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Friction and wear behaviour and abrasability of abradable seal coating

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The friction and wear behaviour of several kinds of middle temperature abradable seal coatings used in aircraft turbine engine was investigated. Their abrasability was evaluated by sliding worn volume. 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 results show that the abrasability decreases with the increase of the hardness for a given kind of coating. Even if the hardness is close, the abrasability is very different in different kinds of coatings. So, only by the hardness can the level of abrasability not be not judged and the coating not be chosen and designed. The abrasability of M313 type of coating is the best, M310 is close to M601 and M307 with low hardness is fairly good, but M307 with high hardness is the worst.

Keywords: Abradable seal coating; Sliding friction and wear; Abrasability

1. Introduction

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

coating should provide a good balance between the abrasability and the erosion resistance.

The researchers have paid attention to the study [4] of the powders, spray processes, properties of the coating and the relationship among them. But, the basic researches about the abrasability and erosion resistance have not been well-made [5]. The simple methods, such as scratch hardness method, cutting method, and so on, are used for the evaluation of the abrasability [6]. The abrasability is simply divided into several qualitative grade indexes, such as excellent, good, qualified, and unqualified [6]. That is, there are no standard experimental method and criterion for the evaluation. The hardness of the coating is mostly used as the basis of the coating design, and the criterion for quality control in the preparation of the coating is only the hardness [7]. This paper evaluated the abrasability 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 al-

Table 1
Microstructure and hardness of coating specimens

Specimen	Metal phase (%)	Non-metal phase (%)	Porosity (%)	HR15y	Specimen	Metal phase (%)	Non-metal phase (%)	Porosity (%)	HR15y
M307-1	43.7	25.9	30.4	18	M313-1	74.0	18.3	7.7	74
M307-2	46.8	26.0	27.2	20	M313-2	70.1	21.8	8.1	70
M307-3	53.6	27.3	19.1	60	M313-3	74.9	17.9	7.2	77
M310-1	43.9	20.4	35.7	-12	M601-1	29.4	69.3	1.3	51
M310-2	62.9	14.5	7.6	28	M601-2	34.1	65.2	1.7	53

loy), which were made by METCO, USA. The sprayed coating specimens were called M307, M310, M313, and M601, respectively. M307 and M310 coatings were sprayed on the blasted surface of the low carbon steel plate by a METCO-6P flame spray system. M313 and M601 coatings was 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 coating specimens were shown in Ref. [8]. The microstructure and the hardness of the specimens 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 counterpart ring with 36 mm in diameter and 10 mm in width was made of AISI152100 steel with HRC63. 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 abrasability. It is thought that the larger the worn volume, the better the abrasability. The surface of worn specimen was analyzed by SEM and EDAX.

3. Experimental results and discussion

3.1. Rules of sliding friction and wear of abrasable 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 common rule of the sliding wear. In general, the worn volume of the coating with high hard-

Fig. 1. Worn volume vs. test load (a) M307, (b) M310, (c) M313, (d) M601.

Fig. 2. Worn volume vs. hardness of coating (a) 70 N, (b) 100 N.

Fig. 3. Friction coefficient vs. test load (a) M313, (b) M601.

ness is small. But, the worn volume is very different in different kinds of coatings under the same experimental conditions. For example, the hardness of M313 is higher than that of M307, but the worn volume of M313 is larger than that of M307 at 100 N test load. So, it can be seen that the hardness of coating has an obvious influence on the worn volume (abrability), but the abrability does not only rely on it.

Fig. 2 shows the worn volume vs. the hardness of all coating specimens at 70 and 100 N test load. On the whole, the worn volume or abrability is not obviously related to the hardness of coating. It can be also seen from Figs. 1 and 2 that the abrability of M310 type coating is good at all test load, the abrability of M313 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 also indicate that the abrability of the coating is influenced by other factors, such as the composition, microstructure of the coating, and so on. So, the designer cannot choose and design the abrable seal coating, and cannot lay down spray processes only by the hardness.

On the basis of the sliding worn volume, it is obtained that the abrability of M313 type of coating is the best, M310 is close to M601 and M307 with low hardness is fairly good, but M307 with high hardness is the worst. The trend of the results is the same as that of cutting method [8] and energy method [9].

Fig. 4. Friction coefficient vs. hardness of coating.

Fig. 3 shows the relationship between the friction coefficient of M313 and M601 coatings and the test load. The friction coefficient of M313 increases slightly with the increase of the load, but that of M601 decreases. Fig. 4 shows the friction coefficients of all coating specimens vs. their hardness at 100 N load, and indicate that the coefficients of M601 and M313 are lower, but those of M307 and M310 are higher.

3.2. Mechanism analysis of sliding friction and wear of 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 angle-like along the sliding direction by the friction shear stress. This indicates that large 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 wear and is protruding on the surface of the coating, and the graphite and worn bits lie in the pores or hollow.

The results of EDAX of the worn hits in A zone, the metal phase at B zone and C zone in Fig. 5(a) are listed in No. 1, 2, 3 of Table 2, respectively. A large amount of Fe, O in the worn bits (No. 1) indicates that there is some

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) M601-1, 70 N.

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

Specimen	No.	C	O	Fe	Ni	Cr	Al	Si
M307	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	–	–	–
M310	4	0.09	24.77	38.25	–	–	32.26	4.64
	5	0.06	14.75	11.75	–	–	68.08	5.37
M313	6	0.214	24.05	22.05	–	–	47.95	5.73
	7	15.74	6.99	20.98	–	0.48	53.00	2.80
M601	8	0.439	23.44	3.27	–	–	65.39	7.46
	9	9.33	25.60	20.79	–	0.47	40.53	3.28

oxide of the counterpart material. There are more amounts of Fe and a little Cr at the B zone, sharp angle-like which indicates that 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 angle-like in Fig. 5(a)). At non-sharp angle-like zone, the main composition is Ni, and there is a certain amount of O, Fe, which indicates that the adhesion is lighter. Thus, the abrasive wear, oxidation wear, and adhesion wear occur in the sliding wear of M307 type of coating.

Fig. 5(b) shows the surface morphology of the scar of M310-2 coating after 70 N, 1 h wear, and a large amount of worn bits and ploughing ditches occur on the scar. The ditches of M310 coating are wider and deeper than that of M307, which indicates that the abrasive wear resistance of Al–Si metal phase is worse than that of Ni. The results of EDAX at the white worn bit zone D, and ploughing ditch zone E in Fig. 5(b) are listed in No. 4, 5 of Table 2, respectively. The worn bits may be Fe, Al, Si and their oxides. Fig. 5(c) shows the surface morphology of M310-2 coating after 100 N, 1 h 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 makes the surface of Al–Si metal phase soften [10,11]. The surface layer of the metal phase presents plastic flowing deformation and becomes the scale-like zone.

Fig. 5(d) shows the surface morphology of 40 N, 1 h worn M313-2 coating. The ploughing ditches and scraps beside the ditches can be clearly seen. The curled parts produced by ploughing are milled, deformed, and broken into the scraps. The result (No. 6 in Table 2) of EDAX of the scar, which is a large amount of oxygen and iron, indicates that the adhesive wear and oxidation wear occur.

Fig. 5(e) shows the surface morphology of the scar of M601-1 coating after 1 h, 70 N wear. The ploughing ditches, oxidation wear and adhesive wear also occur on the surface of worn M601 type of coating. The EDAX analysis of the scar (No. 8 in Table 2) indicates that the amount of Fe is the lowest and the adhesive wear of M601 coating is the lightest in all types of coatings.

3.3. Discussion on behaviour of friction and wear of abradable seal coating

The rule of influence of abradable seal coating hardness on worn volume is similar to that of the common wear. The influence embodies the effect of the hardness on the rate of the abrasive wear and the adhesive wear. Suppose that the rule of the wear of the coating accord with the simplified abrasive wear model advanced by Rabinowicz.

$$W_{abr} = \frac{K_{abr}}{\pi} \frac{L}{H} \quad (1)$$

and the adhesive wear model put by Archard:

$$W_{adh} = K_{adh} \frac{L}{3\sigma_s} \quad (2)$$

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 material 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 Eqs. (1) and (2) that the rate of both abrasive wear and adhesive wear is in inverse proportion to the hardness under given wear conditions. Eqs. (1) and (2)

Fig. 6. Surface morphology of worn M313-2 (a) 40 N, (b) 100 N.

Fig. 7. Surface morphology of worn counterpart with (a) M313-2, (b) M601-1.

only explain qualitatively the effect of the coating hardness on the worn volume.

Because the hardness of Ni metal phase in M307 type of coating (HV 50 g 130–170) is higher than that of Al–Si (HV 50 g 50–90), the width and depth of ploughing ditches on the surface of the coating with Ni metal phase are smaller, the abrasive wear is lighter, but the adhesive wear is more severe. Fe is close to Ni in element periodic table, and their inter-dissolubility is good, so the tendency to adhesion is large. Although the content of the graphite in M307 type of coating is high up to 25–30 wt.%, the friction coefficient in Fig. 4 is not low, and the average value is about 0.53. The reason is that the continuous solid lubricating film of the graphite does not form on the surface of the counterpart, the role of the lubrication of the graphite is not fully played, and there is severe adhesion in the sliding wear of M307.

The metal phase in M313 type of coating endures abrasive wear. But at a higher load (100 N), the phase bears more severe adhesive wear and the worn volume increases rapidly. The difference in the morphology shown in Fig. 6(a,b) of the scar of M313-2 coating between 40 and 100 N test load indicates that the adhesive smeared zone is larger and the worn volume is larger at 100 N. The film layer shown in Fig. 7(a) forms on the surface of the counterpart with M313 type of coating in the sliding wear test. The result (No. 7 in Table 2) of EDAX analysis indicates that there are C, O, Al, and Si in the film, which are adhered to the surface of the counterpart from the coatings. The film makes the friction coefficient of M313 type of coating low, and the average value in Fig. 4 is about 0.29.

The metal phase and non-metal phase in M310 type of coating are similar to that in M313 type of coating, but the amount of graphite is less and the complete graphite lubricating film does not form on the surface of the counterpart. So, the friction coefficient in Fig. 4 is higher, and the average value is 0.61. In addition, the higher porosity in the coating is also one of the reasons of large worn volume.

A complete film layer shown in Fig. 7(b) formed on the surface of the counterpart with M601 type of coating. The EDAX analysis (No. 9 in Table 2) indicates that the main components in the film are C and O, which are the elements of the polyester and Al and Si, which are adhered to the surface of counterpart from the coatings. The film makes the friction coefficient of the coating composed of polyester the lowest and the adhesive wear of M601 coating is slighter than that of M307, M310, and M313. The mean friction coefficient in Fig. 4 is only 0.25, and the main wear form is abrasive wear. Thus, wear rate of M601 type of coating is at a lower level.

4. Conclusions

(1) The abrasability of several kinds of middle temperature abrasable seal coatings is evaluated by sliding worn volume. The abrasability of M313 type of coating is the best, M310 is close to M601 and M307 with low hardness is fairly good, but M307 with high hardness is the worst.

(2) The abrasability decreases with the increase of the hardness for a given kind of coating. Even if the hardness is close, the abrasability is very different in different kinds of coatings. So, only by the hardness can the level of the abrasability not be judged and the coating not be 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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