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To cite this article: A Salman *et al* 2009 *IOP Conf. Ser.: Mater. Sci. Eng.* **4** 012006

IOP Conf. Series: Materials Science and Engineering **4** (2009) 012006 doi:10.1088/1757-899X/4/1/012006

Tribological properties of thermally sprayed TiAl-Al_2O_3 composite coating

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Abstract. The use of thermal spray coatings provides protection to the surfaces operating in severe environments. The main goal of the current work is to investigate the possibility of using a high velocity oxy fuel (HVOF) thermally sprayed wear resistant TiAl/Al_2O_3 coating on tool steel (H13) which is used for making dies for aluminium high pressure die casting. A feedstock of TiAl/Al_2O_3 composite powder was produced from a mixture of Al and TiO_2 powders by high energy mechanical milling, followed by a thermal reaction process. The feedstock was then thermally sprayed using a high velocity oxy-fuel (HVOF) technique onto H13 steel substrates to produce a composite coating. The present study describes and compares the tribological properties such as friction and sliding wear rate of the coating both at room and high temperature (700°C). The results showed that the composite coating has lower wear rate at high temperature (700°C) than the uncoated H13 sample. At Room temperature without using lubricant there is no much significant difference between the wear rate of the coated and uncoated samples. The experimental results showed that the composite coating has great potential for high temperature application due to its lower wear rate at high temperature in comparison with the uncoated sample at the same temperature. The composite coating was characterized using scanning electron microscopy (SEM), optical microscopy and X-ray diffractometry (XRD). This paper reports the experimental observations and discusses the wear resistance performance of the coatings at room and high temperatures.

1. Introduction

The intermetallic compounds based on titanium, such as Ti_3Al, TiAl, and $TiAl_3$ have been examined and developed for high temperature applications [1,2]. Compared with titanium, these titanium aluminides present several advantages; i.e. higher elastic modulus, lower density, higher oxidation resistance, and better mechanical behaviour with temperature [1,3]. In addition, Ti_3Al and especially TiAl have much better "titanium fire" resistance than titanium and its alloys [4]. Moreover, titanium aluminide coatings show better wear resistance than that of pure Ti [5]. However, low ductility at room temperature is the major obstacle to the use of Ti_3Al, TiAl and $TiAl_3$ as structural materials [3,6]. Titanium aluminide surface coatings are considered to be another promising application of these intermetallic compounds [5,6].

One effective way to improve the wear resistance of intermetallic compounds is to obtain a hard phase reinforced intermetallic matrix composite (IMC), which is expected to possess high hardness and subsequently good wear resistance. The interest in intermetallic matrix composites has grown in recent years due to the realization that monolithic intermetallics would not be likely to satisfy the balance of properties needed for advanced aerospace systems. Processing of intermetallic matrix composites is a critical issue and a number of methods have been explored to fabricate such composites with either continuous or discontinuous reinforcements. While the latter category in general provides less improvement in mechanical behaviour, this is the type of composite where mechanical alloying may provide an inexpensive processing route.

Al_2O_3 is found to be a suitable reinforcement for improving the wear resistance of metal matrix composites (MMCs) due to its excellent chemical and thermal resistance and high hardness [5,7]. The high hardness of the titanium alloy intermetallics and composites make their application appropriate as wear resistant coating materials.

Thermal spraying is a well established means of forming relatively thick coatings. In particular, high velocity oxy fuel (HVOF) spraying has been developed into a reliable technique to apply hard, tribologically superior and well adherent metallic and composite cermets coatings to a great variety of metallic surfaces [8]. Among the thermal spraying techniques, HVOF is effectively used to prepare coatings with dense structure at a particle velocity of above 700 m/s HVOF is a good candidate to deposit metal ceramic coatings.

The reciprocating wear properties of plasma and HVOF thermally sprayed $TiAl/Al_2O_3$ based composite coatings were investigated by Hung [9] under ambient conditions. Results showed that an HVOF sprayed $TiAl/Al_2O_3$ coating is more wear resistant than a plasma sprayed coating.

2. Experimental procedure

The details of composite powder production and coating characterisation have been have been reported previously [10]. The feedstock was thermally sprayed using a HVOF process (Aerospray, Browning Co., New Hampshire, US) on heat-treated H13 tool steel discs. The GMA Microjet gun was used with 100Psi oxygen pressure, 50Psi fuel pressure (propane), 100Psi carrier gas (N_2) pressure. The powder feed rate was 110rpm with the 7-10cm stand-off distance and eight number of passes.

The hardened H13 tool steel substrate with hardness of about 50 HRC was grit blasted using alumina (36grit). The surface roughness of the grit blasted uncoated specimen was Ra 4.98μm. After thermal spraying the $TiAl/Al_2O_3$ composite coating had an average thickness of about 25μm with an average surface roughness of the coating of Ra 8.05μm (as-sprayed).

The thermally sprayed coating was characterised using optical microscopy and scanning electron microscopy (SEM, Hitachi S-4700). X-ray diffraction analysis (XRD) was performed to determine the phase constituents using an X'pert diffractometer (Philips, the Netherlands) using Cu Kα radiation. The microhardness of the coating surface was measured with a Leco LM-700 micro-indenter with a load of 100g and dwell time of 20s.

The friction and wear tests were carried out using an MG-2000 high temperature pin on disc tribometer (Beilun Cop.) for high temperature testing without lubrication and room temperature testing under dry and lubricating conditions. The wear performance of the composite coating was assessed using a spherical ended alumina pin (φ = 10mm) as a counter body at a load of 20N with a sliding speed of 0.5m/s. The pin was rubbed against the rotating coated H13 disc (70mm dia).

The surface roughness of both the uncoated H13 tool steel and coating were measured at two different positions before conducting the wear test using a T1000A roughness profiler (MTF, Harbin, China). The frictional movements were continuously recorded by a computer. After each test the wear rate of the coating was measured from the depth of the wear track by using a profiler/surface texture measuring perthometer (S3P, Germany). For each wear track, two readings were recorded to calculate the average wear track depth. Friction test data was used to estimate the friction coefficient and average life of the coating under a given condition. The specific wear rate of the coating was assessed both at high temperature and room temperature.

3. Results and discussion

3.1. Coating characterisation

The results for coating characterization have been reported previously [10]. The micro-hardness of the coating surface varied from HV900 to HV4218 with an average value of HV1888.

The surface topology of the coating examined using SEM in 'figure 1a' indicates that the coating is composed of a well deposited flat area (in dotted-line rectangle) and sloping areas (in solid-line rectangle) that derive from a pile up of splats on the top of un-melted/resolidified particles and from the cast off debris from the splashed splats. EDX analysis of the coating in 'figure 1c' suggests that the dark lamellae phase is Al_2O_3, while the bright lamellae phase was identified as a metallic phase, consisting of $Ti_3Al(O)$, TiAl(O). XRD analysis of the coating also confirms the presence of similar phases.

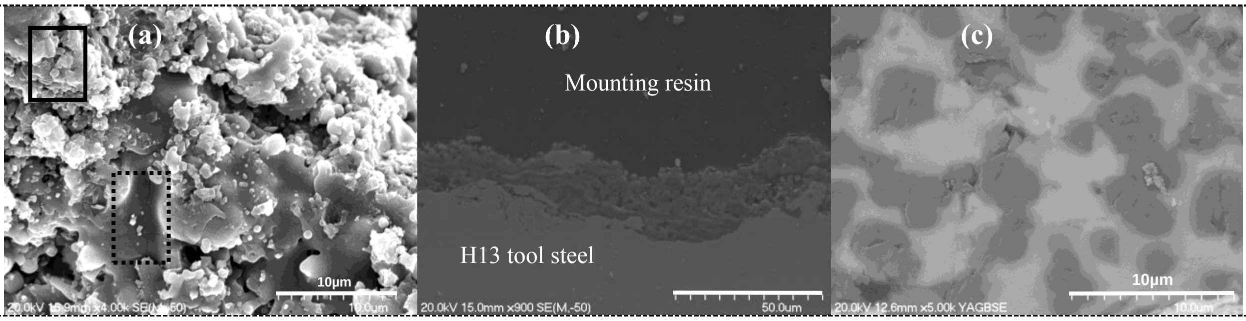

Figure 1. SEM micrograph of TiAl-Al_2O_3 coating on H13 tool steel; (a) as-sprayed surface topology (b) coating cross section.(c) back scattered image of coating cross section showing a dispersion of un-melted alumina particles(dark phase) in a metallic matrix(bright phase).

3.2. Tribolgical properties of a TiAl-Al_2O_3 coating

Besides determining the friction coefficient of the coating, the test data was also used to evaluate the approximate coating life. Thus the particular choice of sliding distance for a given friction test condition is based upon the ultimate coating failure.

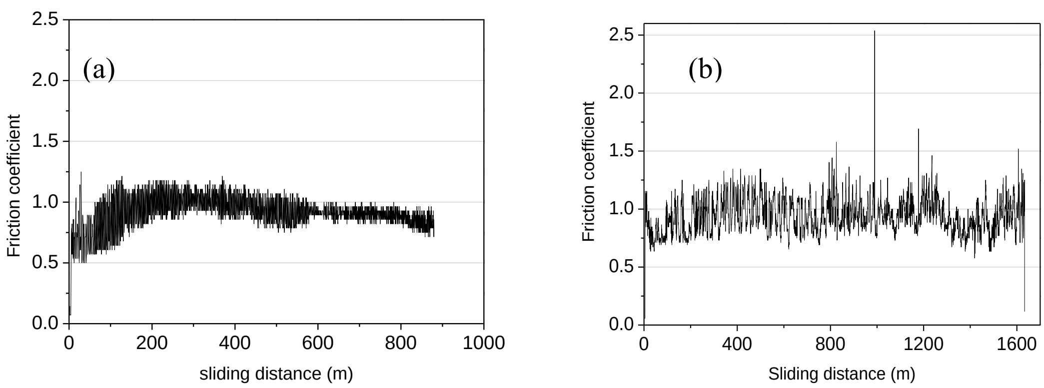

Figure 2. Friction coefficient at high temperature (a) coated disc (b) uncoated disc.

At high temperature (700°C), the average value of the friction coefficient for the coated sample was 0.82 and the coating failure occurred at approximately 100m sliding distance 'figure 2a'. The high friction and wear of ceramics sliding on ceramics has been reported by others to be generally of the order of 0.5-1.0 [11,12]. The friction coefficient for uncoated H13 tool steel was 0.94 and was stable over the 1600m sliding distance. An increase in the weight of the pin material was observed during measurements on the uncoated disc due to the sticking of steel onto the pin. This results in more wear/damage of the uncoated steel discs.

In tribology, oxidation of a test specimen plays an important role in determining its friction and wear behavior. High temperature, studies [13] have reported the oxidation kinetics of H13 tool steel in the temperature range of 200-800°C and found that oxidation is prominent only at high temperatures >800°C with less oxidation at temperatures <800°C.

Studies [14] have reported a remarkably decreased rate of oxidation and increased spallation resistance of Ti_3Al-Al_2O_3 coating at 800°C, so the role of oxidation was not considered to be significant during high temperature tribological testing.

The average value of the friction coefficient at room temperature is 0.57 and is unstable throughout the sliding distance of 80m. This is because alumina particles were pulled out of the metallic matrix and this resulted in a decrease of the coefficient of friction. Moreover the metallic matrix itself comprises of different phases Ti_3Al and TiAl with varying hardnesses so this factor also contributes to the instability of the friction coefficient. The alumina was pulled out of the matrix during ploughing action which acted as an abrasive during testing and thus increased the wear rate at room temperature. The room temperature friction coefficient for uncoated tool steel was about 1.0.

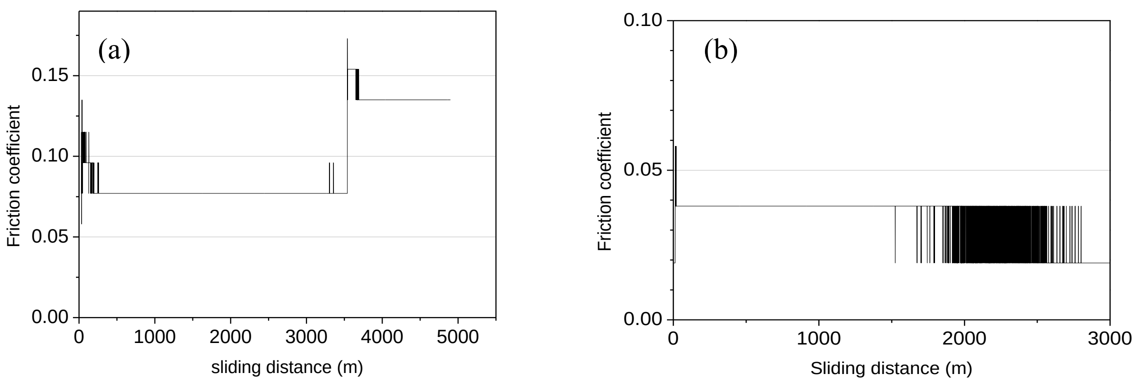

Figure 3. Friction coefficient at room temperature using oil lubricant (a) coated disc (b) uncoated disc.

Using an oil lubricant, the value of friction coefficient for the coated sample is initially high due to the high surface roughness of the coating as shown in 'Figure 3a'. After a run-in period, the surface became smoother. The average value of friction coefficient for the coated sample is 0.08.There is no coating failure, however high surface roughness of the coating led to oil film failure at about 3500m sliding distance. The average value of friction coefficient for the uncoated sample is 0.03 'figure 3b'. These values are lower than the friction coefficients with an un-lubricated alumina pin both at room temperature under dry sliding and at high temperature. The uncoated sample has a lower friction coefficient than the coated sample due to the high surface roughness of the coated sample.

3.3. Specific wear rate

For the pin on disc test, a worn volume was calculated from the dimensions of the worn track [15]. Using the wear track profile, the depth and width of the wear track were easily measured due to its regular profile. The wear rates of the coated and uncoated materials are compared at room and high temperatures (Table 1).

Table 1. Wear rate comparison at room and high temperature.

Samples	Wear Rate (mm^3/N.m)		
	High temperature (700°C)	Room temperature	Room temperature with oil lubrication
Coated	$3.37x10^{-04}$	$2.50x10^{-04}$	$5.70x10^{-05}$
Uncoated	$2.02x10^{-03}$	$6.95x10^{-04}$	$6.89x10^{-06}$

4. Summary

The results of this study show the tribological properties, such as friction and wear rate, of a $TiAl/Al_2O_3$ composite coating. The experimental results show that the wear rates of un-lubricated coated and uncoated samples are of the same order of magnitude at room temperature. For the un-lubricated test specimens, the wear rate of a coated sample is also similar at room temperature and 700°C, however the wear rate of the uncoated sample at 700°C is an order of magnitude greater than its wear rate at room temperature. The use of this coating at the higher temperature is therefore beneficial. At room temperature, under lubrication, the results show a further decrease in the wear rate of the coated and uncoated samples, but the recorded wear rate for the coated sample is higher than that for the uncoated sample. However the wear rate is better than that recorded for the un-lubricated and coated sample. This is probably because of the high surface roughness of the coating. The experimental results show that the composite coating has potential for high temperature applications and that the tribological properties of the coating can be improved by reducing the degree of surface roughness in the as-sprayed coatings.

Acknowledgement

The authors would like to thank the Foundation for Research, Science and Technology (FRST), New Zealand and New Zealand Postgraduate Study Award Abroad (NZPSAA) for their support and funding for the project. Special thanks to Prof. Xiong from the Nanjing University of Science and Technology, China and Peng Cao from the University of Waikato for their valuable assistance and arrangements to carry out this work in China.

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