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The influence of size and distribution of graphite on the friction and wear behavior of Ni–graphite coatings

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ABSTRACT

In this work, the METCO 307 (75 wt.% Ni + 25 wt.% graphite, M307) abradable seal coatings were deposited by conventional atmospheric plasma spraying system (APS) and high efficiency supersonic atmospheric plasma spraying system (SAPS), respectively. Comparative dry reciprocating sliding wear experiments on the as-sprayed coatings against a 440-C stainless steel ball were conducted on the CETR UMT-3 friction and wear tester. The results indicated that the average width and length of lubrication phase (graphite) were 3.54 ± 0.06 and 7.51 ± 0.13 μm in the SAPS-coating, which were lower than 4.15 ± 0.11 and 8.03 ± 0.09 μm in the APS-coating. The fine graphite phase improved the formation of homogeneous and continuous tribofilm during the reciprocating sliding friction process. The track depth of APS-coating increased from 0.093 to 0.161 mm, while that of SAPS-coating increased from 0.087 to 0.151 mm when the test temperature rose from 25 to 400 °C, indicating that the SAPS-coatings had a higher wear resistance.

1. Introduction

Abradable seal coating has been widely used in the high-speed dynamic sealing and mechanical wear-resistant antifriction devices, such as internal engine, etc., because it can significantly improve the mechanical and/or tribological properties of part surface [1–6]. It acts as a sacrificial layer between the blades and the casing, and is soft enough to avoid significant wear to blade tips, thus allowing much smaller clearances [7]. The selection of materials for the abradable seal coating in the internal engine depends on the operating temperature. The Ni–graphite coatings are mainly used in the engine fan and compressor components [2,8–12]. The METCO 307 (75 wt.% Ni + 25 wt.% graphite, M307) for temperature applications up to 480 °C had a well applicability in higher temperature portion of the high-pressure compressor [2,3,13].

Atmospheric plasma spraying (APS) and high velocity flame spraying (HVOF) are widely used to deposit abradable seal coating [2, 14–17]. Since the plasma has a higher enthalpy, APS can deposit the different feedstock powers with a large range of melting points. However, compared with low-cost APS, due to a higher impact velocity when the in-flight particles impinge on the substrate, the adhesion or cohesion strength of HVOF-coating is greatly improved [14,17,18]. Therefore, in order to deposit high-performance abradable seal coatings, a new spray method combining the advantages of APS and HVOF is needed to be developed.

Recently, an advanced high efficiency supersonic plasma spraying system (SAPS) has been successfully developed by the national key laboratory for remanufacturing (China) [19–22]. The SAPS system, with a single anode and internal injection port, has a supersonic velocity for the particles while just consuming lower power (<80 kW) and smaller gas flow (6 $m^3 \cdot h^{-1}$). The speed of in-flight particles in the SAPS was in the range of 350–800 m/s, which was significantly higher than those in the APS (130–220 m/s). Results obtained so far have shown that the SAPS-coating has a finer microstructure and higher adhesion strength than the APS-coating [23–26]. Thus, in the present work, two types of Ni–graphite coatings were deposited by SAPS and APS, respectively. The sliding friction and wear behavior of the as-sprayed coatings was evaluated using the CETR UMT-3 friction and wear tester with the aim of obtaining high-performance abradable seal coatings.

2. Experimental

2.1. Materials

The substrate, Q235A steel with the dimension of 34 mm × 24 mm × 8 mm, was ultrasonically cleaned with acetone and then grit-blasted with alumina powder to enhance the adherence capability between bond coat and substrate. The abradable seal coating system consisted of a bond coat and a top coat. A commercially available $Ni_{35}Cr$ powder (Beijing Yi Xin An Technology Development Co., Ltd, China) was used to deposit the bond coat. The METCO 307 powders (75 wt.% Ni + 25 wt.% graphite, M307) were used to deposit the top coat.

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The morphology and cross-section of M307 powder are shown in Fig. 1. As depicted in it, the feedstock powders exhibited an irregular shape and a nonuniform particle size distribution.

2.2. Plasma spraying

The coatings were deposited by the Metco 9M atmospheric plasma spraying (APS) system and high efficiency supersonic atmospheric plasma spraying (SAPS) system, respectively. The plasma spraying parameters are presented in Table 1. During spraying, a commercially available Spray Watch 2i system (made by Osier, Finland) was used to monitor the velocity and surface temperature of in-flight particles for each operating condition.

2.3. Specimen characterization

The microstructure of as-sprayed coatings was examined by a scanning electron microscopy (SEM, VEGAII XMU, Tescan, Czech Republic). The phase composition of coatings was characterized by X-ray diffraction (XRD, D/MAX-2400X, Rigaku, Japan) using Cu Kα radiation ($\lambda = 0.15406$ nm), the angle in the range of 15°–80°, and the step size at 0.008°. The content and size of lubrication phase in coatings were calculated by quantitative image analysis of the Image-Pro Plus software (Media Cybernetics, Silver Springs, MD). The final statistical result was the average value from ten micrographs of the coatings.

2.4. Hardness and bonding strength

Two types of hardness testing methods were applied. One is HR15Y tester (HSRN-45, Wuzhong City Material Testing Machine Co., Ltd., China). The polished surface of the coating was measured 10 times in different areas with a load of 150 N and a holding time of 3 s. The other is Vickers microhardness-scale HV tester (Akashi Corporation, Japan). The polished cross-section of the coating was measured 10 times in different areas with a load of 1 N and a holding time of 10 s. The bonding strength of the as-sprayed coatings was measured by using a material tester (Instron1196, USA) in accordance with ASTM C633-79 standard. The film epoxy adhesive (FM1000, USA) was used to bond the samples. The final result represented the average value of five coatings deposited at the same parameters.

Table 1
Plasma spray parameters for the top coat and bond coat.

Spray parameters	APS		SAPS	
	$Ni_{35}Cr$	M307	$Ni_{35}Cr$	M307
Primary gas Ar (slpm)	48	95	71	70
Second gas H_2 (slpm)	4.6	5	9	6
Powder feed rate (g/min)	40	40	40	40
Voltage (V)	70	68	120	105
Current (A)	500	460	380	340
Spray distance (mm)	100	100	100	100
Coating thickness for tensile test (μm)	80	250	80	250
Coating thickness for tribological test (μm)	80	1000	80	1000

2.5. Friction coefficient test

The surface roughness of both coatings after spraying was measured by a Color 3D Laser Scanning Microscope (VK 9510, KEYENCE, Japan). The friction coefficient of the surface coat was evaluated by the ball-on-flat mode on the UMT-3 friction and wear tester (CETR Corporation Ltd, USA) with the reciprocating and sliding wear method. The counterpart was a 440-C stainless steel ball with the diameter of Φ 12.7 mm and the hardness of HRC 62. The friction and wear tests were carried out for 150 N with the reciprocating and sliding wear method and without lubricant at room temperature (about 25 °C) and the high temperature (about 400 °C), respectively, sliding distance of 10 mm per pass with the frequency of 5 Hz, sliding time of 5 min. Before the formal testing, a pre-grinding of 20 s with the load of 5 N was taken. The friction coefficient and the track depth of the test were recorded automatically by a computer in the test process. After the test, the worn surface morphologies of coatings were observed by SEM.

3. Results and discussion

3.1. XRD analysis

X-ray spectra of feedstock powder and coatings are shown in Fig. 2. As seen from Fig. 2, the diffraction peaks of feedstock powder only

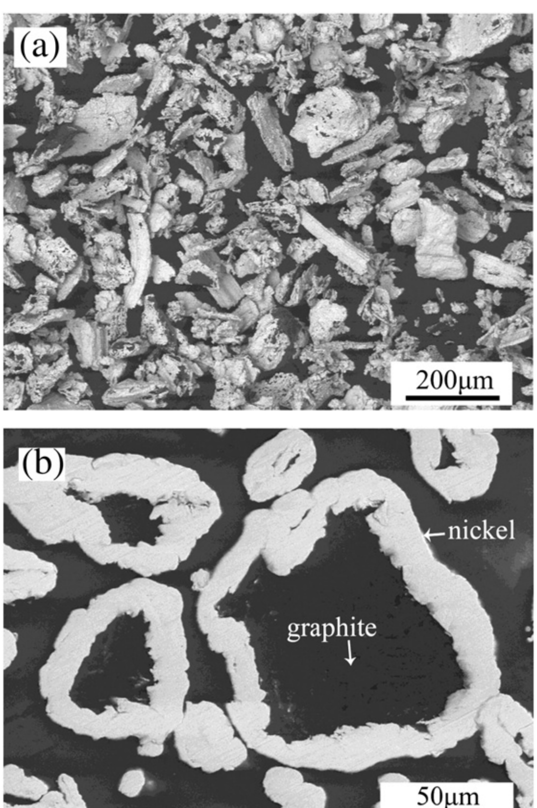

Fig. 1. SEM images of Ni–graphite powder: (a) surface, (b) cross-section.

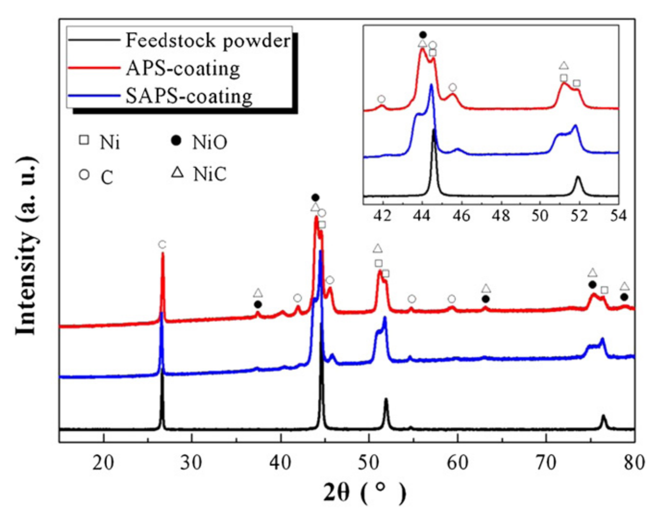

Fig. 2. X-ray spectra of feedstock powders and SAPS-/APS-coatings.