



Wear resistance enhancement of the titanium alloy Ti–6Al–4V via a novel co-incident microblasting process

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ABSTRACT

In this study a room temperature coating deposition technology was investigated as a means of enhancing wear resistance of the titanium alloy Ti–6Al–4V. This process, termed CoBlast™, consists of co-incident particle streams of abrasive and coating materials which impact a substrate to create a modified surface. Al₂O₃ powder was chosen as the abrasive, while Teflon, SiC and B₄C powders were investigated as coating precursors.

Ti–6Al–4V surfaces modified via CoBlast using either Al₂O₃–SiC or Al₂O₃–B₄C powder mixtures both demonstrated increased hardness compared with the unmodified alloy, however, wear testing performed using a pin-on-disc tribometer revealed that this did not translate to an appreciable improvement in wear resistance performance. In contrast, under the same wear test conditions, Al₂O₃–Teflon CoBlast modified Ti–6Al–4V demonstrated a significantly reduced friction coefficient and average pin-on-disc wear track widths and depths of 68 and 90% less than those which formed on the unmodified alloy. Through the deposition of either SiC or B₄C coatings in combination with a Teflon top layer a further improvement in wear resistance was confirmed by a 81/97% reduction in wear track width/depth.

In conclusion, the deposition of Teflon coatings onto unmodified, SiC modified or B₄C modified Ti–6Al–4V using the CoBlast process yielded surfaces with significantly enhanced wear performance.

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1. Introduction

The superior specific strength [1–5] and corrosion resistance [1,2,4–11] of titanium and its alloys over many commonly available ferrous- and non-ferrous-based metals has drawn considerable attention to these materials within areas such as medical device manufacturing [1–5,12–15], automotive production [6], aerospace frame construction [1] and armoured material fabrication [16,17]. However, the scope of applications for Ti/Ti alloys has been somewhat impeded due in part to issues concerning cost-effectiveness ratio versus alternative metal/metal alloys and poor wear resistance under abrasion/erosion conditions [4,18–20].

The issue of Ti/Ti alloy cost-effectiveness can be attributed largely to the relatively high costs associated with traditional manufacturing approaches [21,22]. Nevertheless, the recent development of a novel processing route for commercial production of a lower grade of Ti (non-FDA approved material) [22] should alleviate this issue and facilitate wider application of these materials, particularly in areas outside of the medical device and aeronautical industries.

A common approach for enhancing Ti/Ti alloy tribological properties for improved wear resistance is to perform surface modifications for increased hardness and/or reduction in friction coefficient [4,6,21,23–30]. For example, Johnson et al. have applied thermal oxidation as a low-cost approach for the production of modified Ti–6Al–4V surfaces demonstrating friction coefficients of as low as 0.1, corresponding to an approximately 70% reduction in comparison to the untreated alloy [6]. However, this approach suffers from similar limitations as other thermal processes such as nitriding [31–33], carburisation [34,35] and boriding [36,37], in that the high thermal stresses produced can lead to torsional twisting of substrates [4,23]. Similar problems are encountered with respect to thermal plasma coating techniques, as substrate surface structure damage can arise [38,39].

The recently developed CoBlast process, represented schematically in Fig. 1 [40], is a novel ambient temperature surface modification technique which enables application of coatings onto metal/metal alloy substrate surfaces [40–42]. In this process, two independent compressed air streams, one incorporating an abrasive powder and the other a powder of a coating material of choice, are simultaneously directed at the same region on a substrate surface with the effect of depositing the coating material on the treated surface. The CoBlast process has already proved successful for the deposition of hydroxyapatite (HA) coatings onto Ti–6Al–4V, at which point it was reported

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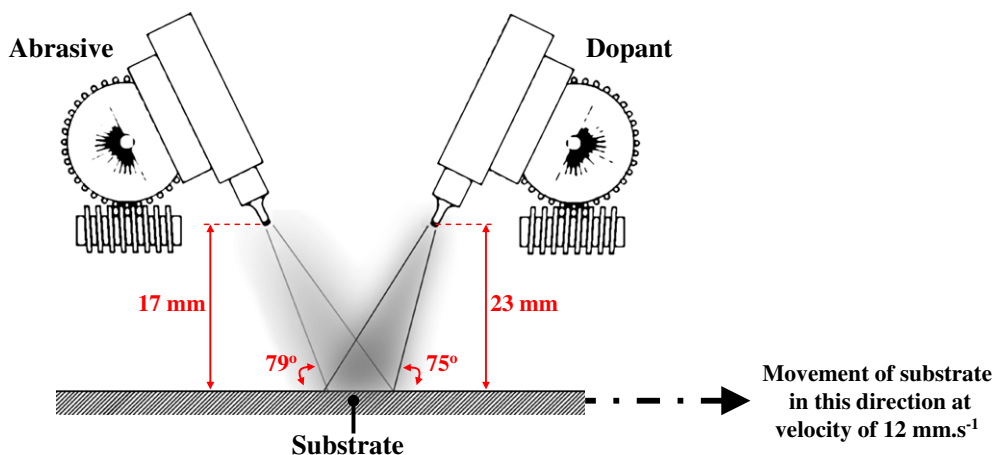


Fig. 1. Schematic representation of CoBlast process depicting abrasive and dopant coating particle streams impacting surface to be modified [40].

that although abrasive particles are not themselves found to be incorporated into the resultant modified surfaces, their role in the process is still imperative as they cause surface roughening which leads to enhanced HA adhesion [40–42]. As the outer passivated oxide layer of the metal alloy is disrupted regions of underlying active titanium become exposed to impacting coating particles resulting in impregnation, mechanical interlocking and chemical bonding of HA [40,42].

In this study use of the CoBlast process for deposition of solid lubricant, hard ceramic and lubricant/ceramic combination coatings onto Ti-6Al-4V for the purpose of enhanced wear performance is investigated for the first time. Teflon is routinely used as a solid lubricant and was selected for inclusion in this study on the basis of properties of high melting point and low friction coefficient [43–48]. Silicon carbide [49–52] and boron carbide [53–56] were selected as the hard ceramic powders on the basis of both high-hardness and favourable wear resistance.

2. Materials and methods

2.1. Surface modifications

15 mm × 15 mm × 3 mm substrate coupons were cut from sheets of the titanium aluminium vanadium alloy Ti-6Al-4V. These coupons were ground using P1200 grit SiC grinding paper to provide a uniform surface roughness ($R_a = 8.5 \times 10^{-2} \mu\text{m}$). Prior to coating coupons were immersed in isopropyl alcohol, placed in an ultrasonic bath for 10 min and dried in air.

The CoBlast process was applied for surface modification of Ti-6Al-4V coupons with alumina powder (Al_2O_3 , $d_{50} = 100 \mu\text{m}$, Comco Inc.) used as the abrasive material in all cases. Teflon ($\text{C}_n\text{F}_{2n+2}$, $d_{50} = 12 \mu\text{m}$, Zonyl MP 1300, DuPont®), ‘green’ silicon carbide (SiC, $d_{50} = 20 \mu\text{m}$, F400, Electro Abrasives Corp.) and boron carbide (B_4C , $d_{50} = 18 \mu\text{m}$, F500, Electro Abrasives Corp.) were selected as dopant coating materials. Abrasive and coating powders were both fed at pressures of 90 psi to independent MB 1500-29 microblast nozzles (1.2 mm diameter circular nozzle, Comco Inc.) arranged so as to produce controlled convergent blast zones on coupon substrate surfaces (as depicted in Fig. 1). The abrasive nozzle was set 79° to and 17 mm above substrates, with the dopant nozzle fixed 75° to and 23 mm above the same plane. All modifications were performed at room temperature using a substrate stage speed of 12 mm s^{-1} (equating to a process time of approximately 30 s). Selected coupons also underwent surface treatment via an alternative approach termed

‘microblasting’ and were prepared as per CoBlast modified surfaces but with the absence of the Al_2O_3 abrasive stream. All surfaces were blasted post-modification with clean dry air at 60 psi to remove loosely adhered material.

2.2. Surface characterisation

The surface morphologies of unmodified and modified coupons were examined via a tabletop Hitachi TM-1000 SEM (scanning electron microscope) with a BSE detector using an accelerating voltage of 15.0 kV and working distances of 6.1–7.1 mm. Elemental compositions at coupon surfaces were determined using an Oxford Instruments SwiftED-TM EDS (energy dispersive X-ray spectrometer) system attached to the Hitachi SEM. Friction coefficient quantification was performed in air on a TEER Coatings POD-2 pin-on-disc tribometer at room temperature using an indexable 3 mm tungsten carbide (WC) ball. These particular parameters were selected on the grounds that this manner of testing would replicate the environment to which Ti alloys would be challenged under extreme conditions of abrasive wear on coming into contact with a material of higher hardness than itself. Surface roughness and wear track characteristics were examined using a Wyko NT 1100 optical profilometer (50× objective, 1.0× field-of-view lens) operating in phase shift interferometry (PSI) mode. Contact angle (CA) measurements were obtained via the sessile drop technique using an OCA 20 video capture apparatus from Dataphysics Instruments. 1.0 μl drops of deionised water, ethylene glycol and diiodomethane were used for surface energy measurements via the OWRK (Owens, Wendt, Rabel and Kaelble) method [57]. The principal assumption of this method is that surface energy is a sum of two components: dispersion and polar surface energies, where the former reflects the dispersion interaction occurring on an interface while the latter is the sum of polar, hydrogen, inductive and acid–base interactions [57,58]. Surface hardness was assessed at CSM Instruments (Peseux, Switzerland) using a Nano Indentation Tester (NHT) in conjunction with the Instrumented Indentation Technique (IIT) [59]. The NHT test equipment was particularly apt for characterisation of the μm -thick modified surfaces fabricated throughout this work as it allowed for control of load and quantification of penetration depth and, thus, minimised influence of bulk Ti-6Al-4V on measurements. Tests were performed in air at 26°C and 40% humidity using a Berkovich indenter at an approach speed of $2 \mu\text{m min}^{-1}$. Surfaces were loaded linearly at a rate of 50 mN min^{-1} to a maximum of 25 mN. Unloading at a rate of 50 mN min^{-1} commenced 15 s after arrival at maximum load. All hardness and elastic modulus

results were obtained using the Oliver and Pharr method and via a supposed Poisson's ratio of 0.3 for estimations of the latter [60].

3. Results and discussion

3.1. Lubricant coatings

A baseline study was initially performed on the unmodified Ti-6Al-4V substrate control. Fig. 2(a) shows the surface morphology of this material when viewed under SEM at 500 \times magnification and reveals some scarring due to efforts to improve surface roughness uniformity. Pin-on-disc wear tests were performed using 1000–9000 pin cycles at fixed loads of 1–10 N

and angular velocities of 1–19 cm s⁻¹. Friction coefficients in the 0.35–0.65 range and wear track widths/depths of 353–1393 μm /11–172 μm were recorded, indicating that Ti-6Al-4V offers poor wear resistance in the native state. The expected Ti, Al and V elemental composition of the substrate control was confirmed via EDS (Table 1). Unmodified Ti-6Al-4V demonstrated an average water droplet CA and surface energy of 47 $^\circ$ and 48.7 mN m⁻¹ respectively.

Preliminary Ti-6Al-4V surface modifications concerned microblasting (i.e. no concurrent abrasive flow) with Teflon. SEM of coatings produced in this manner established that Teflon depositions were non-homogeneous and particulate in nature, as can be seen in Fig. 2(b). The presence of a substantial Teflon composition within

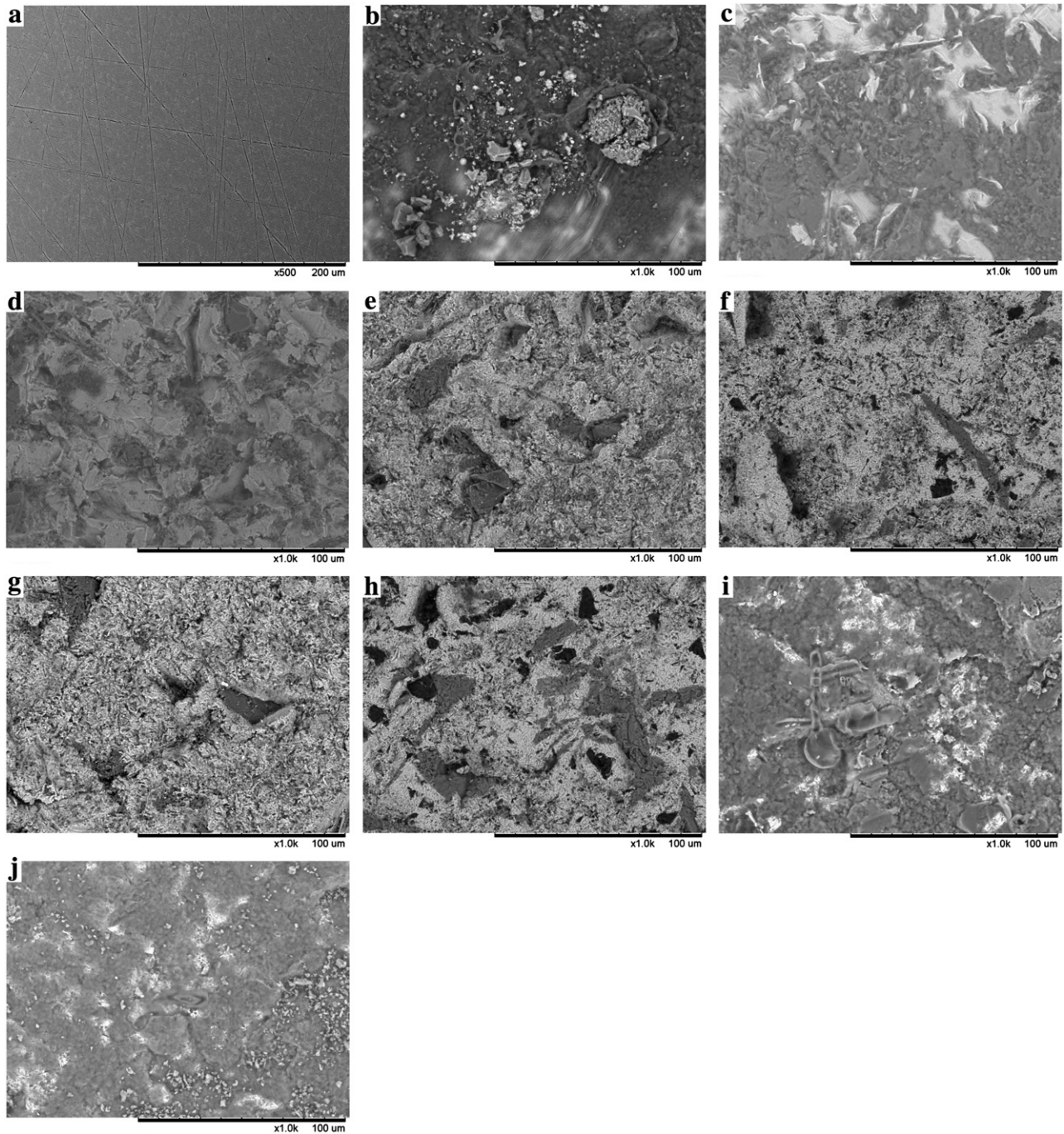


Fig. 2. SEM micrographs of surfaces of unmodified (a), Teflon microblasted (b), Al₂O₃-Teflon modified (c), Al₂O₃ microblasted (d), Al₂O₃-SiC modified (e), Al₂O₃-B₄C modified (f), heat-treated Al₂O₃-SiC modified (g), heat-treated Al₂O₃-B₄C modified (h), Teflon microblasted on heat-treated Al₂O₃-SiC modified (i) and Teflon microblasted on heat-treated Al₂O₃-B₄C modified Ti-6Al-4V (j).

Table 1
Summary of EDS and contact angle (CA) measurements.

Ti-6Al-4V surface	Elemental composition (at.%)					Contact angle (CA) with water droplets (°)
	Ti	Al	V	F	Si	
Unmodified	85.1	9.6	5.3	–	–	47 ± 5
Teflon microblasted	22.6	1.4	2.1	73.9	–	112 ± 2
Al ₂ O ₃ -Teflon CoBlast modified	17.8	1.4	1.0	78.7	1.1	128 ± 3
Al ₂ O ₃ microblasted	79.4	16.1	4.5	–	–	70 ± 7
Al ₂ O ₃ -SiC CoBlast modified	60.1	11.1	4.6	–	24.2	73 ± 8
Heat-treated Al ₂ O ₃ -SiC CoBlast modified	65.5	7.1	3.3	–	24.1	103 ± 7
Teflon microblasted heat-treated Al ₂ O ₃ -SiC CoBlast modified	6.5	1.6	0.4	89.1	2.4	112 ± 2
Teflon microblasted heat-treated Al ₂ O ₃ -B ₄ C CoBlast modified	24.4	1.6	1.3	72.7	–	122 ± 5

these coatings was confirmed by the EDS detection of an average fluorine concentration of 74 at.% and also due to their hydrophobicity revealed in the form of an average water droplet CA of 112° [61]. As was the case for all modified surfaces produced in this study, EDS also detected significant levels of Ti, Al and V from the underlying alloy substrate due to the analysis depth associated with this technique (Table 1). Pin-on-disc wear analysis of Teflon microblasted surfaces was carried out using a test load of 1 N at an angular velocity of 5.2 cm s⁻¹ and determined a friction coefficient of approximately 0.6. This value is towards the upper-end of the 0.35–0.65 range which was established for the untreated alloy, indicating that Teflon microblasting did not yield the reduction in surface friction anticipated for this solid lubricant material. Inspection of the tracks which formed on Teflon microblasted surfaces as a result of pin-on-disc wear testing (not given) suggested that complete coating removal had occurred, indicating poor adhesion to the Ti-6Al-4V. It was concluded from this study that microblasting alone did not yield Teflon layers with sufficient adhesion to serve as a solid lubricant coating on the metal alloy.

A second set of trials combined flows of Al₂O₃ abrasive with Teflon powder using the CoBlast process. The SEM micrograph provided in Fig. 2(c) shows the surface morphology of an Al₂O₃-Teflon CoBlast modified Ti-6Al-4V surface. Cross-sectional SEM characterisation of the modified surfaces produced in this study was not performed, however, previous studies concerning the CoBlast deposition of a range of powders of similar average particle sizes to the coating materials selected herein determined coating depths in the range of 10 µm [40]. The white layered coating was confirmed as Teflon due to both a high fluorine composition (79 at.% detected via EDS) and high average water droplet CA (128°). This CA value is significantly higher than that which was recorded for Teflon microblasted Ti-6Al-4V and may suggest that additional surface roughening combined with the natural hydrophobic properties of Teflon to produce a surface with an

increased degree of water repellency. Profilometry supported this effect by determining that Teflon microblasting led to a slight reduction in surface roughness ($R_a = 1.7 \times 10^{-2} \mu\text{m}$) relative to the unmodified metal alloy ($R_a = 8.5 \times 10^{-2} \mu\text{m}$), whereas Al₂O₃-Teflon CoBlast modification resulted in a significant increase in roughness ($R_a = 2.1 \mu\text{m}$).

Pin-on-disc wear testing of Al₂O₃-Teflon modified Ti-6Al-4V using the same test conditions of 1 N load and 5.2 cm s⁻¹ angular velocity as were employed for Teflon microblasted surfaces led to estimation of a friction coefficient of approximately 0.1. This represents a considerable reduction compared with the 0.35–0.65 range obtained for unmodified Ti-6Al-4V and is in line with the value reported by Johnson et al. for low friction oxidative treatments [6]. The wear resistance of Al₂O₃-Teflon modified surfaces was further scrutinised by running numerous other pin-on-disc tests under significantly more wear-intensive test conditions up to the maximum fixed loads and angular velocities of 20 N and 23.6 cm s⁻¹ respectively. The friction coefficient remained at approximately 0.1 for all test conditions, even after 6000 pin cycles. The wear tracks which formed on Al₂O₃-Teflon modified surfaces following pin-on-disc testing under 10 N at 19 cm s⁻¹ for 1800 s had an average width and depth of 448 and 17 µm, representing a 68 and 90% reduction respectively in these dimensions in comparison to the wear tracks which formed on unmodified Ti-6Al-4V under the same test conditions (refer to Fig. 3).

It is reported in the literature that blasting of metals/metal alloys with particulate material can lead to work hardening and that this increased hardness can give rise to enhanced surface wear resistance [62,63]. SEM characterisation of Al₂O₃ microblasted Ti-6Al-4V (Fig. 2(d)) suggests a significant increase in surface roughness in comparison to the unmodified alloy and the profilometry results presented in Table 2 verify this. Fig. 4 exhibits the wear tracks which formed on Al₂O₃ microblasted (coupon (a)) and Al₂O₃-Teflon modified Ti-6Al-4V (coupon (b)) as a

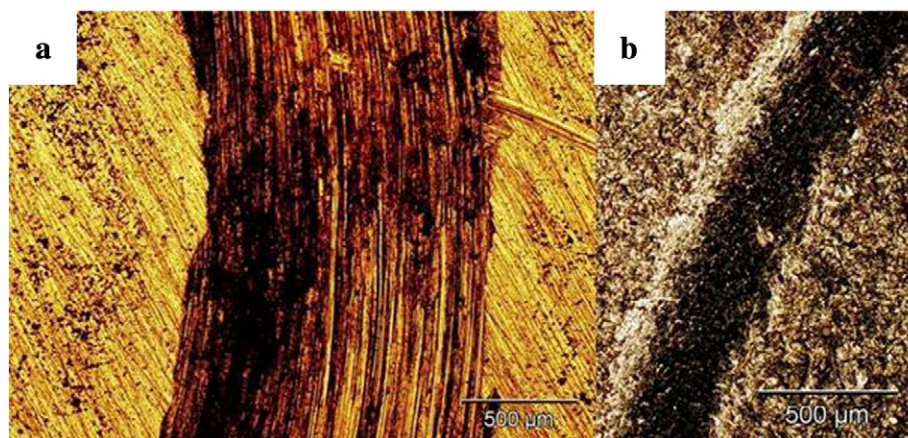


Fig. 3. Pin-on-disc wear tracks which formed on unmodified (a) and Al₂O₃-Teflon modified Ti-6Al-4V (b) under test conditions of 10 N load at 19 cm s⁻¹ angular velocity for 1800 s.

Table 2
Summary of pin-on-disc, surface energy and surface roughness measurements.

Ti-6Al-4V surface	Friction coefficient	Pin-on-disc wear track width, depth (μm)	Surface energy (mN m^{-1})	Average surface roughness ($R_a, \mu\text{m}$)
Smoothened unmodified	0.35–0.65	353, 11 ^a 1393, 172 ^b	48.7	$8.5 \times 10^{-2} \pm 0.8 \times 10^{-2}$
Teflon microblasted	0.6	380, 12 ^a	13.5	$1.7 \times 10^{-2} \pm 0.9 \times 10^{-2}$
Al ₂ O ₃ -Teflon CoBlast modified	0.1	448, 17 ^b	6.5	2.1 ± 0.2
Al ₂ O ₃ microblasted	0.7	483, 19 ^a	30.2	2.2 ± 0.4
Al ₂ O ₃ -SiC CoBlast modified	0.6	323, 9 ^a	40.7	2.1 ± 0.4
Al ₂ O ₃ -B ₄ C CoBlast modified	0.6	342, 10 ^a	38.6	1.7 ± 0.1
Heat-treated Al ₂ O ₃ -SiC CoBlast modified	0.6	265, 6 ^a	48.0	1.8 ± 0.2
Heat-treated Al ₂ O ₃ -B ₄ C CoBlast modified	0.65	358, 11 ^a	41.6	2.0 ± 0.2
Teflon microblasted heat-treated Al ₂ O ₃ -SiC CoBlast modified	0.1	288, 7 ^b	13.4	1.6 ± 0.3
Teflon microblasted heat-treated Al ₂ O ₃ -B ₄ C CoBlast modified	0.1	267, 6 ^b	7.0	1.8 ± 0.2

^a Test conditions: 1 N load at 1 cm s⁻¹ angular velocity for 1800 s.

^b Test conditions: 10 N load at 19 cm s⁻¹ angular velocity for 1800 s.

result of various pin-on-disc tests. The two tracks on the Al₂O₃ microblasted surface and the two inner tracks on the Al₂O₃-Teflon modified surface were generated using identical test conditions (1 N at 0.67/1.0 cm s⁻¹ for 1800 s). The contrast in physical appearance between these tracks demonstrates that the degree of wear experienced by the Al₂O₃ microblasted surface was significantly greater than for the Al₂O₃-Teflon modified surface. This suggests that, although Al₂O₃ microblasting may have increased Ti-6Al-4V surface hardness in accordance with reports in literature [62,63], this did not translate to a positive effect in terms of wear resistance. In fact, following identical pin-on-disc tests it was found that the average wear track depth on Al₂O₃ microblasted Ti-6Al-4V was even greater than for the unmodified alloy (refer to Table 2). As mentioned above, the surface roughness of Al₂O₃ microblasted Ti-6Al-4V was substantially higher than for the unmodified alloy and this likely attributed to the increased degree of wear experienced in the case of the former as a greater accumulation of particulate material would have formed during testing with the effect of making test conditions even more wear-intensive.

These results indicate that CoBlast-processed Al₂O₃-Teflon surface coatings exhibit superior wear resistance over surfaces processed using either Al₂O₃ or Teflon in isolation. The authors postulate that this enhancement may be due to impregnation of Teflon into the metal alloy surface with the energetic alumina bombardment producing a tribochemical bond formation between the substrate and Teflon particles, as similar effects have been reported for

deposition of bioceramic coatings using the same process [40,42]. This could be responsible for enhanced bonding to the metal alloy substrate for the case of Teflon coatings deposited via CoBlast relative to microblasting and may explain the enhanced wear resistance demonstrated by Al₂O₃-Teflon modified Ti-6Al-4V.

3.2. Hard coatings

Independent CoBlast deposition studies were carried out for both SiC and B₄C powders to investigate the effect of these hard ceramics on Ti-6Al-4V wear resistance. SEM examination of Al₂O₃-SiC (Fig. 2(e)) and Al₂O₃-B₄C modified Ti-6Al-4V (Fig. 2(f)) showed surfaces both exhibiting similar morphologies to that of Al₂O₃ microblasted surfaces. EDS confirmed the presence of elemental Si on the surface of Al₂O₃-SiC modified Ti-6Al-4V (24 at.%, Table 1). The EDS system used during this study did not possess the capability to detect elements with atomic weights of as low as boron, however, since deposition of SiC particles of similar size and hardness proved successful there was no reason not to assume the same was also the case for B₄C. Pin-on-disc wear analysis of both Al₂O₃-SiC and Al₂O₃-B₄C modified surfaces under identical test parameters (1 N at 1 cm s⁻¹ for 1800 s) established friction coefficients and wear track widths/depths comparable to those recorded for the unmodified alloy (refer to Table 2), indicating that neither modification demonstrated appreciable enhancement of wear resistance performance over Ti-6Al-4V in its native state. So, while incorporation of SiC and B₄C particulate into the Ti-6Al-4V matrix was accomplished, it is suggested that weakly attached powder grains resulted in adhesion levels which were insufficient in relation to generating a positive impact on wear performance. In an effort to enhance coating adhesion heat-treatment of both Al₂O₃-SiC and Al₂O₃-B₄C modified coupons was performed at a ramp rate of 2 °C min⁻¹ under vacuum within an Ar atmosphere to 673 °C. Coupons were held at this temperature for 6 h before cooling to room temperature at 2 °C min⁻¹. The surface morphologies of Al₂O₃-SiC (Fig. 2(g)) and Al₂O₃-B₄C modified Ti-6Al-4V (Fig. 2(h)) were similar in appearance to these same surfaces prior to undergoing heat-treatment. The Vickers Hardness of heat-treated Al₂O₃-SiC (546 HV, 5.4 GPa) and Al₂O₃-B₄C (563 HV, 5.5 GPa) modified surfaces was found to have increased in comparison to the unmodified metal alloy (468 HV, 4.6 GPa). However, pin-on-disc wear analysis of these heated-treated surfaces established friction coefficients and wear tracks/depths which suggested no considerable improvement in wear resistance over either their non-heat-treated counterparts or the unmodified alloy (Table 2).

3.3. Hard and lubricant combination coatings

Since heat-treated Al₂O₃-SiC and Al₂O₃-B₄C modifications were found to enhance Ti-6Al-4V surface hardness, while Al₂O₃-Teflon modifications decreased friction coefficient and improved wear

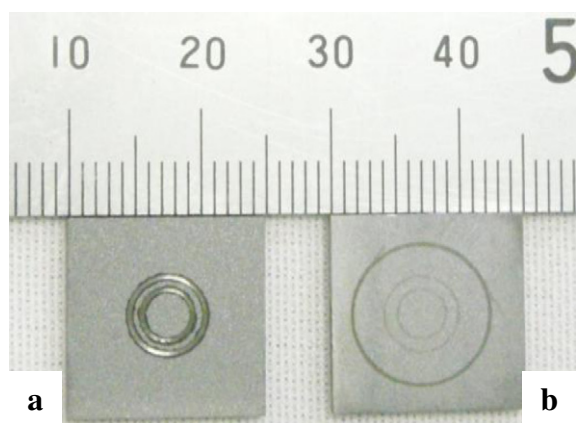


Fig. 4. Pin-on-disc wear tracks which formed on Al₂O₃ microblasted (a) and Al₂O₃-Teflon modified Ti-6Al-4V (b) (scale = mm). The inner tracks on both surfaces resulted from tests under 1 N load at 0.67 cm s⁻¹ angular velocity for 1800 s, while the outer and second furthest out tracks on the former and latter modified surfaces respectively resulted from tests using 1 N load at 1.0 cm s⁻¹ angular velocity for 1800 s.

performance, it was proposed that a surface modification comprising a combination of both hard and solid lubricant properties may lead to further enhancement of wear resistance. Such coatings were prepared via microblasting a layer of Teflon over heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ and $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified surfaces.

The white material observed during SEM of both Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ (Fig. 2(i)) and $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified surfaces (Fig. 2(j)) was confirmed as Teflon via EDS (89 and 73 at.% F concentrations respectively) and CA analysis (average water droplet CA's of 112 and 122° respectively). The higher levels of F detected for the former surface was likely caused by a slightly thicker deposition of Teflon in this instance. Detection via EDS of a low concentration of Si atoms (refer to Table 1) for Teflon coated heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ modified surfaces suggests that lubricant deposition via microblasting did not lead to removal of the underlying SiC layer.

Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ and $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified Ti-6Al-4V surfaces were subjected to pin-on-disc testing under 10 N load at 19 cm s^{-1} angular velocity for 1800 s and both surfaces demonstrated friction coefficients of approximately 0.1, corresponding to the same low friction levels as were associated with $\text{Al}_2\text{O}_3\text{-Teflon}$ modified Ti-6Al-4V. The improvement in Ti-6Al-4V wear performance from modifications comprising hardened surfaces with low surface energies was further verified from inspection of the tracks which formed during these wear tests. While unmodified metal alloy surfaces showed an average track width and depth of 1393 and 172 μm respectively, and $\text{Al}_2\text{O}_3\text{-Teflon}$ modified surfaces an average width and depth of 448 and 17 μm respectively, their Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ and $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified counterparts demonstrated average widths/depths of just 288/7 and 267/6 μm respectively. This represents a 79 and 96% reduction in track width and depth respectively for Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ modified surfaces, and 81 and 97% reduction in track width and depth respectively for Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified surfaces.

The fact that CoBlast surface modifications combining increased hardness with solid lubricant behaviour significantly enhanced Ti-6Al-4V wear resistance was further scrutinised by carrying out pin-on-disc tests under the significantly increased load and angular velocity of 30 N and 44 cm s^{-1} respectively. Under these more challenging test conditions Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ and $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified surfaces exhibited resistance to sliding wear for almost 3000 pin cycles (refer to Fig. 5), after which time coating failure occurred in both cases and friction coefficients increased from approximately 0.1 to the 0.35–0.65 range associated with the underlying bulk Ti-6Al-4V substrate. Interestingly, on application of the same pin-on-disc test conditions for the unmodified alloy, the extent of wear taking place was so extreme that testing had to be halted immediately on commencing due to concerns regarding detrimental impact on test equipment.

4. Conclusions

This study established that certain coatings deposited using the CoBlast process significantly decrease the level of wear and friction observed for the case of the titanium alloy Ti-6Al-4V.

Attempts to increase the tribological performance of Ti-6Al-4V using SiC or B_4C coatings alone was found to have no significant impact on wear performance, despite a measured increase in surface hardness. In contrast, $\text{Al}_2\text{O}_3\text{-Teflon}$ deposited coatings did demonstrate superior wear resistance when compared to the unmodified metal alloy (68/90% reduction in average pin-on-disc wear track width/depth). This was achieved by decreasing the surface friction coefficient from values in the 0.35–0.65 range to approximately 0.1. A further improvement in Ti-6Al-4V wear performance was achieved when a Teflon layer was applied by microblasting onto heat-treated SiC and B_4C CoBlast modified coatings. These Teflon over ceramic coated surfaces exhibited similar 0.1 friction coefficients as for Teflon only coated surfaces, but demonstrated increased resistance to pin-on-disc wear track formation (79/96% and 81/97%

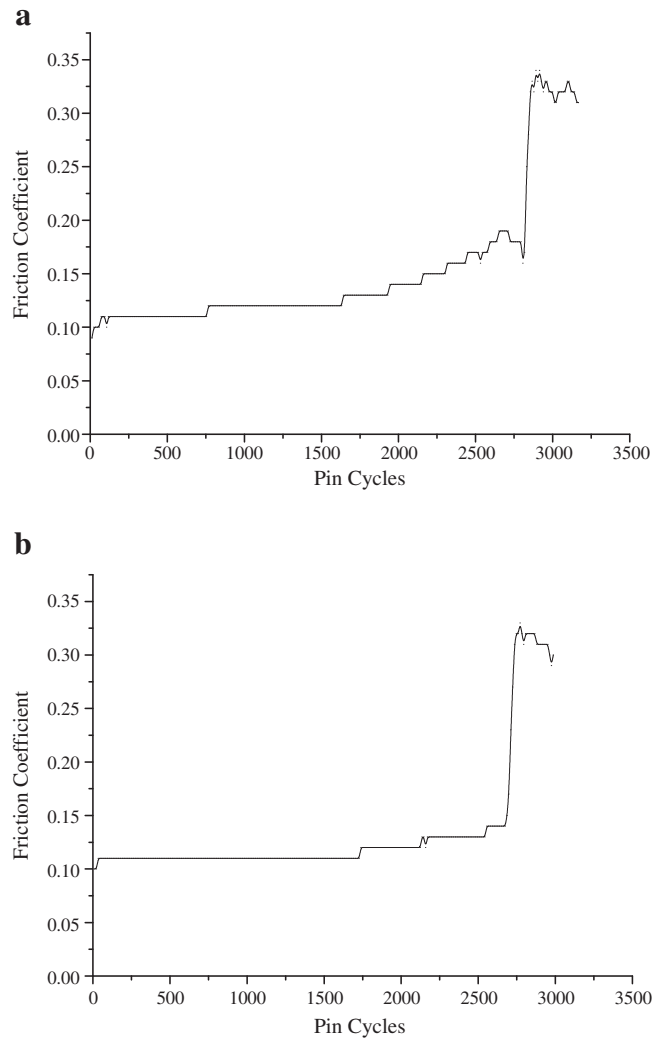


Fig. 5. Number of pin cycles versus friction coefficient plots for Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-SiC}$ (a) and Teflon microblasted heat-treated $\text{Al}_2\text{O}_3\text{-B}_4\text{C}$ modified Ti-6Al-4V surfaces (b) following wear tests under 30 N load at 44 cm s^{-1} angular velocity.

reductions in average track width/depth respectively in comparison to unmodified Ti-6Al-4V).

In conclusion, the CoBlast technique shows considerable potential as a low temperature deposition technology for the application of low friction and wear resistant coatings onto titanium alloys. The widespread use of such metal alloys has met limitations in applications where wear resistance is required, for example in machinery part construction [64–66], and so CoBlast may be an economical and straight-forward option by which surface modified Ti/Ti alloys with enhanced wear performance can be considered for use in applications where traditionally they would not have been.

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