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Material transfer behaviour between a Ti6Al4V blade and an aluminium hexagonal boron nitride abradable coating during high-speed rubbing

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ABSTRACT

Material transfer behaviour between a Ti6Al4V blade and an Al–hBN abradable coating during high-speed rubbing was investigated by a high-speed rubbing test rig built by our research group. The effects of single pass depth and linear speed were studied. The transfer mechanism was discussed on the basis of observations of the blade and coating surface and section morphologies as well as comparisons between section morphologies of the coating transfer layer and the original coating. Material transfer from the coating to the blade was significant under the condition of high linear speed and low single pass depth. The coating transfer layer adhered to the blade at low linear speeds, whereas it was melted and smeared on the blade at high linear speeds. With an increase of the linear speed at a constant single pass depth, the wear mechanism of the coating changed from cutting and micro-rupture to plastic flow and melting. The high frictional heat brought about by the high linear speed was found to be the requirement of coating transfer, and the low single pass depth was the key to accumulation of the transfer on the blade.

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1. Introduction

To minimise the clearance between the rotating blades and the casing wall in the compressor and turbine sections of aero-engines, as a means of achieving high aero-engine efficiency, and most importantly, to diminish incidents of engine failure, an abradable seal coating is used in an aero-engine's gas path sealing [1–5]. An abradable seal coating is sprayed on the engine's casing wall facing the blade, and a friction pair is formed between the coating and the high-speed rotating blade [6]. The friction pair is assumed to have the following characteristics: the interaction is rubbing, the linear speed of the relative movement is very high and it is expected that the blade does not wear, and at the same time, the coating which acts as a sacrificial material does not adhere to the blade.

Al-based abradable seal coatings have been widely used in compressors of aero-engines. It forms a friction pair with the titanium blade in the compressor. The wear mechanism and material transfer behaviour of the friction pair during high-speed rubbing have been studied by many researchers. According to Ghasripoor et al. the main wear mechanism of aluminium silicon hexagonal boron nitride (AlSi–hBN) was micro-rupture due to the cracks originating from the breakage of hBN. Meanwhile, the AlSi metal substrate was found to be deformed and partially melted [7]. Wang built a thermal model to calculate the temperature changes during blade and seal interaction. He found that, when the titanium blade contacted with an AlSi coating, the modulus of the blade was always higher than that of the coating; consequently, the blade did not wear, while the coating underwent densification and plastic deformation [8].

Laverty studied frictional energy and found that the incursion speed had the largest influence on both transfer from the coating to the blade and blade deterioration at high incursion speeds [9]. Bounazef et al. discovered that the BN–SiAl-bounding organic element coating transferred to the blade during rubbing, and the blade suffered no wear. The transfer was slight at high linear speeds and high incursion speeds, whereas it became severe at low linear speeds and low incursion speeds [10]. By a stroboscopic imaging system, Stringer acquired images of the blade during rubbing and thereby studied in detail the transfer behaviour between an AlSi–hBN coating and a Ti6Al4V blade during high-speed rubbing [11,12]. It was found that, at a low incursion rate, transfer from the coating to the blade was significant, and the corresponding coating wear scar was grooved. At a high incursion rate, the coating was cut, and wear occurred on the blade. The transfer process underwent three phases: an initiation phase with a low rate of adhesion, a steady adhesion state and fracture of the adhered material was followed by re-initiation.

An understanding of the wear mechanism of a friction pair composed of an Al-based coating and a blade during high-speed rubbing has been improved by the above mentioned research

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works. At the same time, the specific wear behaviour characterised by material transfer during high-speed rubbing has been researched a little. However, the wear behaviour and mechanism of this specific friction pair has not been adequately evaluated. Especially the mechanism of the coating transfer to the blade which is very important has not been studied attentively. Focus on the transfer mechanism is one of the most important novelties in this work. In addition, the reason why the blade continues to wear even when it is covered by the transferred coating has not yet been determined. In fact, different researchers have different opinions regarding the influences of various test variables on the transfer behaviour.

The aluminium hexagonal boron nitride (Al–hBN) seal coating, in conjunction with titanium blades, have been widely used in aero-engine compressors. This paper evaluated the wear mechanism and material transfer behaviour of the Al–hBN coating and Ti6Al4V blade friction pair under simulated working conditions using a high-speed rubbing test rig and focused on the material transfer behaviour.

2. Materials and methods

2.1. Materials

The blade of the rubbing test rig was made of annealed Ti6Al4V material, which is widely used in aero-engine compressors, and was formed by wire-electrode cutting. The area of the rubbed face on the cube sample was 4 mm × 4 mm. The surface was abraded with sand paper, and the final surface roughness R_a was about 0.5 μm. The blade sample was then rinsed with absolute ethanol, dried in a warm air and preserved in a dryer. The blade and coating ready for testing are shown in Fig. 1.

The abradable seal coating used in the study was an Al–hBN coating. The metal Al served as the substrate and provided strength to the coating. The hBN served as a solid lubricant, which could generate cracks to help with chip formation and also decrease the coating transfer to the blade [7]. The Al–hBN coating was fabricated by Sulzer Metco UniCoat plasma spray equipment, namely, Al–BN powders with around 75 wt% Al, 20 wt% BN, and 5 wt% Na_2SiO_3 binder as spray feedstock was sprayed on a stainless steel plate using air plasma thermal spray technology. To enhance the bonding strength between the coating and the substrate, a NiAl transitional layer was first sprayed on the plate. Details of the spraying parameters used to produce NiAl layer and Al–hBN layer were given in Table 1. The final thickness of the coating was about 2 mm. The hardness of all the coating samples was tested before the experiments and only the samples of which the HR15Y hardness value were around 50 were used. The section morphology of the Al–hBN coating is shown in Fig. 2. The surface of the Al–hBN coating sample was first ground flat using a grinding machine and then abraded with sand paper until R_a was about 6 μm.

2.2. Methods

The rubbing test was conducted on a high-speed rubbing test rig built by our research group [13]. A schematic of the test rig, together with a photograph of the test rig are shown in Fig. 3. Before testing the blade (rotating sample) was mounted into a metal disc driven by the high-speed motorised spindle, a dummy blade which was shorter than the blade was installed in the disc 180°from the blade for balancing. The coating (stationary sample) was fastened onto the dynamometer device by four bolts. By adjusting the radial sliding table, the dynamometer device and the coating could slide to the rotating blade at a given incursion speed and depth. The whole incursion system was placed on a horizontal sliding table which could move the coating horizontally, so three to four tests could be conducted on a single coating sample. The irradiation heating system was employed to heat the coating sample.

A high-frequency three-direction dynamic force transducer (PCB M260A02) was installed in the dynamometer device. The rubbing forces were firstly magnified by the mechanical structure of the dynamometer device. Then the magnified forces acted on the

Table 1
Spray parameters of the coating.

Spray parameters	Unit	
	NiAl transition layer	Al–hBN coating
Spray distance	140 mm	110 mm
Plasma gas (Ar) flow rate	90 l min^{-1}	90 l min^{-1}
H_2 flow rate	10 l min^{-1}	5 l min^{-1}
Arc current	550 A	400 A
Voltage	60 V	52 V
Powder feed rate	40 g/min	50 g/min
Carrier gas (N_2) flow rate	4 l min^{-1}	4 l min^{-1}

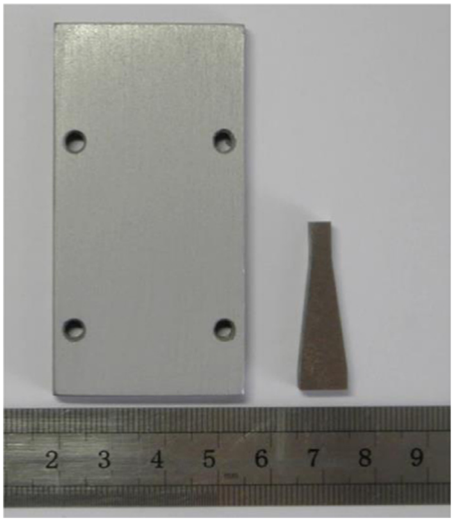

Fig. 1. Picture of the Al–hBN coating and the Ti6Al4V blade ready for test.

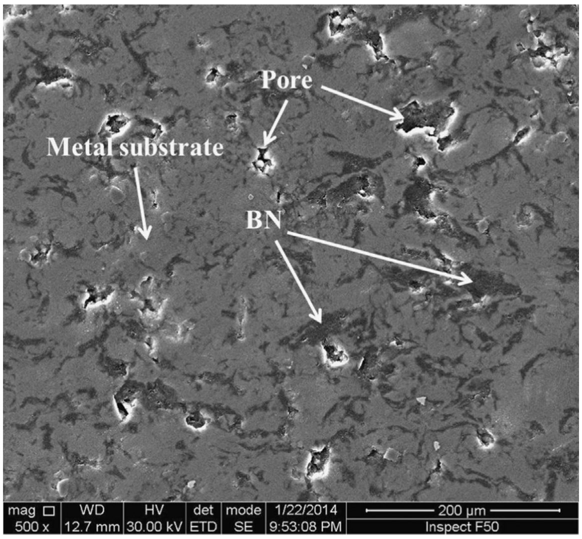

Fig. 2. SEM micrograph of Al–hBN coating's cross section.

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