solution compared to pure engine oil case. In the pure engine oil condition, the maximum wear depth decreased with increasing the hardness of coatings, which is well-known phenomena, as shown in Fig. 5. The hardness of the coatings decreased as nickel

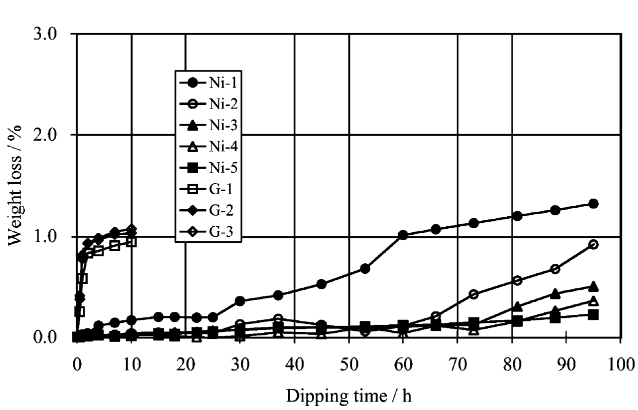

Fig. 3. Corrosion test results of spray coatings.

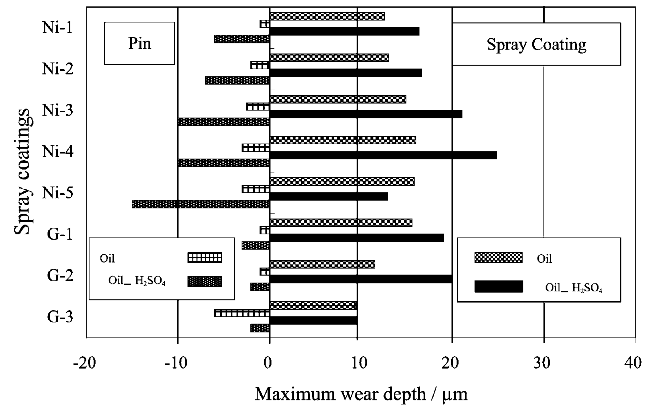

Fig. 4. Maximum wear depth of test piece (spray coating) and counter pin under different wet conditions.

contents increase, also the wear resistance decreased with the nickel content increase. In the situation of engine oil mixed with sulfuric acid water solution, only the highest nickel content Ni-5 coating and molybdenum content ferrous G-3 coating showed a good wear resistance. Comparing Ni-5 with Ni-4, hardness of the coating was almost the same level, but microstructure of Ni-5 was finer than Ni-4 as shown in Fig. 2. It is believed that finer structure has higher potential against sulfuric acid water solution attack through the interface of cellular structure. Excellent wear property of G-3 coating is considered because of its pearlite structure and molybdenum effect [6].

4. Summary

(1) Corrosion resistance of plasma spray coatings of Fe–C–Ni–Cr–Cu–V–B alloy against sulfuric acid water solution was increased as the nickel content increase.

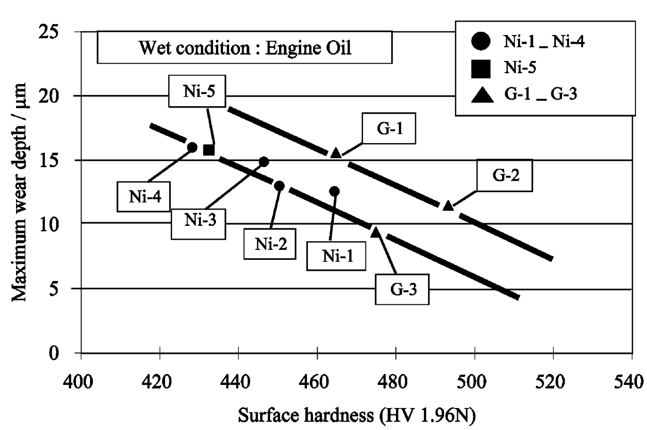

Fig. 5. Relation between surface hardness of coatings and maximum wear depth at wet wear condition of engine oil.

(2) Wear resistance was decreased in engine lubrication oil as the nickel content increase, due to the declining of coating's hardness.

(3) There is no relationship between wear resistance and nickel content of the coatings in the engine oil mixed with sulfuric acid water solution. For example, in the range of 4.04–11.21 mass% Ni; wear resistances of both coating and counter pin decreased with the nickel content increase. But, the highest nickel content powder (13.59 mass%) showed a good wear resistance of the coating, although the damage of counter pin was increased.

(4) Nickel plays a trade-off role in corrosion and wear resistances. As a result, suitable nickel content for ferrous powder should be investigated further.

(5) Molybdenum containing Fe–3 mass% C coating showed good wear resistances in two engine oil test conditions (with and without sulfuric acid water solution mixed).

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