ABRADABILITY EVALUATION AND TRIBOLOGICAL BEHAVIOUR OF ABRADABLE SEAL COATING①

Yi Maozhong†, He Jiawen††, Huang Baiyun† and Zhou Huijiu††
† *State Key Laboratory for Powder Metallurgy,*
Central South University of Technology, Changsha 410083, P. R. China
†† *State Key Laboratory for Mechanical behaviour of Metallic Materials,*
Xi′an Jiaotong University, Xi′an 710049, P. R. China

ABSTRACT The abradability is one of the most important properties of abradable seal coating used in aircraft turbine engine. The abradability of several kinds of middle temperature abradable seal coatings was evaluated by sliding worn volume. Their tribological behaviour and wear mechanism were investigated. The results show that the abradability decreases with the increase of the hardness for a given kind of coating. Even if the hardness is the same, the abradability is largely different in different kinds of coatings. So, only by hardness, the level of abradability can not be judged and the coating can not be chosen and designed. The abradability of 313 type of coating is the best, 310 is close to 601 and 307 with low hardness is fairly good, but 307 with high hardness is the worst. The mechanisms of sliding wear of the coatings are abrasive wear, adhesive wear and oxidation wear, but the weight of the adhesive wear and abrasive wear is different in different coatings and under different test loads.

Key words abradable seal coating abradability sliding friction and wear

1 INTRODUCTION

Large propulsive force, high efficiency and low fuel consumption are the objective of the design and manufacture of aircraft turbine engine[1]. So, the clearances between the rotating blades and the casing in the engine should be as small as possible[2]. The gas path sealing has become an important method for this purpose[3]. The thermally sprayed abradable seal coating has been used because of its simple manufacturing processes, easy repair of the components and adjustment of its properties, good sealing effectiveness. Also, it can provide thermal barrier for the casing, and reduce the influence of high temperature fuel gases on the casing[3]. The coating is mostly composed of metal phase and self-lubricating non-metal phase with high porosity [4]. It is required that the blades scrape the coating to form a minimum gap. The coating should not only be soft enongh to be scraped easily without damaging the blades —good abradability, but also has high resistance againt erosion by the high speed gas flow and solid particles in the gas — good erosion resistance. Therefore, the abradability and erosion resistance are the most important properties in the abradable seal coating. But they are contradictory to each other[5], and the coating should provide a good balance between the abradability and the erosion resistance.

The oversea researchers have paid attention to the study[5] of the powders, spray processes, properties of the coating and the relationship among them. But, researchers and users in our country are on the state of imitating and trial-producing the powders of the coating, importing powders from abroad and spraying according to the parameters provided by the powder-maker. The basic researches about the abradability and erosion resistance have not been well made[6]. The simple methods, such as scratch hardness method, cutting method and so on, are used for

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the evaluation of the abradability[7]. The abradability is simply divided into several qualitative grade indexes such as excellent, good, qualified and unqualified[7]. That is, there are not standard experimental method and criterion for the evaluation. The designers use mostly the hardness of the coating as designing basis, and the criterion for quality control in the preparation of the coating is only the hardness[8,9]. This paper evaluated the abradability of several kinds of medium temperature abradable seal coatings by sliding wear method, and researched their sliding friction and wear behaviour.

2 EXPERIMENTAL METHOD

The sprayed powders were METCO 307 (75% Ni+ 25% graphite (G)), METCO 310 (57% Al+ 8% Si+ 35% G), METCO 313(40% Al+ 5.5% Si+ 45.5% G+ 9% organic binder) and METCO 601(40% polyester+ 60% Al-Si alloy), which were made by METCO Corp in USA. The sprayed coating specimens were called M307, M301, M313 and M601 respectively. Four kinds of domestic powders, which are being developed or have been developed successfully with the chemical composition similar to the corresponding METCO powders, were also used. The coating specimens prepared by the domestic powders were called F307, F310, F313 and F601 respectively. M307 and F307 are called 307 type of coating. The others are called in the same way. M307, F307, M310, and F310 coatings were sprayed on the blasted surface of low carbon steel plate by a METCO-6P flame spray system. M313, F313, M601 and F601 coatings were sprayed by a METCO-7MB plasma spray system. The different hardness of the coatings were prepared for one kind of powder by changing spray parameters. The spraying processes, microstructure and properties of all coatings were shown in Ref [10]. The microstructure and the hardness of the coatings are listed in Table 1.

The sliding wear test was carried out on an MM-200 wear testing machine using the form of block-ring. The block specimen was the coating, and the counnterpart ring with 36 mm in diameter and 10 mm in width was made of AISI52100 steel with HRC63. The roughness of the ring surface contacted with the block was Ra 0.2 μm, and that of the block surface was Ra 0.4 μm. The sliding speed was 0.377 m/s and the test loads were 40, 70 and 100 N for 1 h without lubricant. The worn volume was calculated by the width and length of the scar, and was used to evaluate the abradability[11]. It is thought that the larger the worn volume, the better the abradability. The surface of worn specimen was analysed by SEM and EDAX.

Table 1 Microstructure and hardness of coating specimens

Specimen	Metal phase / %	Non-metal phase / %	Porosity / %	HR15y
M307-1	43.7	25.9	30.4	18
M307-2	46.8	26.0	27.2	20
M307-3	53.6	27.3	19.1	60
F307-1	35.3	31.6	33.1	-52
F307-2	39.1	28.3	32.6	-34
F307-3	46.6	26.1	27.3	-20
M310-1	43.9	20.4	35.7	-12
M310-2	62.9	14.5	7.6	28
F301-1	82.5	13.0	4.5	73
F310-2	78.8	16.5	4.7	57
M313-1	74.0	18.3	7.7	74
M313-2	70.1	21.8	8.1	70
M313-3	74.9	17.9	7.2	77
F313	62.7	26	11.3	57
M601-1	29.4	69.3	1.3	51
M601-2	34.1	65.2	1.7	53
F601	53.9	44.6	1.5	65

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Rules of sliding friction and wear for abradable seal coating

Fig. 1 shows that the worn volume of four types of the coatings increases with the increase of the test load, which is the same as the general rule of the sliding wear. The worn volume is greatly different in different kind of coatings under the same experimental conditions. In general, the worn volume of the coating with high hardness is small. but, though the hardness of M310-1 coating (HR15y= − 12) is largely different from that of F301− 1(HR15y= 73), the worn volume of M310− 1 coating is close to that of F310− 1. The worn volume of M313 coatings is close because their hardness is close. Although the hardness of F313 is lower than that of M313, the worn volume of F313 is smaller than that of M313, that is, the abradability of F313 is worse than that of M313. For 601 type of coating, though the hardness of F601 is higher than that of M601, the worn volume of F601 is larger and the abradability is better. So, it can be seen that the hardness of coating has an obvious influence on the worn volume (abradability), but the abradability does not only rely on it.

Fig. 2 shows the worn volume vs. the hardness of all coating specimens at 70 N and 100 N test load. On the whole, the worn volume or abradability is not obviously related to the hardness of coating. The worn volume of different kind of coating with same or close hardness differs several times under same experimetal conditions. It can be also seen from Fig. 2 that the abradability of 310 type coating is better at all test load, the abradability of 313 increases remarkably with the increase of the test load and is the best at 100 N load. It is difficult to explain these results only by the hardness of the coating. The results indicate that the abradability of the coating is influenced by other factors such as the composition and microstructure of the coating

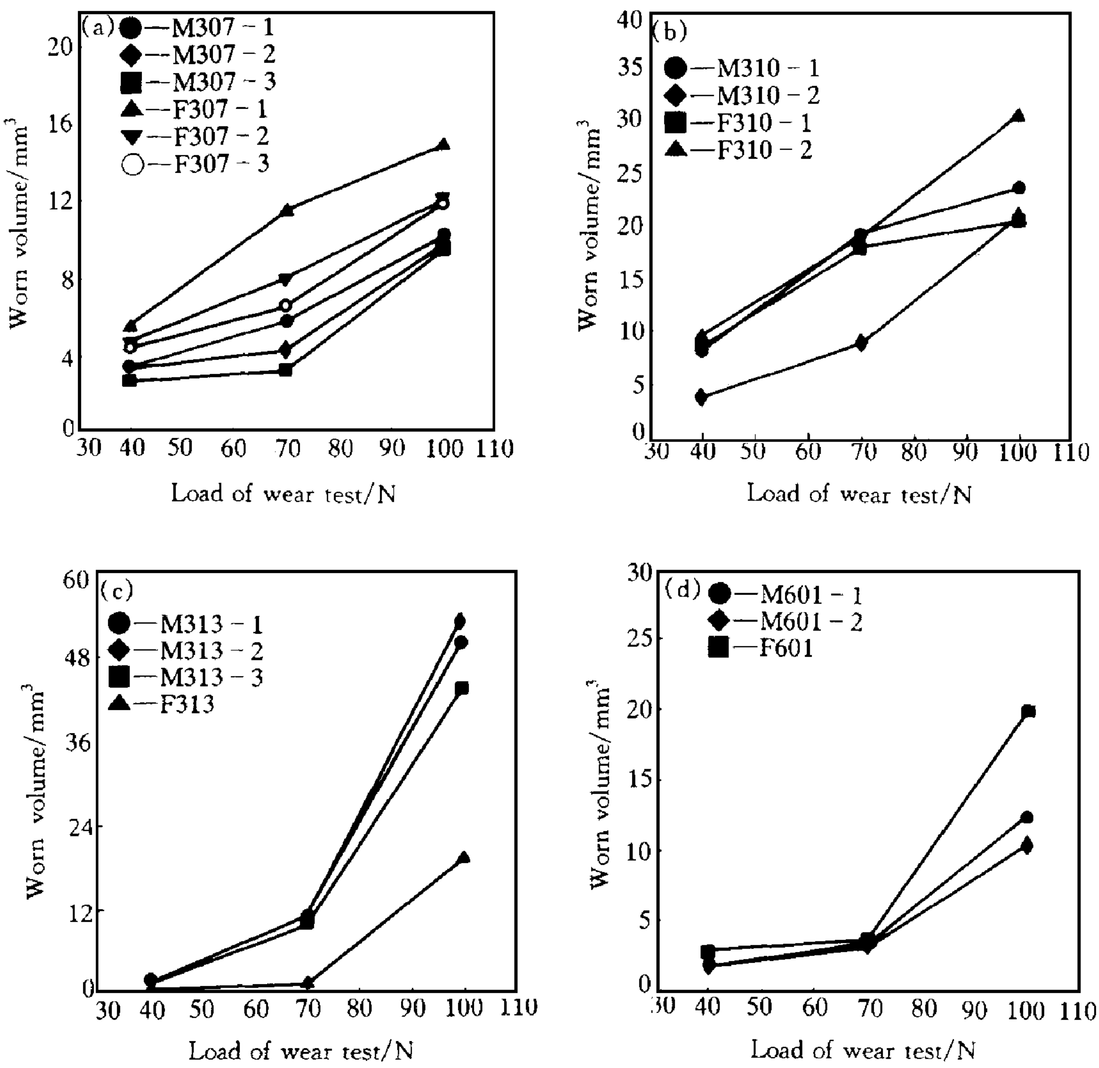

Fig. 1 Worn volume vs test load
(a) —307; (b) —310; (c) —313; (d) —601

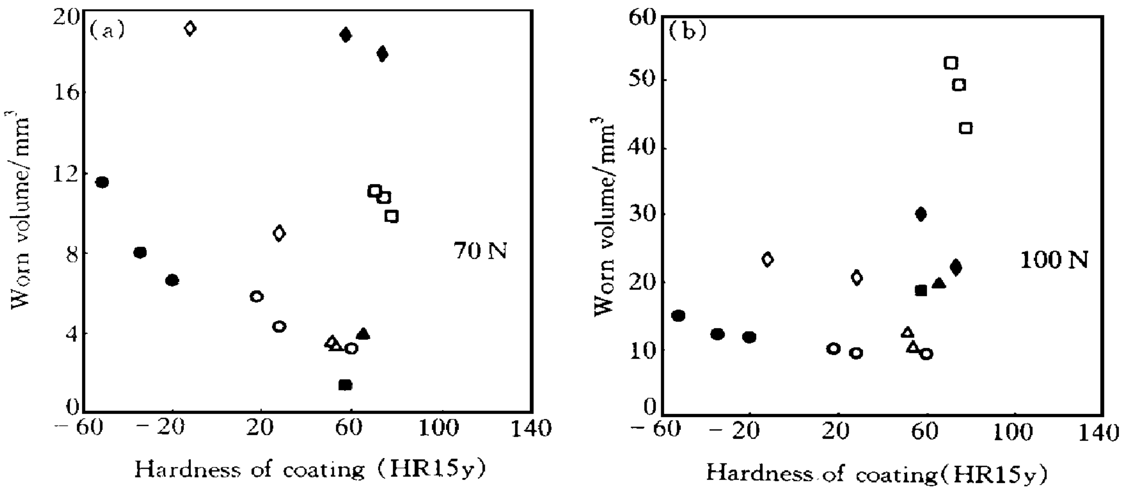

Fig. 2 Worn volume vs hardness of coating

(a) —70 N; (b) —100 N

○—M307; ●—F307; ◇—M310; ◆—F310; □—M313; ■—F313; △—M601; ▲—F601

and so on. So, the disigner can not choose and design the abradable seal coating, and lay down spray processes according to only the hardness.

On the basis of the sliding worn volume, it is obtained that the abradability of 313 type of coating is the best, 310 is close to 601 and 307 with low hardness is fairly good, but 307 with high hardness is the worst. The trend of the results is the same as that of cutting method[10, 11] and energy method[12].

Fig. 3 shows that the relationship between the friction coefficient of 313 and 601 coatings and the test load. The friction coefficients of 313 and F601 increase slightly with the increase of the load, but that of M601 decreases. Fig. 4 shows the friction coefficient of all coating specimens vs. their hardness, and indicates that the coefficients of 601 and 313 are lower, but that of 307 and 310 are higher. That is, it is related to the type of coating.

3.2 Mechanism analysis of sliding friction and wear for abradable seal coating

Fig. 5 (a) shows the surface morphology of the scar of M307-1 coating after 40 N, 1 h wear. The ploughing ditches produced by abrasive wear on the surface of the metal phase in the coating are clearly exhibited. The metal phase Ni is dragged into sharp-shaped horn along the sliding direction by the friction shear stress. This indicates that severe plastic deformation occurs on the surface layer of the metal phase. The metal phase separates from the matrix, and the pores form behind the phase. So, the metal phase is the main component to resist against the wear and is protruding on the surface, and the graphite and worn bits lie in pores or hollows.

The results of EDAX of the worn bits in the scar, the metal phase at the sharp-shaped horn and non-sharp-shaped horn in Fig. 5(a) are listed in No. 1, 2, 3 of Table 2. A large amount of Fe, O in the worn bits indicate that there is an oxide of the counterpart material. There are more amount of Fe and a little Cr at the sharp-shaped horn, and this indicates the Fe and Cr of the counterpart material adhere to the metal phase in the coating. A smeared layer forms on the adhesive zone (the black region of the sharp-shaped horn in Fig. 5 (a)). The main composition is Ni and there is a certain amount of O, Fe at non-sharp shaped horn, which indicates that the adhesion is lighter. So, the abrasive wear, oxidation wear and adhesion wear occur in the sliding wear of 307 type of coating. The adhesion increases the friction coefficient. In addition, the solid lubricating layer of the graphite in the coat-

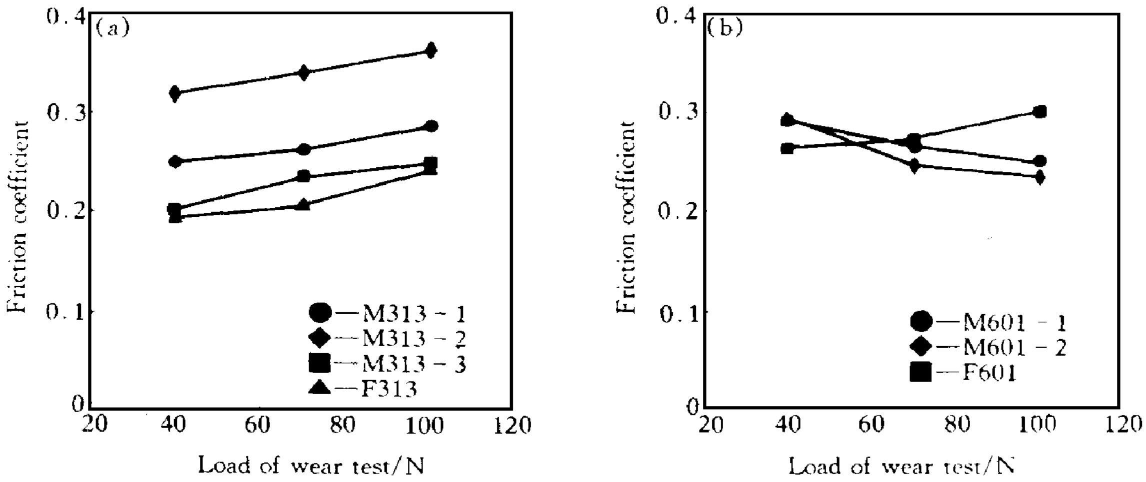

Fig. 3 Friction coefficient vs test load
(a) —313; (b) —601

Table 2 EDAX result of scar and worn bits(%)

Specimen	No.	C	O	Fe	Ni	Cr	Al	Si
307	1	1.15	10.11	46.24	42.50	-	-	-
	2	0.15	12.07	60.05	26.73	1.00	-	-
	3	0.06	2.78	5.91	91.25	-	-	-
310	4	0.09	24.77	38.25	-	-	32.26	4.64
	5	0.06	14.75	11.75	-	-	68.08	5.37
313	6	0.214	24.05	22.05	-	-	47.95	5.73
	7	0.47	27.57	6.00	-	-	58.57	7.42
	8	15.74	6.99	20.98	-	0.48	53.00	2.80
601	9	0.439	23.44	3.27	-	-	65.39	7.46
	10	9.33	25.60	20.79	-	0.47	40.53	3.28

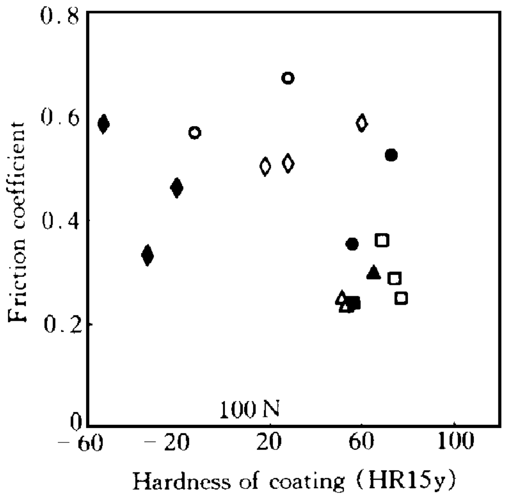

Fig. 4 Friction coefficient vs hardness of coating
○—M310; ●—F310; △—M601; ▲—F601;
◇—M307; ◆—F307; □—M313; ■—F313

ing does not form and makes also friction coefficient higher.

Fig. 5(b) shows the surface morphology of the scar of M310-2 coating after 70N, 1h wear, and a large amount of worn bits and ploughing ditches occur on the scar. The ditches of 310 coating are wider and deeper than that of 307. This indicates that abrasive wear resistance of AlSi metal phase is worse than that of Ni. The results of EDAX at the white worn bits zone in Fig. 5(b) and ploughing ditch zone are list in No.4, 5 of Table 2. The worn bits can be Fe, Al, Si and their oxides. Fig. 5(c) shows the surface morphology of M310- 2 coating after 100 N, 1h wear and ultrasonic wave cleaning. The fish-scale-like adhesive wear zone occurs on the worn surface. Because of low melting point of Al-Si alloy and high test load, the friction heat changes the surface of the coating into softening state. This results in that the surface layer of the metal phase presents plastic flowing deformation and becomes the fish-scale-like zone.

Fig. 5 (d) shows the surface morphology of 40N, 1h worn M313-2 coating. The ploughing ditches and scraps beside the ditch can be clearly seen. The curled parts produced by ploughing

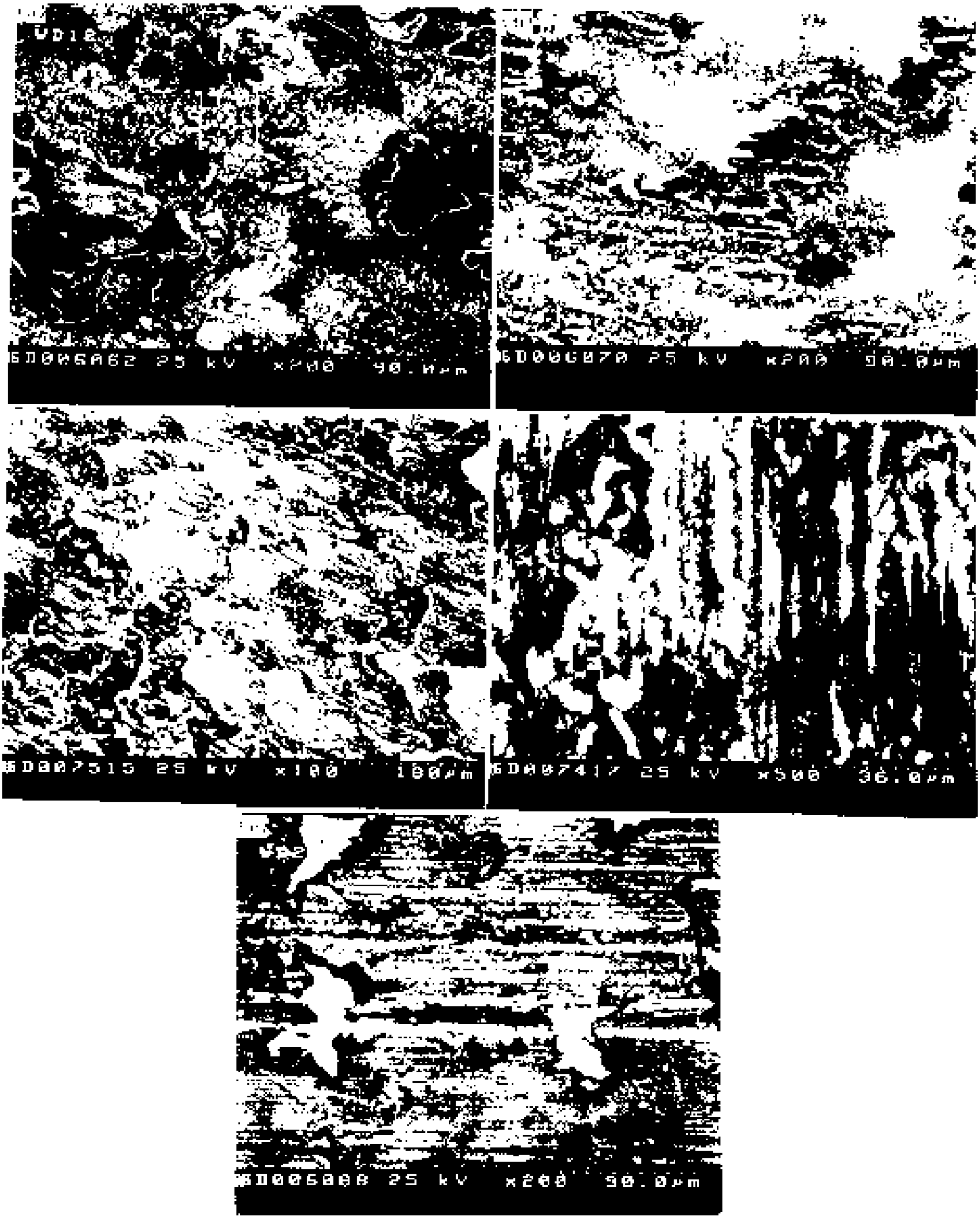

Fig. 5 Surface morphology of worn
(a) —M307- 1, 40 N; (b) —M310- 2, 70 N; (c) —M310- 2, 100 N; (d) —M313- 2, 40 N; (e) —F601, 70 N

are milled, deformed into layer-like structure and broken into the scraps. The result (No. 6 in Table 2) of EDAX of the scar, which are a large amount of oxygen and iron, indicates that the adhesive wear and oxidation wear occur. Compared with the results (No. 7 in Table 2) of EDAX of F313, the amount of Fe on the surface of worn M313 is higher. This indicates that more severe adhesive wear occurs on M313 coatings. The adhesive wear makes the friction coefficient higher and wear volume larger. The film layer shown in Fig. 6(a) formed on the surface of the counterparts with 313 type of coating in the sliding wear test. The results (No. 8 in Table 2) of EDAX analysis indicate there are C, O, Al and Si in the film, which are adhered to the surface from the coatings. The film makes the friction coefficient of 313 type of coating lower.

Fig. 5 (e) shows the surface morphology of the scar of F601 coating after 1 h, 70 N wear. The ploughing ditches, oxidation wear and adhesive wear occur also on the surface of worn 601 type of coating. The EDAX analysis of the scar (No. 9 in Table 2) indicates that the amount of Fe is the lowest, and the adhesive wear of 601 coating is the lightest in all types of coatings. A complete film layer shown in Fig. 6 (b) formed on the surface of the counterpart with 601 type of coating. The EDAX analysis (No. 10 in Table 2) illustrates that the main components in the film are C and O, which are the elements of polyester, and Al and Si, which are adhered to the surface of the counterpart from the coatings. The film makes the friction coeffecient of the coating composited of polyester lowest, and the adhesive wear of 601 coating is slighter than that of 307, 310 and 313.

3.3 Discussion on rule of friction and waer for abradable seal coating

The rule of influnence of coating hardness on worn volume is similar to that of the general wear. The influence embodys the effect on the rate of abrasive wear and adhesive wear. Suppose that the rule of the wear of the abradable seal coating accord with the simplified abrasive wear model advanced by Rabinowiez[15]:

$$W_{abr} = \frac{K_{abr}}{\pi} \cdot \frac{L}{H} \tag{1}$$

and the adhesive wear model put by Archard:

$$W_{adh} = K_{adh} \frac{L}{3\sigma_s} \tag{2}$$

where K_{abr} is the coefficient of abrasive wear which is related to the properties of abrasive particle, K_{adh} is the coefficient of adhesive wear which is related to the materials of frictional pairs, L is normal load, H is hardness and σ_s is the yield strength of material to be tested. It can be seen from Eq. (1) and Eq. (2) that the rate of both abrasive wear and adhesive wear is in inverse proportion to the hardness under given wear conditions.

Eq. (1) and Eq. (2) only explain qualitatively the effect of the hardness of the coating on the worn volume. But the experimental results indicate that different types of coatings with the same hardness hold a large difference in the worn volume under same wear condition. This is related to the type, composition and microstructure of the coating.

Because the hardness of Ni metal phase in 307 type of coating (Hv50g 130- 170) is higher than that of Al-Si(Hv50g 50- 90), the width

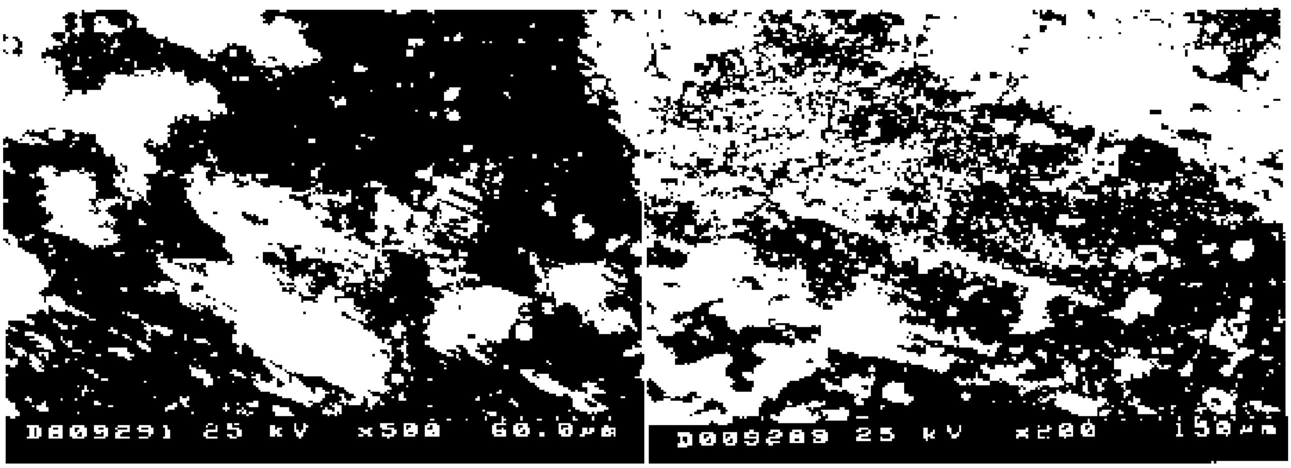

Fig. 6 Surface morphology of worn counterpart
(a) —M313- 2; (b) —F601

and depth of ploughing ditches in the scar are smaller, the abrasive wear is lighter, but the adhesive wear is more severe. Fe is close to Ni in element periodic table, and the inter-dissolubility is good, So the tendency to adhesion each other is large. Although the content of graphite in 307 type of coating is high up to 25% ~ 30%, the friction coefficient is not low, and the average value is about 0.5. The reason is that continuous solid lubricating film of the graphite does not form on the surface of the counterpart, and the role of the lubrication of the graphite is not fully played.

Because of the higher content of the graphite in 313 type of coating, the complete solid lubricating film of the graphite forms on the surface of the counterpart under lower test load. The friction coefficient is lower, and the average value is about 0.26. The metal phase in the coating endures abrasive wear. But at higher load (100 N), the phase bears severe adhesive wear, and the worn volume increase rapidly. The difference in the morphology (shown in Fig. 7(a), (b)) of the scar of M313-2 coating between 40N test load and 100N indicates that the adhesive smeared zone is larger and the worn volume is larger at 100N. Because the content of the graphite in F313 is higher than that in M313, and the solid lubricating film on the surface of the counterpart is more complete, the friction coefficient is lower, the adhesion wear is slighter. Therefore, although the hardness of F313 coating is lower than that of M313 coating, the worn volume is smaller and the abradability is worse.

The metal phase and non-metal phase in 310 type of coating are similar to that in 313 type of coating, but the amount of graphite is less, and the complete graphite lubricating film can not form on the surface of the counterpart. So, the friction coefficient is higher, and the average value is 0.53. In addition, the high porosity in the coating is also one of the reasons of large worn volume. Even though the hardness of F310 is higher than that of M310, the graphite flakes in F310 coating are finer and more dispersive, and the continuity of the metal phase is worse. This results in that the difference in the hardness between F310 and M310 is large, but their worn volume is close.

During the friction and wear of 601 type of coating, the complete polyester lubricating film layer, which forms on the surface of the counteterpart, makes the friction coefficient lowest, and the mean value is only 0.25. So, the adhesive wear is slight, and the main wear form is abrasive wear. This result in that wear rate of 601 type of coating is at a lower level. The amount of polyester in F601 is less, the friction coefficient increase slightly with the increase of the test load (as shown in Fig. 3(b)). Because there is more severe adhesive worn in F601 at

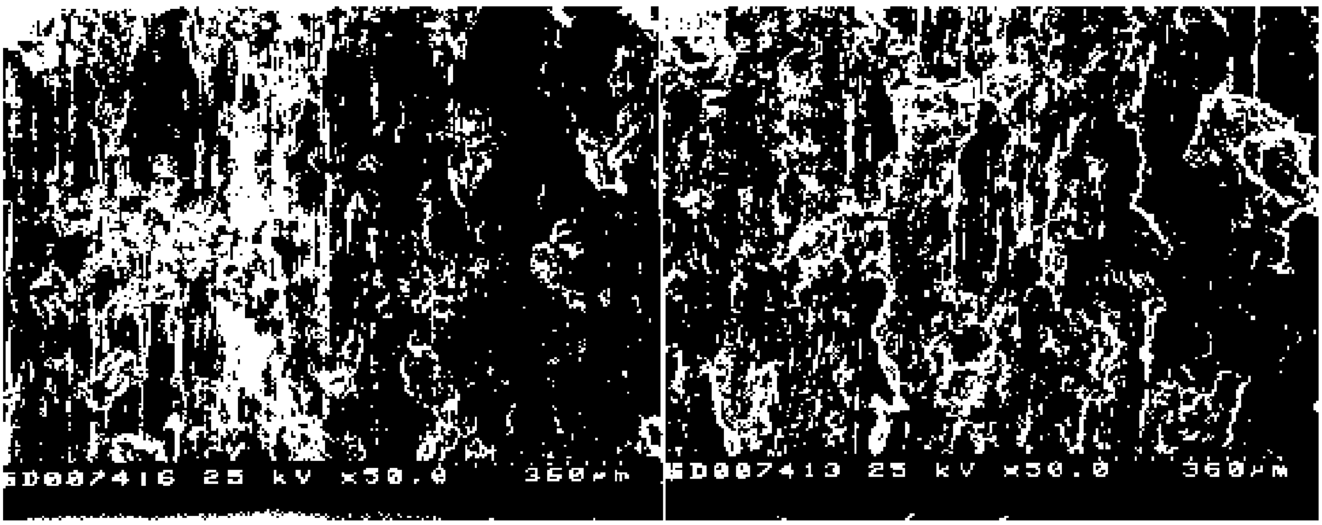

Fig. 7 Surface morphology of worn M313-2
(a) —40N; (b) —100N

larger test load, the increment of worn volume of F601 is larger than that of M601.

4 CONCLUSIONS

(1) The abradability of several kinds of middle temperature abradable seal coatings is evaluated by sliding worn volume. The abradability of 313 type of coating is the best, 310 is close to 601 and 307 with low hardness is fairly good, but 307 with high hardness is the worst.

(2) The abradability decreases with the increace of hardness for a given kind of coatings. Even if the hardness is the same, the abradability is largely different in different kinds of coatings. So, only by hardness, the level of the abradability is not judged and the coating is not chosen and designed.

(3) The mechanisms of the sliding wear of the coatings are abrasive wear, adhesive wear and oxidation wear, but the weight of the adhesive wear and abrasive wear is different in different coatings and under different test loads. The weight of the adhesive wear increases with the increase of test load.

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