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Multi-layer coating design architecture for optimum particulate erosion resistance

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ABSTRACT

The hard particle, erosion resistance of multi-layer, magnetron-sputtered, physical vapor deposited (PVD), titanium nitride/titanium (TiN/Ti) coatings for protection of AM355 steel turbine components was investigated. Multi-layer coatings, of 25 μm total thickness, were deposited on AM355 substrates with variable numbers and thicknesses (equivalent to volume fractions) of the TiN and Ti layers. The coatings were eroded using glass beads, quartz and alumina media with particle velocities ranging from 75 to 180 m/s. Erosion performance was found to depend strongly on the TiN/Ti PVD coating multi-layer design architecture and the erosion conditions. The results showed that coatings with two layers, one of TiN, and a low volume fraction of metal gave optimal erosion performance against the alumina erodent, whereas coatings with 32 layers, (16 each of TiN and Ti), offered the best erosion performance against the glass beads. These results explain the variability of coating erosion performance described in the literature, and provide guidance in the design of optimal multi-layer coating systems for a range of particle erosion conditions.

1. Introduction

Numerous studies have been conducted to improve particle erosion resistance using TiN monolithic and ceramic/metal multi-layer coating design architectures [1–10]. However, the erosion performance of multi-layer coating systems have had mixed results. Bromark et al. [1] and Dobranski et al. [2] showed dramatic decreases in erosion performance for multi-layer TiN/Ti coatings over their single TiN layer counterparts. Both used small (50–90 μm), angular alumina erodent, which caused failure by microchipping.

Leyland and Mathews [3] investigated 12 layer, 30 μm total thickness, TiN/Ti coatings on tool steel substrates impacted by 220 μm alumina particles at 37 m/s (low velocity). These coatings had 2:1 and 1:1 TiN to Ti thickness ratios. Both underperformed an equally thick monolithic TiN coating.

In contrast, Gachon et al. [11] used large, sand particles (250–500 μm) and discovered significant improvements in erosion resistance for multi-layer WN/W on Ti–6Al–4V substrates over its WN single layer counterpart. They reported that the failure mode in these multi-layer coatings occurred by a multi-step progression of cracking, referred to as crack coalescence, and material removal.

Quesnel et al. [12] investigated 60 μm total thickness coatings with WC/W multi-layers on a Ti–6Al–4V substrate. These coatings were impacted by 80–600 μm angular silica particles at 240 m/s (high velocity). The coating with 12 layers total (6 of each material) outperformed a coating with 6 layers total. Both multi-layer coatings outperformed a monolithic 60 μm thick WC coating. The W and WC layers were of equal thickness; this may be considered a near-optimum condition, as tungsten is a very stiff metal. However, for the TiN/Ti system, an optimal design is expected to require a lower volume fraction of titanium, as titanium is a more compliant metal.

1.1. Mechanics

Hassani et al. [13] modeled the impact of alumina spheres on a variety of TiN-based coatings and found a transition from median (normal to the surface) to median plus lateral (in-plane) cracking as the impact velocity increased from 150 m/s to 180 m/s. In terms of erosion mechanism, this correlated with a transition from microchipping to crack coalescence.

Rutherford et al. [14] experimentally determined that for erosion of a TiN film on an ASP23 tool steel substrate, using small SiC particle erodent with low energy impact, the total film thickness was directly related to the minimum critical particle velocity. This

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is defined as the minimum velocity of the erodent particles for a specific coating/substrate system required to cause damage.

Hassani et al. [13] showed, by finite element analyses, that large particles (>100 μm) at even 50 m/s greatly exceed the minimum critical velocity for 8 μm thick TiN coatings on 17-4 precipitation hardened stainless steel (PH SS), 410 stainless steel, and Ti–6Al–4V substrates. The particle velocities of interest for jet turbine applications are typically much greater than 50 m/s. Their research indicated that coatings designed to resist erosion by high velocity and large particles must incorporate additional compliance, where possible, to minimize the damage caused by the impacts.

Coating systems subject to small (<50 μm), hard particles and low velocity (<100 m/s) impacts should be designed to minimize the erosion caused by each individual impact. This requires moderately thick coatings (typically 8+ μm) and, most importantly, the coating material must be hard and highly resistant to microchipping, particularly for angular erodent particles such as alumina. However, one could also deduce from contact dynamics [15] and continuum mechanics [16] that excessive stiffness should be avoided in order to minimize the tensile contact stresses at the coating surface [13,17,18], unless the materials have sufficient toughness to overcome the increase in stress. Choosing coating materials with high hardness, high fracture toughness, and moderate elastic moduli are thus considered the key components to design of erosion resistant coatings.

1.2. Ultra-hard ceramic/metallic coatings

Koehler [19] originally outlined the fundamentals of ultra-hard multi-layer design. He stated that a ductile interlayer should be sufficiently thin that dislocations were not generated within the metal layer. This effectively stiffened the ductile material, as confirmed experimentally by Yang et al. [20] for layer thicknesses in the low tens of nanometers.

Jankowski [21] proposed that the increased modulus was the result of atomic short range ordering of atoms, creating a metastable single phase marked by alternating higher and lower lattice spacings from the pure material; essentially, a strain wave. This behavior was limited to bilayer thicknesses (wavelengths, λ) from 1 nm to 3 nm and observed in FCC/FCC and FCC/BCC transition metal multi-layers (e.g., Cu/Ni, Ag/Pd, Cu/Nb and Mo/Ni). Within this range, the lattice spacing perpendicular to the direction of coating growth was measured to be larger than that of the bulk metal. The change in lattice spacing may explain the changes in moduli normal to coating growth. This has been somewhat discounted as its effect should be much smaller than dislocation blocking [22].

Yashar and Sproul [23] reviewed several explanations for the higher than calculated stiffness found in coatings. These include: dislocation blocking at layer interfaces, Hall–Petch strengthening, strain effects at layer interfaces, and the supermodulus effect. The supermodulus effect, described by Cammarata et al. [24], is a strengthening mechanism related to the residual stresses within the layers as well as the change in bonding. Yashar and Sproul [23] primarily supported Koehler's [19] dislocation blocking explanation of the hardening effects.

Alternatively, Wolf [25] suggested that the layered structure generated highly distorted grain boundaries at the layer interfaces, causing increased elastic moduli. Regardless of the final explanation for the stiffening of the material, the supermodulus effect continues to be a source of potential property modification for selected thin coatings.

However, if one were to view a hard multilayer system as a material, used in conjunction with a pure metal compliant system, this would create a superlatice system. Yang et al. [20] used alternating nano layers of TiN/CrN and pure Ti. The TiN/CrN superlatice had a period of 10 nm, where the overall Ti/[super lattice] structure had a period of approximately 0.4–0.8 μm. These coatings performed very poorly in erosion testing. Conclusive evidence has yet to be provided as to the effectiveness of this layer design on erosion performance.

Rutherford et al.'s conclusion [14] suggested that coatings designed to resist erosion by small particles with low energy impact, should have a hard, top layer that is as thick as possible, in contrast to Koehler's suggestion, that the layers should be very thin and of equal thickness. In addition, the interlayer should be no thicker than necessary to reduce coating residual stress sufficiently to prevent coating spallation, and not reduced to the nanometer range.

1.3. Compliance optimized coatings

Burnett and Rickerby [26] found that thick, hard coatings of TiN on stainless and mild steel substrates were more resistant to angular particles, whereas thin coatings were more resistant to blunt particles, such as glass beads, as the velocity increased from 14 to 24 m/s. The hardest coatings were not optimal for all erosive conditions.

The optimization scheme outlined by Chai and Lawn [27] is a useful design reference for impacts that cause damage by crack coalescence (at energies sufficient to cause cracks to extend well beyond the contact area). They suggested that, for a particular combination of materials, there may exist a design where the critical load to cause failure of the first layer of a multilayer coating (P_1), would be higher than that for a similar thickness monolithic coating (P_D). Relatively thin interlayers (<1/10th to 1/100th the hard layer) as well as a low number of total layers (typically less than 10), would provide a critical static load (greater than that to cause failure of a similar monolithic coating).

Of further importance, Chai and Lawn's model [27] indicated that greater loads would be required for each successive layer to fail (P_n). If a multi-layer TiN/Ti coating design had $P_1 > P_D$, it should be selected for high energy impact conditions, as it would provide additional damage tolerance in addition to increasing the minimum critical velocity for erosion. However, for their model to be applicable, the ductile interlayers should not be so thin that they restrict dislocation motion and thus stiffen the ductile metal. In addition, Chai and Lawn's model [27] must be modified to account for contact dynamics and the effect of compliance in reducing the instantaneous particle contact forces. While their model predicted the critical load for a quasi-static system, it did not take into account the reduction in maximum contact load as a function of material compliance. For a TiN/Ti system, Kim et al. [28] and Lee et al. [29] showed experimentally that interlayers of Ti with thickness in the range 0.5–1.0 μm were optimal.

Here the literature hits a fundamental divide: whether to follow Koehler's recommendations [19] and to keep the respective ceramic and metal layers both in the nanometer scale, or to use thicker layers and follow a modified Chai and Lawn [27] inspired approach. The nanoscale layers have the potential to provide much greater hardness and more resistance to microchipping; however, the potentially high elastic moduli of nanolayered coatings may only act to increase the contact forces. While thick layers improve resistance to crack coalescence, the additional ductile material decreases overall resistance to microchipping and the minimum critical velocity.

As there are multiple relevant failure mechanisms and respective mitigation strategies, a wide range of design architectures must be interrogated with a wide array of testing conditions in order to better understand the nature of erosion of multilayer erosion resistant coatings (ERC). The success of multi-layer WN/W coating systems developed by Gachon et al. [11], contrasted with the multilayer TiN/Ti coating failures by Bromark et al. [1] and Dobranski