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The influence of substrate material on the erosion resistance of TiN coated tool steels

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Abstract

In the present study the influence of substrate material on the erosion resistance of three different TiN coated tool steels (two high speed steels and one cold work steel) has been investigated. The particle velocity was 20 m s^{-1}, two angles of impingement (20° and 30°) were used and silicon carbide was used as erodent.

The results showed that, the carbide volume fraction and the impact toughness of the substrate material controlled the erosion rate of both coatings and substrates. It was concluded that as long as the test parameters allow the impinging particles to significantly affect the substrate material during erosive testing of a coated composite, the substrate material will influence the erosive response of the coating.

Keywords: Erosion; TiN; Coatings; Tool steel

1. Introduction

Coatings are today deposited onto substrates for a variety of reasons, e.g. for their optical properties, for decorative purposes or for improving the tribological performance in some engineering application. In all cases, a main problem is the characterization and evaluation of the mechanical and tribological properties of the coating. Knowing these are useful, e.g. for wear life estimations or ranking of wear resistant coatings but also as a general check of the overall mechanical quality of the coating. The small dimensions of thin, wear-resistant coatings (usually 1–10 μm thick) make mechanical and tribological evaluations particularly difficult and in most methods [1–4] both coating and substrate will contribute to the overall tribological performance. This is definitely also the case in erosion testing. Still, several features combine to make erosion testing a highly suitable method for tribological evaluation of thin, hard coatings. The most important are that;

- it can detect insufficient adhesion [5];
- its nature ensures statistically significant results (the results constitute an "automatic" mean value obtained from the entire eroded surface);
- it is highly reproducible;
- variations over the specimen surface can be detected;
- the test parameters are relatively few and comparatively easy to control.

However, in order to facilitate interpretation of results from erosive testing of coating–substrate composites a better understanding of e.g. the role of the underlying substrate material is needed. The present study constitutes an attempt to evaluate the influence of substrate material on the overall tribological performance of coating–substrate composites (titanium nitride (TiN) on three different tool steels) exposed to solid particle erosion.

2. Experimental

2.1. Materials

Three different, industrially important tool steels were used as substrate materials; two powder metallurgical (PM) high speed steels (HSS), ASP23 (similar to AISI M2) and ASP60 (Erasteel Kloster AB designation), and a PM cold work steel, VANADIS 4 (Uddeholm Tooling AB designation), see Tables 1 and Table 2. The HSSs were heat-treated by austenitization at 1180 °C and tempered 3 × 1 h at 560 °C, while

Table 1
Nominal chemical composition of the tool steels

Steel	Chemical composition (wt.%)							
	C	Si	Mn	Cr	Mo	W	V	Co
ASP23	1.28	0.6	0.4	4.2	5.0	6.4	3.1	–
ASP60	2.30	0.6	0.4	4.2	7.0	6.5	6.5	10.5
VANADIS 4	1.5	1.0	0.4	8.0	1.2	–	4.0	–

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Table 2
Substrate hardness, impact toughness and carbide volume fraction of the tool steels

Steel	Substrate hardness ($HV_{30\,kg}$)	Impact toughness [a] (J)	Carbide volume fraction (%)
ASP23	900 ± 20	35	13
ASP60	1000 ± 20	14	19
VANADIS 4	700 ± 10	54	11

[a] Nominal values obtained by the Charpy test.

Table 3
Coating thicknesses on all investigated specimens

Angle of impingement (deg)	Coating thickness (μm)		
	ASP23	ASP60	VANADIS 4
20	4.2 ± 0.2	4.4 ± 0.2	4.5 ± 0.2
30	4.1 ± 0.2	4.7 ± 0.2	4.7 ± 0.2

VANADIS 4 was heat-treated at 1020 °C for 0.5 h and then tempered 2 × 2 h at 525 °C.

Before coating, all specimens were face ground to a thickness of 3 mm, polished with 1 μm diamond in the last step and then cleaned in an USI 2000 industrial cleaning unit using three alkaline washing steps separated by rinsing and completed by a PCKW-free drying step with hot air. The TiN coatings were then deposited (all in the same batch) in a Balzers BAI 830 coating unit using a standard isothermal three step procedure:

(1) high current density plasma beam heating to a temperature of approximately 450 °C,
(2) triode etching in argon in the plasma provided by the high current density beam and
(3) reactive ion plating with high current density plasma beam evaporation. The coatings were deposited at constant nitrogen partial pressure.

The coating thickness (Table 3) was measured using a Fischerscope X-ray 1000 based on the non-destructive X-ray principle (as described in ISO 3497, ASTM B568 and DIN 50987). The standard deviation is used as a measure of the scatter.

High purity (99.7%), angular silicon carbide particles, with a particle size distribution of 150–212 μm, were used as erodent. The hardness of the eroding particles was 2700 ± 200 HV (L = 0.25 N).

2.2. Experimental

The composite hardness (the as-measured hardness of a coated specimen) was measured using a conventional Vickers microhardness indenter and a load of 0.5 N.

Both TiN coated and uncoated substrates were eroded using a centrifugal erosion tester ("erofuge") in which up to 18 specimens (20 × 20 mm) can be eroded simultaneously under identical testing conditions, see Fig. 1. The tests were performed using angles of impingement of both 20° and 30° and a particle velocity of 20 m s^{-1}.

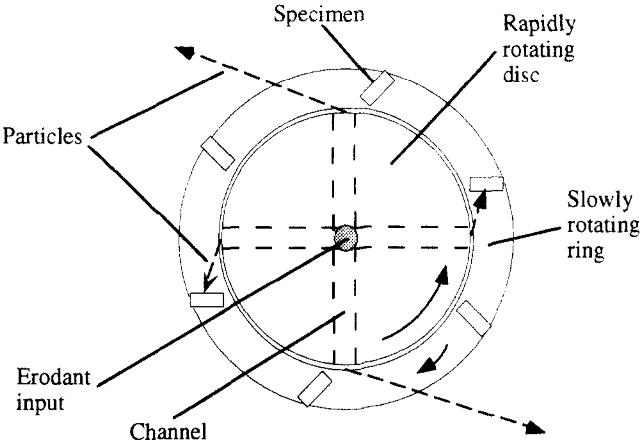

Fig. 1. Schematic view of the centrifugal erosion tester. The eroding particles are fed into the centre of the rapidly rotating disc. They are then accelerated by the centrifugal force through four radial channels and eventually hit the specimens. A more detailed description of the test equipment is given in Ref. [6].

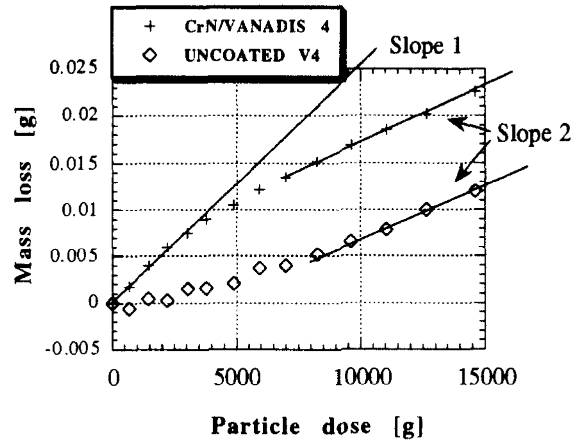

Fig. 2. Example of a mass loss vs. particle dose plot (From [7]. The eroded specimen consists of PVD chromium nitride on VANADIS 4. The same silicon carbide particles as in the present study were used as erodent, the particle velocity was 20 m s^{-1} and the angle of impingement 45°.). Please note the different slopes corresponding to erosion of coating and substrate material, respectively.

When determining the intrinsic wear rate of thin, wear-resistant PVD coatings the mass loss technique is not commonly utilized. This is mainly because the mass losses involved often are too small to be accurately measured. However, a recent investigation by the present authors has shown that the mass loss technique can be used for erosion rate (e) determination of PVD coatings [7]. Basically, it was shown that if a number of careful mass loss measurements are made at regular intervals during the test and the accumulated mass loss is plotted vs. the particle dose, two distinct, linear parts of the resulting curve can be discerned (Fig. 2). One of these linear parts corresponds to the erosion rate of the coating and the other to e of the substrate.

This technique was utilized in the present tests, but the amount of time needed for the experiments was decreased by

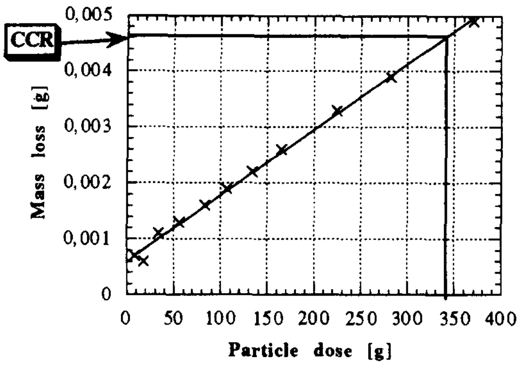

Fig. 3. Representative mass loss vs particle dose plot from the present tests (TiN/ASP23, 20°). The mass loss and particle dose corresponding to complete coating removal (CCR) are both indicated.

removing the individual specimens well below an accumulated mass loss corresponding to complete coating removal over the entire eroded surface (i.e. remaining in the "slope 1 region" of Fig. 2). A linear relation between mass loss and particle dose was obtained for all specimens (see e.g. Fig. 3) and the coating erosion rate is considered to be given by the slope of these lines.

3. Results

3.1. Hardness

The composite hardness was found to increase in the order TiN/VANADIS 4<TiN/ASP23<TiN/ASP60, see Table 4.

3.2. Erosion resistance

For a given coating–substrate composite at an angle of impingement of 20°, the erosion rate of the substrate material was generally higher than that of the corresponding TiN coating (Fig. 4(a)). In the case of the coatings, TiN on ASP23 and on VANADIS 4 displayed similar *e*s, both being lower than that of TiN on ASP60. Of the uncoated specimens, the two HSSs displayed a higher erosion rate than VANADIS 4.

At an angle of impingement of 30°, a given composite does not display any dramatic differences in e between the coating and the substrate material, see Fig. 4(b). There is, however, a slight tendency towards higher erosion rates for the coatings. The highest erosion rate was detected for TiN on ASP23 followed by TiN on ASP60 and then TiN on VANADIS 4; the same order was displayed by the substrates.

In many cases the volumetric erosion rate (easily obtained by dividing the results in Figs. 4(a) and 4(b) with the densities corresponding to coating and substrates) is of more interest; it makes it easier to visualize the amount of wear that has taken place. Expressed in this way, it is found that at a 20° angle of impingement the erosion rate of an uncoated specimen is more or less the same as that of the corresponding TiN coating, see Fig. 5(a). The difference between the individual coatings and substrates, respectively, is also small.

Table 4
Composite hardnesses

Coating–substrate composite	Composite hardness (L = 0.5 N) (HV)
TiN/ASP60	2150 ± 200
TiN/ASP23	2000 ± 200
TiN/VANADIS 4	1900 ± 200

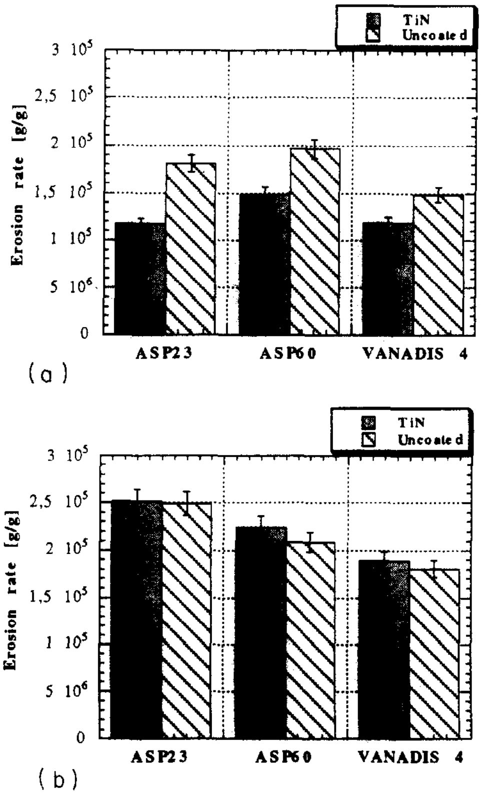

Fig. 4. Erosion rates for an angle of impingement of (a) 20° and (b) 30°.

At 30° (Fig. 5(b)), the volumetric erosion rate of the TiN coatings is generally higher than that of the uncoated substrates. The same performance ranking as described previously (cf. Fig. 4(b)) is obtained for both coatings and substrates.

3.3. Coating erosion mechanisms

Two types of single particle impact damages were observed: pure cutting impacts and indentation-like impact craters, see Fig. 6. Cross-sectional SEM studies showed that some of the single particle impacts resulted in minor plastic deformation of the underlying substrate. The vertical size of the deformation was in the range less than one half micron. However, the great majority of single particle impacts did not cause any detectable plastic deformation of the substrate at all.

As the particle dose increases, two dominant coating erosion mechanisms are discerned (Fig. 7). Initially, coating material removed by cutting impacts is the most important.

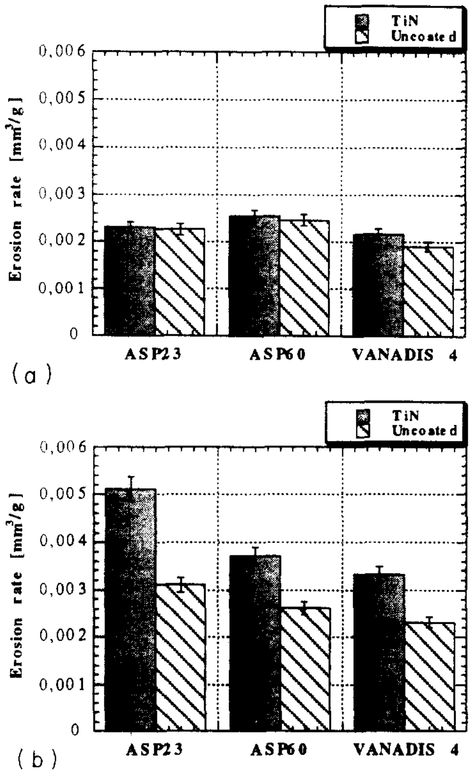

Fig. 5. Volumetric erosion rate for an angle of impingement of (a) 20° and (b) 30°.

However, as the wear process continues a high number of impacts will introduce cracks in the coating. These cracks, mainly lateral, will propagate in the coating and interact with adjacent cracks and, eventually, coating fragments will be detached. This coating erosion mechanism has been named ''erosive fatigue wear'' [8] since its requires a large number of impacts before any coating material is removed. The mechanism is characterized by the removal of fairly big coating flakes (10–30 μm in diameter), see Fig. 8.

4. Discussion

In general, the erosive response of a TiN coating was found to follow that of its substrate material, i.e. a TiN coating deposited on a substrate with a relatively high erosion rate was also found to have a relatively high e. This can be explained by the fact that the present test is too severe when related to the coating thickness (even single particle impacts produced plastic deformation of the substrate material (i.e. the indentation-like impact craters)) and thus the substrate material will strongly influence the results. This naturally means that the substrate properties, such as hardness, impact toughness, etc., are very important for the overall tribological performance of the composite in this test. Consequently, milder experimental conditions (e.g. smaller particles, lower velocities) would make the test more sensitive to differences in coating response.

Somewhat surprisingly, the coating and substrate erosion rates were found to increase with substrate hardness both at 20° and 30° angle of impingement, see Fig. 9. The substrate hardness increases with the volume fraction of carbides in the substrate (cf. Table 2), and if one considers the carbides as being likely points of origin for cracks, the increase in substrate erosion rate with hardness can be understood. The increase in coating erosion rate with substrate hardness can possibly be an effect of decreasing substrate toughness (the substrate toughness decreases with increasing hardness, cf. Table 2). A lower substrate toughness could, qualitatively speaking, mean that less of the energy transferred by the impinging particle would be accommodated by the substrate through plastic deformation and more energy be available for e.g. crack nucleation and propagation in the coating, i.e. an

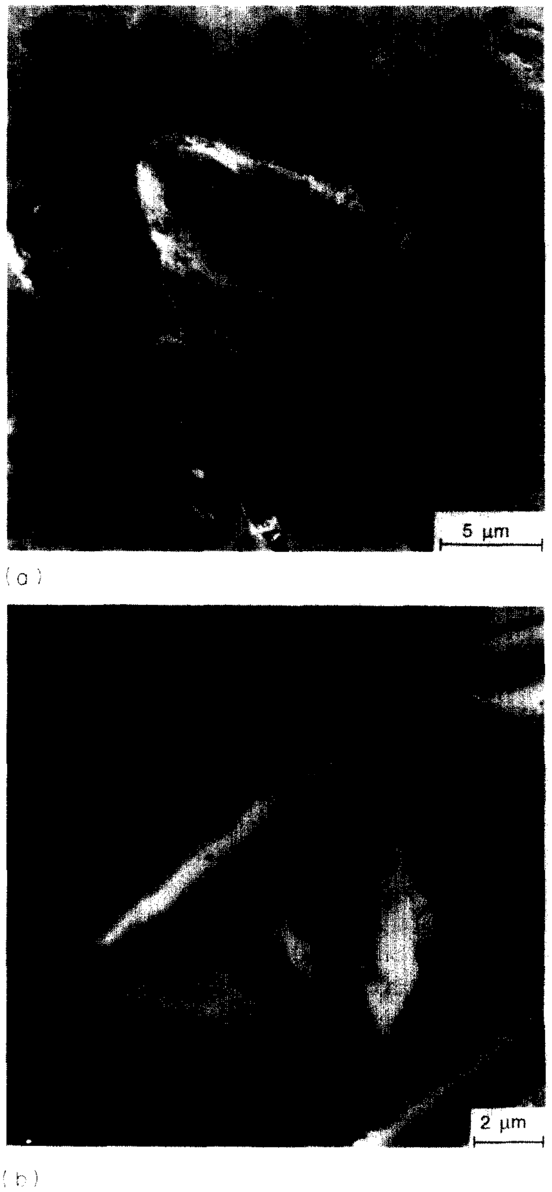

Fig. 6. Representative examples of the two types of single particle impact damages. (a) Cutting impact (TiN coated ASP23) and (b) indentation-like impact (TiN coated VANADIS 4).

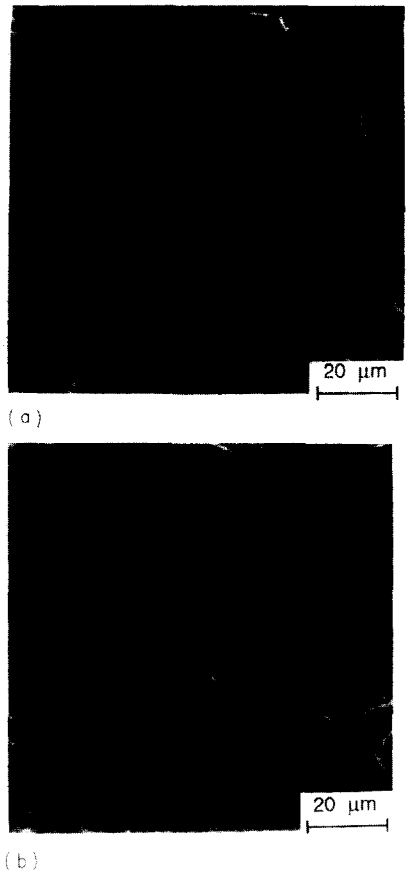

Fig. 7. Eroded surfaces at (a) low particle dose (TiN/ASP23) and (b) high particle dose (TiN/ASP60).

acceleration of the erosive fatigue wear mechanism is obtained. However, no clear experimental support for this hypothesis, e.g. in the form of more large flakings being observed on the harder specimens, was found.

At an angle of impingement of 20°, the (volumetric) erosion rate of a TiN coating is more or less the same as that of its corresponding, uncoated substrate. The situation at 30° is somewhat different; the erosion rate of the TiN coatings is generally significantly higher than that of the uncoated substrates. This is in good agreement with the ''classic'' observation that the erosion rate of a brittle material (such as the ceramic TiN) increases with the angle of impingement to reach its maximum at more or less perpendicular angles of impact (see e.g. Ref. [9]). In addition, more energy will be transmitted to the eroded specimen at 30° than at 20°.

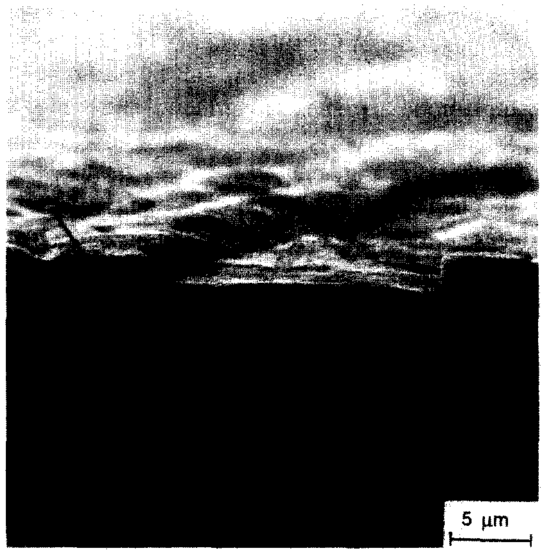

Fig. 8. Erosive fatigue wear (TiN/ASP23). Please note the subsurface lateral crack indicated by the arrow.

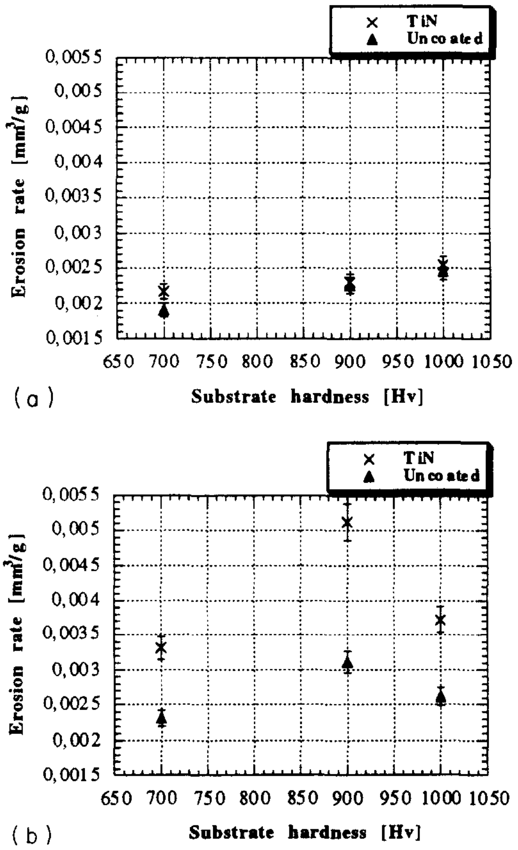

Fig. 9. Erosion rate vs. substrate hardness at an angle of impingement of (a) 20° and (b) 30°.

5. Conclusions

In this work, the influence of substrate material on the erosion resistance of TiN coatings deposited on three different tool steels have been investigated. The main conclusions are:

- As long as the test parameters allow the impinging particles to significantly affect the substrate material during erosive testing of a coated composite, the substrate material will influence the erosive response of the coating.

- In the present tests, the carbide volume fraction and the impact toughness of the substrate material controlled the erosion rate of both coatings and substrates.
- Substrate properties, such as hardness, impact toughness, etc., are important for the overall tribological performance of a coating–substrate composite. In particular, it should be noted that the deposition of a coating never can fully compensate for the negative effects of a wrongly chosen substrate material.

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