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The influence of ductile interlayer material on the particle erosion resistance of multilayered TiN based coatings

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ABSTRACT

The effect of interlayer material on the particle erosion performance of titanium nitride (TiN)-based, magnetron-sputtered, physical vapor deposited (MS-PVD) coatings for the protection of AM355 steel components, subjected to hard particle erosion, was investigated. TiN-based coatings with interlayers of Ti, Zr, Hf, and Nb were compared for hard particle erosion resistance against angular alumina and glass bead mediaat velocities of 75 m/s and 180 m/s. In this study, high values of Vickers microhardness correlated with poor erosion performance. The TiN/Zr multilayer coatings exhibited the worst durability for all erosion conditions, even though they were the hardest coatings and had the lowest erosion rates (mass loss) early in life against glass bead media. The TiN/Nb multilayer coatings provided the best durability in most conditions. Although the TiN/Ti coatings showed best durability against the alumina particles, this difference was small and may be attributed to the relative total thickness of the coatings.

1. Introduction

Finnie [1] reviewed the work of Wellinger et al. [2–6], who identified a material's hardness as a key parameter in erosion performance. In the case of ductile materials, Finnie [7] notes cases where plastic flow stress may also be a key parameter governing erosion performance. Tilly [8] discovered that although higher hardness increased the erosion resistance of ductile materials, it decreased the erosion resistance of brittle materials. More recently, coating architecture and toughness have been recognized as important factors, particularly the erosion and wear benefits of incorporating a ductile layer or interlayers in ceramic-based coatings [9–15]. The change in multilayer coatings system properties such as hardness, adhesion, energy absorption, and fracture toughness have been studied as a function of the number, thickness and materials comprising the ductile interlayers [16–20]. In this study, the effect of the ductile interlayer materials, Ti, Zr, Hf, and Nb, on the hard particle erosion resistance of multilayer coatings is investigated to provide insight into the coating properties governing the erosion of multilayer coatings.

Ductile materials have the ability to blunt crack tips and redistribute stress via plasticity mechanisms. In layered coatings, as cracks approach interfaces, they may be redirected along the interfaces, deflected at the interface, or stopped if there is a significant change in the strain energy release rate, G [21–23]. He et al. showed that crack deflection depended on the interfacial toughness, residual stress fields, and material fracture toughness [24,25]. For multilayered coatings, crack deflection along or at interfaces may provide inherent resistance to crack growth and potentially improve erosion performance; however, it may also cause premature layer delamination.

Increasing strength of multilayered coatings with increasing number of layers (i.e., decreased interlayer spacing) has been related to the Hall–Petch effect [26], where yield strength increases with decreasing grain size [26,27]. Kikuchi et al. [21] found that if two materials chosen for multilayer coatings had similar elastic properties, strengthening did not follow Hall–Petch behavior. This suggests that Hall–Petch strengthening in multilayer materials requires a discrete change in elastic or plastic properties; agreeing with Koehler's principles [28] for designing ultra-tough solids.

In contact mechanics of laminate materials, the ratio of Hertzian contact stresses and flexural stresses depends on the ability of the "adhesive" layers (interlayers) to support the upper layers and transfer shear stresses. Chai and Lawn [29] identified multilayer configurations and material combinations for which the top (hard) layer of a multilayer laminate would fail at a higher load than that required for a hard monolith of equal thickness. They confirmed that a thinner hard layer or a thicker adhesive layer would be more likely to cause premature tensile failure at the underside of the

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Table 1
Material properties for the interlayer materials [33–35].

	TIN	Ti	Zr	Hf	Nb
Structure at 20 °C	FCC	HCP	HCP	HCP	BCC
Lattice parameter *a* (Å)	4.240	2.95	2.665	3.1964	3.3004
Lattice parameter *c* (Å)	–	4.6855	4.947	5.0511	–
Space group	Fm3̲m (225)	P6/mmc (194)	P6/mmc (194)	P6/mmc (194)	Im3m 229
Young's (GPa)	465	116	94.5	137	103
Shear	–	44	33	30	37.5
Bulk modulus (GPa)	261	110	92	110	170
Poisson's ratio	0.205	0.34	0.34	0.37	0.4
% Elongation	–	54	32	25	30
YS (MPa)	–	140	230	240	207
UTS (MPa)	–	220	330	485	300

top (hard) layer, as poor mechanical support would lead to excessive flexural stresses. Similarly, an excessively compliant interlayer material would not support the overlying hard layer and would cause premature failure.

Thin soft interlayers within a multilayer coating reduce the stress concentration at the hard layer's underside by relieving strain, while continuing to support the layer above, thus allowing the structure to have a higher elastic load capacity than a monolithic hard coating of similar thickness. In addition, significantly more load will be required to fail each successively deeper layer from a single contact. Thus, an optimally designed multilayered structure should offer both increased critical load and robustness against rapid coating failure from high-energy impacts.

Chai and Lawn's linear elastic model [29] showed that very thin interlayers (<10% relative thickness) were optimal for maximum critical loadin a macroscopic brittle/complaint system. Complicating the optimization, the mechanics of dislocation are governed by the absolute interlayer thickness. Hsai et al. [30] have shown that ductile interlayers less than 1 μm, generate fewer dislocations than bulk materials and that layer thicknesses less than a few hundred nanometers may even result in cleavage failure of otherwise ductile bulk materials. Mao and Li [31] found that the interfacial fracture toughness of multilayered gold and alumina coatings increased as the gold layer thickness increased, up to 1 μm.

Despite the changes in dislocation mechanics, thin interlayers have been shown to improve coating properties. Castanho and Vieira [18] studied the effect of 80 nm ductile interlayers of titanium, aluminum, and copper on the adhesion, hardness, residual stress, and elastic modulus of TiAlN based multilayer coatings with 3, 7, 11, and 15 layers, for a total thickness of 3.5 μm. The Ti and Al ductile interlayers improved coating adhesion to the substrate by approximately 60%, whereas copper degraded adhesion by up to 74%. Hardness was reduced by up to 27% and 40%, respectively, by the Ti and Al interlayers; however, a decrease in elastic modulus of up to 43% was observed for both Ti and Al based coatings. In contrast, copper decreased the hardness by up to 87% and the elastic modulus by up to 62%. The 11 layer TiAlN/Ti coating had high potential for erosion resistance as it increased adhesion and hardness, while decreasing the elastic modulus compared to the monolithic TiAlN. In contrast, the Cu interlayer decreased hardness, stiffness, and elastic modulus.

Table 2
Dundurs parameters α and β, stress singularity exponent, s, and the nondimensional stress intensity factor f, for conditions where a crack in TiN approaches the metal.

Layer 1	Layer 2	α	β	s	f
TiN	Ti	0.601	0.120	0.646	0.539
TiN	Zr	0.685	0.146	0.680	0.456
TiN	Hf	0.698	0.119	0.669	0.449
TiN	Nb	0.621	0.065	0.669	0.527

Borawski et al. [32] have shown that the erosion performance of multilayer TiN/Ti coatings was a strong function of the layer design, and erodent particle type, size and impact velocity. Their25 μm thick, 8-layer coatings, comprised of 19:1 (TiN:Ti) thickness ratio, provided good erosion durability for a majority of their erosion test conditions. These nominally 300 nm interlayers appeared to accommodate plastic deformation sufficiently. Consequently, this same multilayer design was chosen as the baseline for the present study to determine the optimal erosion performance of a multilayered TiN-based coating as a function of the interlayer materials: Ti, Zr, Hf, and Nb.

Table 1 summarizes the properties of the interlayer materials investigated in this research. Titanium was the most economical option. Hf and Zr were selected as they have similar yield strengths but had notable differences in stiffness. Zr and Nb were similar in terms of elastic moduli, ductility, and yield strength. However, unlike the hexagonal close packed (HCP) group IV metals, niobium is body centered cubic with more active slip systems. Its high Poisson's ratio and bulk modulus, suggest that it should effectively

Table 3
Deposition conditions for the various coating layers.

	Ti bond	TiN	Ti	Zr	Hf	Nb
Target thickness (μm)	0.5	8.9	0.3	0.3	0.3	0.3
Deposition rate (μm/h)	6.2	4.0	6.2	9.0	8.1	7.3
DC power (W)	1200	1200	1200	1200	1200	1200
Target size (cm × cm)	8.9 × 15.2	8.9 × 15.2	8.9 × 15.2	8.9 × 15.2	8.9 × 15.2	8.9 × 15.2
Substrate bias (DC)	−50 V	−50 V	−50 V	−50 V	−50 V	−50 V
Pressure (mTorr)	1.1	1.3	1.1	1.1	1.1	1.1
Temperature (°C)	200	200	200	200	200	200
Rotation (RPM)	18	18	18	18	18	18
Substrate to target (cm)	7.6	7.6	7.6	7.6	7.6	7.6
Argon flow (sccm)	42.2	42.2	42.2	42.2	42.2	42.2
Nitrogen flow (sccm)	–	7.8	–	–	–	–
RF pre-clean	10 min at 300 W	–	–	–	–	–