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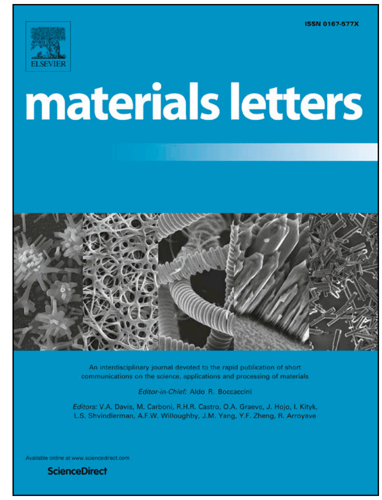

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Contact fatigue behavior of α-Al_2O_3-Ti(C,N) CVD coated WC-Co under dry and wet conditions

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Abstract

The response to cycling contact fatigue load of a WC-6%Co carbide coated with a Ti(C,N)/α-Al_2O_3 CVD multilayer was investigated in dry and wet conditions. Imprints in dry conditions were characterized by small thin cracks forming a circumference at the maximum radii of the imprint. The damaged coating was totally present in the final imprint of the dry test. Wet indentations showcase an area in the imprint where the α-Al_2O_3 layer has been removed throughout a ring but was kept at the center of the indentation, suggesting that the coating damage under cycling contact load in wet conditions is dominated by α-Al_2O_3 degradation, associated with a fretting effect or tangential loads accelerating the fatigue-corrosion of the alumina layer.

Keywords: CVD coating, Cemented Carbide, Contact fatigue, Crack propagation, Wear

Introduction

Coated cemented carbide inserts are used in the machining of metal alloys for the automotive and aerospace industry. WC-Co substrates provide the balance between hardness and toughness, whereas the Ti(C,N)/α-Al_2O_3 coatings produced by chemical vapor deposition (CVD) increase the surface resistance to wear and chemical degradation [1,2]. A critical feature of Ti(C,N)/α-Al_2O_3 CVD coatings in cemented carbides is the formation of a network of microcracks in the coating during the cooling step of the CVD process (due to the large difference of thermal expansion coefficient between carbide and coating). Additionally, a major problem in interrupted machining is the formation and propagation of microcracks due to the oscillating conditions of force and temperature acting at the cutting edge. These microcracks produce macrocracks and chipping, leading to failure of the tools [3]. In a previous work, contact damage induced by spherical indentation on coated cemented carbides has been studied [4,5]. For single- and multilayered CVD coatings, it was found that film cracking under contact loading is governed by load transfer from the plastically deformed substrate into the coating as well as the effective fracture strength and residual stress condition of the film [5]. Furthermore, the contact damage tests were in complete agreement with previous micromechanical tests in terms of crack propagation paths in carbonitride systems [6]. Recently, a new experimental set-up designed by the authors was used to investigate the cyclic contact fatigue behavior of cemented carbides under dry and wet conditions [7]. By immersing the cemented carbides in industrial cutting fluid under oscillating loads, the combination of chemical attack and cyclic contact load was used to visualize the advantage of Cr-containing binders in the corrosion-fatigue resistance of commercial cemented carbide grades. In this work the same experimental set-up is used to investigate the crack propagation in Ti(C,N)/α-Al_2O_3 CVD coated carbide under dry and wet conditions.

Experimental

WC-6wt%Co cemented carbides (grain size: 0.8µm, HV30:1570, K_{Ic}: 9.9 MPa·$m^{1/2}$) coated with a starting layer of TiN (0.5µm) followed by a Ti(C,N) (3µm), a $Ti(C,N,O)_x$ bonding layer (1µm) and a top α-Al_2O_3 layer (3µm) by CVD in an industrial hot wall reactor were investigated. Cyclic indentation tests at the macrometric length scale were assessed by spherical indentation (Hertzian tests) using hardmetal indenters of 2.5 mm of curvature radii. Tests were conducted in a servo hydraulic testing machine (Instron 8511) using a sinusoidal wave with 7 Hz frequency to a total number of $1\cdot10^5$cycles. The force range (ΔF) was constant with an indentation force ratio of 0.17 (ΔF = 200 N/1200 N), allowing the indenter to be in contact with the material surface during the entire experiment. For wet experiments, an industrial cooling fluid (8 vol% stock solution in tap water) was used, Tab.1 [7].

Tab. 1. Chemical composition of stock solution for the cyclic indentation tests.

CAS-nr.	Name	Percentage (%)
68608-26-4	Sulfonic acids, petroleum, sodium salts	< 6
122-99-6	Phenoxyethanol	< 6
68132-46-7	Fatty acids, tall-oil, compounds with triethanolamine	< 2
8012-95-1	Highly refined mineral oil	Rest

Results and discussion

The imprints on the insert's surface at the end of the cycling contact load tests are shown in the LOM images in Fig. 1. A remarkable difference is observed between dry (air) and wet (lubricant) conditions. In dry conditions, the indentation only shows circumferential cracks at the maximum radii of the imprint on the α-Al_2O_3 coating, whereas in the presence of the cooling cutting fluid, a dark ring with absence of the α-Al_2O_3 coating layer is observed (EDS profiles in Fig. 1). Also, the external diameter in wet conditions is larger than in dry ones.

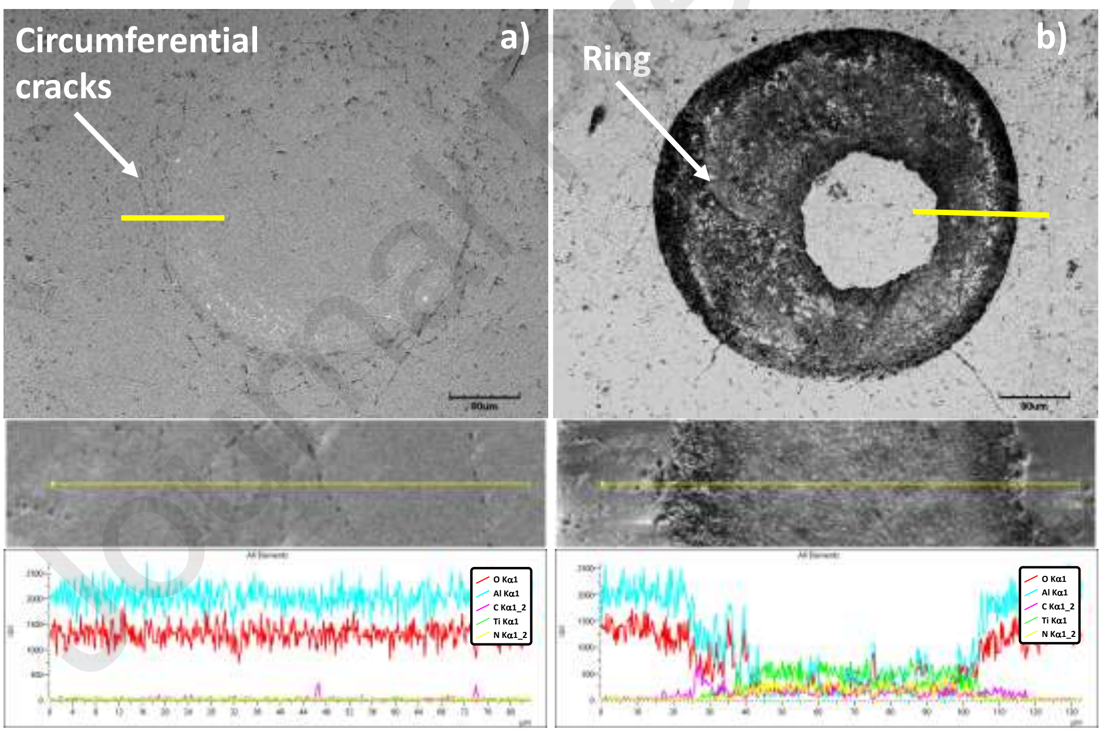

Fig. 1: LOM top-view image of imprints for dry a) and wet b) tests, together with SEM images and EDS images of the yellow marked lines for both conditions.

To observe the crack propagation through the material, cross sections were inspected both in the LOM and in the SEM (Fig. 2).

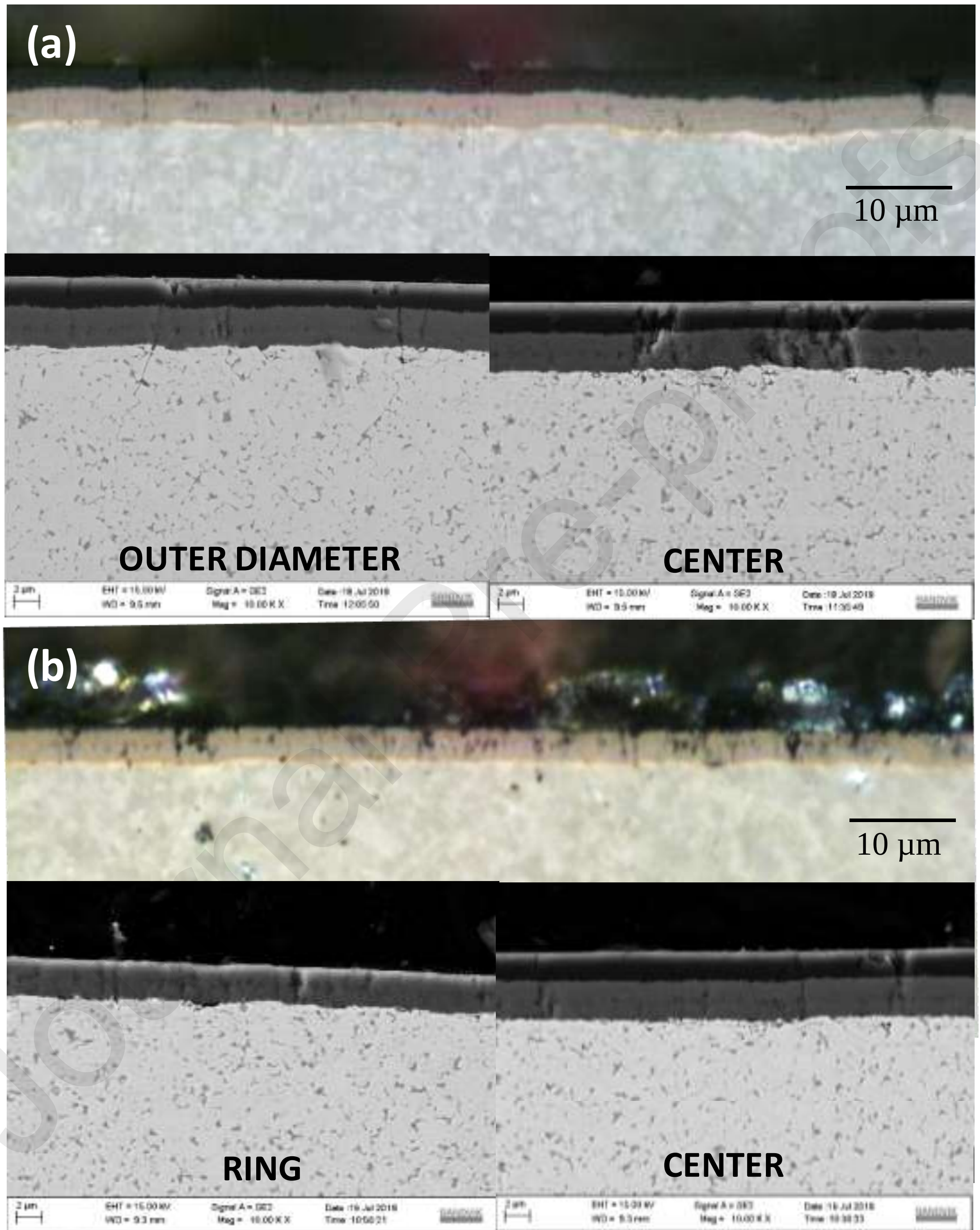

Fig. 2: LOM cross section images of the outer region of the imprints and high magnification SEM images of the center and outer diameter of the imprints for the dry conditions (a), and center and ring for the wet conditions (b).

In dry conditions cracks initiating from the α-Al_2O_3 layer through the rest of the coating were observed, sometimes propagating into the substrate. In wet conditions the absence of the α-Al_2O_3 layer on the ring previously shown on the top view LOM images (Fig. 1) is clearly seen in the SEM image of Fig. 2b. The α-Al_2O_3 layer has either been corroded or detached from the rest of the coating in that area, as verified by EDS (Fig. 1). The ring area is heavily damaged, having a high density of cracks in the coating which is left. Some damage in the substrate beneath the coating can be observed for both conditions, particularly in the center of the imprints, which is the area that has been always in contact (under the maximum stress condition) with the WC sphere during the contact-fatigue tests (Fig. 2). Cracks are observed in the α-Al_2O_3 layer for both conditions, which propagate through the coating and often through the substrate on the laterals of the indentation (the circumference). In Fig. 2 it can be observed that these cracks tend to follow the WC grain boundaries in the near-surface (max. 5um). SEM-FIB cuts along the indentation are shown in Fig. 3. Cracks propagating from the α-Al_2O_3 layer, through the Ti(C,N) layer and also into the substrate are observed in both conditions. In dry conditions (Fig. 3a) a network of microcracks is observed in the α-Al_2O_3 layer, which seems to be connected to the grain size of the polycrystalline layer. However, in wet conditions (Fig. 3b) this microcrack network is present, but part of the layer has been removed during the test. The degradation of such layer appears to be gradual, resulting from the interaction between cyclic loads and the liquid media. The susceptibility of environmental assisted mechanical degradation of alumina is a well-established phenomenon taking place under sustained or variable stresses, i.e. under static or cyclic fatigue [8,9]. Furthermore, besides the Hertzian contact stresses related to the macroscopic contact geometry, two experimental facts should be underlined: a) the existence of repetitive low amplitude relative displacements between the contact surfaces of coating and indenter within the residual imprint (it indeed would resemble a fretting-fatigue scenario yielding local shearing stresses at the surface and subsurface levels) and b) the evidence of a pre-existing cracking-network within the α-Al_2O_3 layer [3]. Both facts indicate that the relative differences observed may be rationalized on the basis of environmentally-assisted cracking under cyclic load of ceramics.

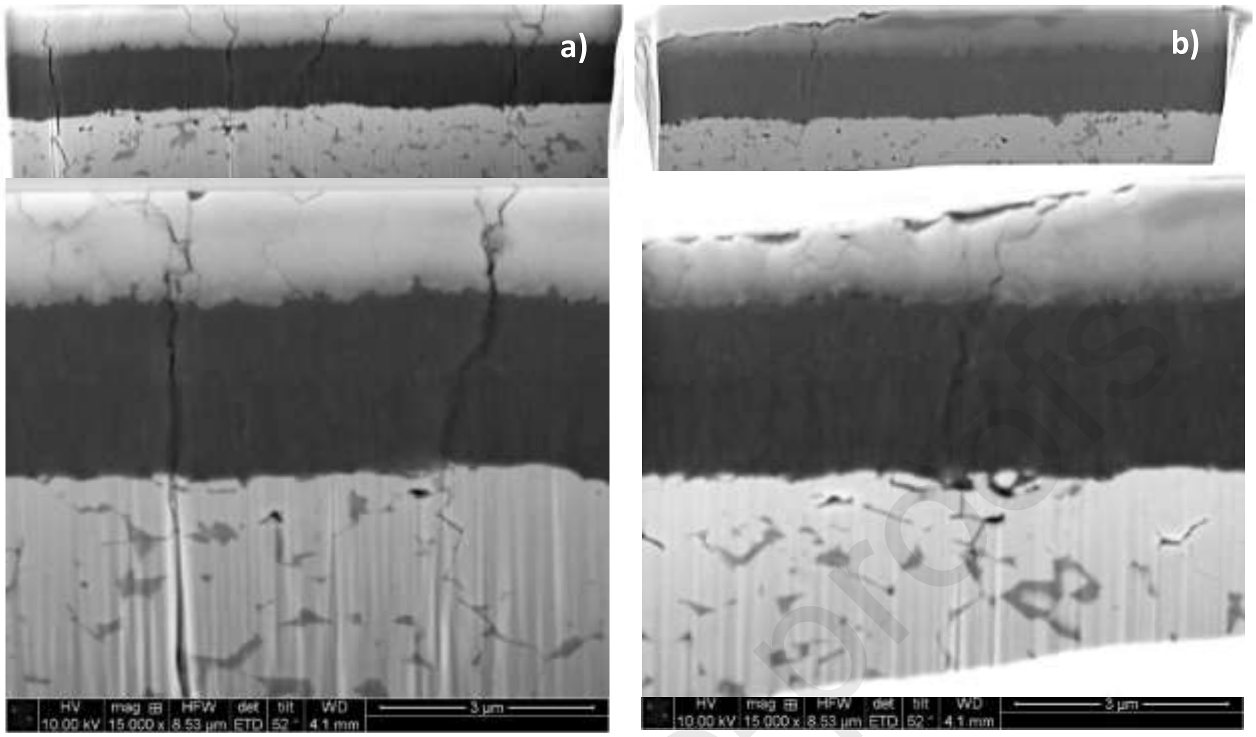

Fig. 3: SEM-FIB images on the outer diameter of the imprint in air (a) and in wet (b) conditions.

Therefore, exposure of the stressed α-Al_2O_3 layer to a liquid media results in applied mode II stress intensity factors higher than the corresponding threshold for driving subcritical propagation of the existing fissures following interlayer paths, i.e. lateral-like ones parallel to the surface (see Fig. 3). Thus, detachment of the α-Al_2O_3 layer finally yields the effective exposure of underneath layers in the presence of the coolant fluid. These then get corroded (dark ring in Fig. 1) under the synergic effect of both liquid media and the fretting-like slip region [10]. The fact that such scenario is not observed in the residual imprints in dry conditions, where a higher threshold for crack extension in alumina should be expected together with the intrinsic chemical stability of the alumina in air, support the above ideas.

Conclusions

A testing method to access information about the early stages and mechanisms that govern degradation of coated cemented carbides under cycling load is presented. In both conditions, we observe widened micro-cracks and damage in the carbide substrate in the center of the indentation, where compressive stresses were higher during the contact-fatigue test. In dry conditions, the coating is kept throughout the indentation despite microcracks are opened and the multilayer shows pronounced deformation. Wet indentations showcase an area in the shape of a ring, where the α-Al_2O_3 layer has been removed throughout the ring but is kept at the center of the indentation. It shows that the faster degradation of the α-Al_2O_3 layer under wet cycling contact loads contributes to the faster widening of pre-existing CVD cooling cracks, which then evolve rapidly into observed large comb-cracks in wet milling operations [3,5].

Acknowledgements

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Research highlights

Response to cycling contact fatigue of Ti(C,N)/α-Al_2O_3 CVD coated carbide

Experimental set-up allows for wet and dry cycling contact tests

Imprints in dry tests characterized by cracks forming a circumference at maximum radii

Wet indentations imprints present a ring where the α-Al_2O_3 layer is removed

Wear dominated by α-Al_2O_3 degradation due to fretting effect and fatigue-corrosion