QUASI-STATIC AND DYNAMIC TORSION TESTING OF CERAMIC COATINGS USING HIGH-SPEED PHOTOGRAPHY

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ABSTRACT

A novel experimental procedure for the testing of ceramic coatings in quasi-static and dynamic torsion is presented. The tests were performed on a Kolsky bar apparatus modified for torsion loading. High-speed photography was used to take snapshots of the surface of the specimen gage during loading, and digitally correlated to determine the full displacement and strain fields. Micro- and nano-Al$_2$O$_3$/TiO$_2$ and WC/Co coatings on thin aluminum substrates were tested. The specimens contained porosity and cracking prior to testing, that resulted from the coating process. This damage was found to be significant and resulted in low shear moduli and strengths. The damage mechanisms of the coatings with respect of the substrate were determined.

SPECIMENS

The specimens were composed of an aluminum 6061-T6 substrate with cylindrical geometry (fig. 1) on which the coatings were sprayed (A&A Company, South Plainfield, NJ). The aluminum substrates were grit blasted with aluminum oxide for better adhesion. Al$_2$O$_3$/TiO$_2$ coatings were obtained by plasma deposition while WC/Co coatings were obtained using High Velocity Oxy Fuel (HVOF). For both materials, micro-and nano-grain sizes were deposited. After spraying (which was done in a single step) the specimen were allowed to cool down in air with no additional post-treatment.

![Figure 1: Cross section of the torsion specimen.](image)

INTRODUCTION

Ceramic coatings are widely employed in a variety of areas including mining, grinding and metal cutting for their excellent wear resistant properties. Their main drawback stems from their low toughness and brittleness. However, recent development have shown that these deficiencies can be improved by reducing the grain size [1],[2],[3],[4].

A challenge in characterization of their properties is the decoupling of their mechanical behavior from the underlying substrate. The objective of this work was to characterize Micro- and nano- Al$_2$O$_3$/TiO$_2$ and WC/Co coatings deposited on thin aluminum substrates under quasi-static and dynamic loading.

A Kolsky bar [6] modified for torsional loading was used. High-Speed Photography and speckle correlation techniques allowed the determination of strains and localized deformations. Optical and Scanning Electron Microscopy were used to correlate the microstructure of the coatings with their mechanical response.

TESTING PROCEDURE

The quasi-static and dynamic tests were performed on a Kolsky bar Apparatus modified for torsion loading (fig. 2). The specimen was glued between the input and the output bar. A high-speed camera equipped with a long-distance microscope was used to take a first “reference” picture of the unloaded gage. To perform the quasi-static tests, a lever arm and a platen were attached to the output bar. Calibrated weights were added incrementally on the platen, increasing the torque in the specimen. At each increment, a picture of the gage was taken. For the dynamic case, a predetermined torque was stored in the bar using a hydraulic rotary actuator. Upon release of the clamp (see fig. 2) a shear stress wave traveled down the input bar, through the specimen and into the
output bar. Incident, reflected and transmitted pulses at the specimen were recorded with strain gage stations for subsequent stress and strain analyses. In addition, strain gage station #1 triggered the high-speed camera, which with adequate synchronization took eight pictures of the gage at different loading stages.

For both quasi-static and dynamic tests, each of the pictures of the loaded gage was correlated with the reference picture, using random dark and light features on the surface of the specimen. These features were either artificially created using black toner on white acrylic paint when testing the substrate alone, or naturally created by the roughness of the coatings. The idea of the procedure is to pick a subset of the reference image and then find its location in the picture of the deformed gage. The subset in the deformed image is allowed to deform linearly. An optimization scheme determines the displacements and subset distortion that best satisfies the matching between reference and deformed subsets. Fitting a spline surface on the intensity distribution of the reference subset allows for sub-pixel resolution. Detail on the method can be found in [7], [8].

**TESTS ON ALUMINUM SUBSTRATE**

Aluminum substrates without coatings were tested in both quasi-static and dynamic modes using the procedure described above. Figure 3 shows the V displacement fields obtained from a dynamic test. The subset size used was 25 by 25 pixels, and a correlation was performed in 5 pixels intervals in both directions. The observed displacements are due to deformation of the gage and rigid body motion resulting from mechanical drift and vibrations. Only the relative displacements are of interest here. Figure 4 Shows a plot of the vertical displacements V as function of the horizontal position x along several horizontal lines. The shear strain $\gamma_{xy}$ was then simply given by the slope of these curves. For the case of dynamic loading, the shear strains in the gage was also determined using integration of the incident, reflected and transmitted pulse at the specimen location. Details on this procedure can be found elsewhere [5],[6].

The shear stress was assumed to be constant through the thickness of the gage (thin walls approximation), and determined using:

$$\tau_{xy} = \frac{2T}{\pi D^2 t}$$

Where $T$ is the applied torque, and $D$ and $t$ are the diameter and thickness of the gage, respectively.

The resulting stress-strain curves in quasi-static and dynamic modes are shown on figure 5. The shear moduli and yield strengths are consistent with reference data for aluminum 6061-T6, i.e. $G=25$ GPa and $\tau_y=150$ MPa. For
the dynamic case, the integration and speckle correlation methods give similar results.

![Figure 4: Displacement V vs. position x along several horizontal lines. The slope yields the shear strain.](image1)

![Figure 5: Stress-strain curves obtained from a torsion aluminum specimen](image2)

**TESTS ON COATINGS**

The next step was the testing of the coated specimens. The same procedure was used, but in this case both the aluminum substrate and coating contributed to the mechanical response of the specimen. It was therefore necessary to subtract the torque taken by the aluminum substrate from the overall torque. This was done using the stress-strain curves obtained above for the substrate, and assuming that the shear strains were continuous through the interface substrate/coating. The resulting stress-strain curves for the coatings alone are shown on figure 6. The curves show an initial linear region (G=20-25 GPa for Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> and G=30GPa for WC/Co). These low values were attributed to initial porosity and damage due to residual stresses in the coatings, revealed in the heterogeneous displacement fields (fig. 7A). At 30-60 MPa the coating exhibited a ductile-like behavior. The displacement field (fig. 7B) revealed that cracks had already developed at this point: Although invisible to the naked eye, they created line discontinuities in the displacements. The ductile-like behavior is in fact due to the ductile underlying aluminum substrate, which bridge the cracks and maintains the pieces of the coating together. The final picture before catastrophic failure (fig. 7C) confirms visually the locations of the cracks previously revealed by the displacement field.

![Figure 6: Stress-strain curves obtained from the coated specimens](image3)

![Figure 7: Pictures and displacements fields for a quasi-static test on a Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub>. A: Linear elastic region, B: Plateau region, C: Final picture before catastrophic failure.](image4)
Optical micrographs of untested specimens confirmed the presence of defects in the coatings (fig. 8 and 9). Porosity, debonding and radial cracking due to residual stresses were observed.

Figure 8: Micrographs of a Al₂O₃/TiO₂ coating. A: Coating, B: Substrate

Figure 9: Micrograph and SEM image of a WC/Co coating. A: Coating, B: Substrate

CONCLUSIONS

A novel experimental procedure for dynamic torsion testing of materials using a Kolsky bar and high-speed photography was presented. The method was validated on an aluminum specimen. Results on Al₂O₃/TiO₂ and WC/Co coatings were obtained. The displacement fields given by the speckle correlation technique allowed the identification of the deformation mechanism, i.e., early crack propagation and crack bridging by the ductile aluminum substrate. No significant difference in modulus and strength was found between the nano and microstructured materials, but an eventual difference between them is probably masked by the initial damage in the coatings, as observed in optical and SEM pictures.

Manufacturing coatings free of initial microcracks remains a significant challenge. Research on optimization of the spray deposition parameters should be pursued to produce high quality nanostructured coatings that can fully exploit the benefits of nanosize grains.

REFERENCES


