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Mechanical response under contact loads of AlCrN-coated tool materials

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Abstract. The mechanical behavior under contact loading of systems consisting of PVD AlCrN film deposited onto two distinct hard substrates - cemented carbides and tool steel is studied by means of indentation testing techniques, under monotonic and cyclic condition. Experimental work includes assessment of critical applied loads for emergence of circular cracks at the coating surface, as well as evaluation of both surface and subsurface damage evolution. Results indicate that both coated systems are susceptible to mechanical degradation associated with repetitive contact load. Furthermore, significant differences on contact fatigue behavior between the two studied coated systems are evidenced under consideration of cracking evolution at top surface and penetration towards the substrate. In this regard, the intrinsic mechanical properties of the substrate are pointed out as key feature for rationalizing the experimental findings.

1. Introduction

Surface coatings are widely applied to improve the lifetime and performance of a large variety of tool materials because of their attractive properties, such as high hardness, good wear and chemical stability. Recently, a new ternary nitride AlCrN obtained by physical vapor deposition (PVD) techniques with higher percentage of aluminum has become the subject of ever-increasing interest due to its excellent tribomechanical properties particularly under high temperature [1,2].

Considering the complex service conditions to which coated tool systems are subjected (abrasive and adhesive wear, impact, repetitive mechanical contact, etc.) continuous research has been conducted in order to investigate the mechanical response of these coated systems and optimize the design process. In general, extensive literature exists on tribomechanical response primarily concentrated on evaluation of hardness, scratch resistance, friction coefficient and wear behavior as a function of either film nature or architecture-single versus multilayer [3–6]. However, experimental data on the mechanical performance of coated tools subjected to repetitive contact loading are rather scarce. On the other hand, experimental and analytical approaches using spherical indenters to deliver stresses over a small area of specimen surface, i.e. testing protocols based on the Hertzian theory, have been proven to be successful on the assessment of contact damage in bulk polycrystalline ceramics [7–9], layered structures, and more recently in cemented carbides and tool steels [10,11]. Within this framework, it is the aim of this study to assess the contact mechanical response and the corresponding damage mechanisms, under both monotonic and cyclic loading conditions, of an AlCrN film deposited onto two different hard substrates- cemented carbides and tool steels. In doing so, experimental protocols based on spherical indentation testing techniques are conducted.

2. Experimental procedure

Two different substrates were used in this study: a commercial fine-grained WC-10%wt Co cemented carbide grade, and a powder metallurgy processed tool steel developed by UDDEHOLM and commercialized as VANADIS. Elastic modulus and hardness for both base materials, were approximately 540 GPa and 14.5 GPa for cemented carbide [12], and 230 GPa and 7.4 GPa for the tool steel, respectively.

Aluminum chromium nitride coating was deposited on both substrates following cathodic arc PVD process. In all the cases, dense and uniform coatings with a crystalline fine-grained structure were attained (figure 1). The coatings thickness was found to be similar: 2.8 μm and 3.1 μm for the coatings deposited on the cemented carbide and the tool steel, respectively. Intrinsic hardness for coatings on both substrates was determined by means of a nanoindentation testing device (MTS Nanoindenter XP) equipped with a continuous stiffness modulus. For the two cases: coated cemented carbide and coated tool steel, hardness-penetration depth curve showed a plateau around 35 GPa and 32 GPa respectively, associated with the intrinsic hardness of the coating. Adhesion resistance was determined by means of scratch testing (Revetest, CSM Instruments) on the basis of the critical normal load related to initial coating detachment. Critical loads in both cases were higher than 30N, as given by values of 84N and 51N onto cemented carbide and tool steel respectively. Load levels above 30N are generally described as sufficient in scratch testing with a Rockwell C diamond tip for tooling applications [13].

Mechanical contact response of the coated system was investigated by means of spherical indentation. Hertzian tests were conducted in a servohydraulic testing machine (Instron 8511) by using a hardmetal spherical indenter with a curvature radius of 1.25 mm. They were focused on the failure scenario at the

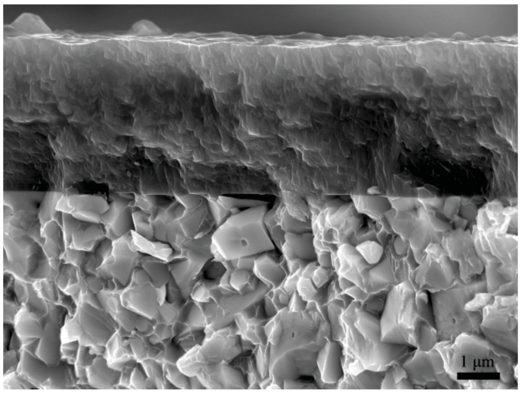

Figure 1. SEM micrograph of a fractured cross-section of the deposited AlCrN film showing the columnar character of the coating.

surface of the coated systems (i.e. circumferential cracks, cohesive failures, etc.), under monotonic and cyclic loading. In doing so, the first stage on the experimental protocol followed was the determination of the critical load for circular crack emergence at the coating surface under monotonic loading, P_c. Once it was assessed, fatigue testing was carried out at discrete maximum cyclic loading levels, P_{max}, corresponding to values equal to or close to the monotonic critical load. The cyclic loading was imposed by means of a sinusoidal waveform at a frequency of 10 Hz and corresponding ratio of 0.1 for 10^5 cycles. Subsurface damage features associated with spherical indentation were inspected by means of FIB (Zeiss Neon 40) cross-section observation.

3. Results and discussion

3.1 Monotonic spherical indentation

As applied load increases, irreversible deformation of the coated system through residual surface traces was discerned. At relatively high load levels, first signs of damage were observed at the edge of the corresponding residual imprints in terms of circumferential cracks (figure 2). The critical load for discerning film rupture was about 50% higher (1500 N as compared to 1000 N) for the WC-Co substrate with respect to the tool steel one. From a simple optical observation of the indentation imprints, it was clear that plastic yielding of the coated sets was required for the subsequent cracking in the film, in agreement with previous studies by other authors (e.g. Ref[14]) The above monotonic critical loads were then used as baseline reference for comparison purposes with the ones determined under cyclic loading conditions.

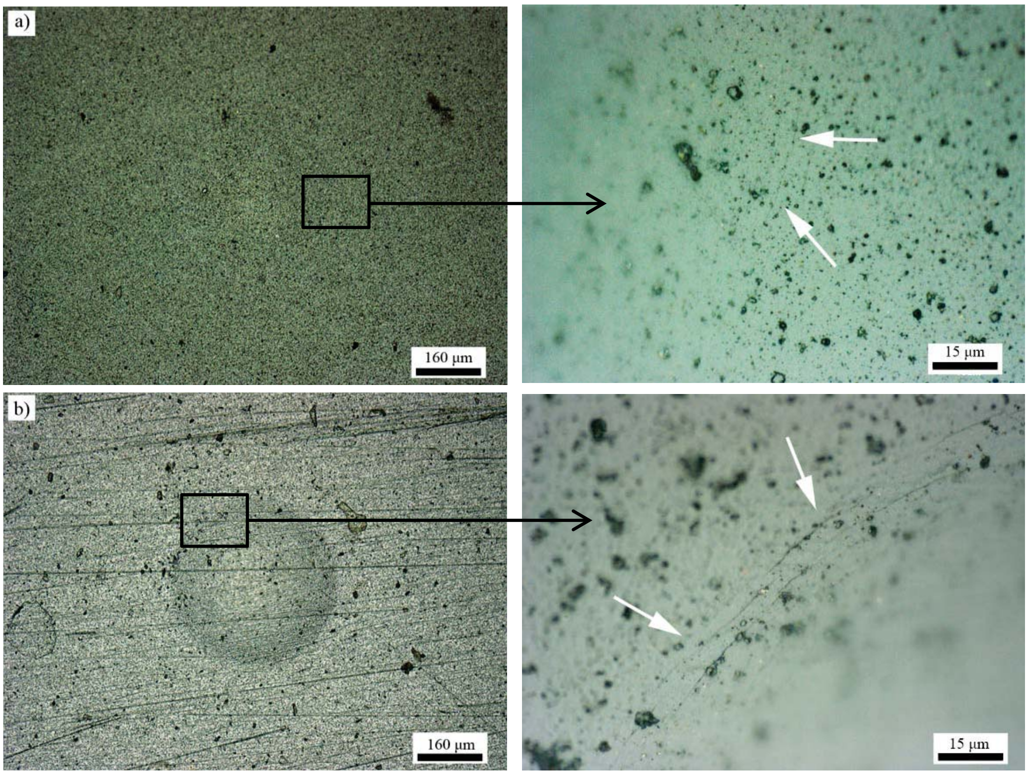

Figure 2. Circumferential cracks (indicated by white arrows) discerned under monotonic loading at the surface of the AlCrN deposited onto: a) WC-Co, and b) tool steels. (Lines on left figure 2b are inherited from the coating's original surface)

3.2 Cyclic Spherical indentation

Cyclic indentation tests were conducted attempting to evaluate the damage evolution on the studied systems as applied cyclic load increases. In both cases, experimental result showed that under cyclic loading, coated substrates exhibited accumulated damage as well as evidence of other failure mechanisms which were not observed under monotonic loading. This was clearly indicated in figure 3. Regarding the images, it should be mentioned that they correspond to insets from residual cyclic indentation imprints, as those given at the right-hand side ones in figure 2.

For the WC-Co+AlCrN system, it can be seen that under cyclic conditions, at 1000 N, a load lower than the corresponding critical monotonic load, circular cracks and small cohesive failures were observed. After applying 1500 N under fatigue condition, damage becomes more severe. For the Tool Steel+AlCrN system, cohesive failure and circular cracks were visible at 1000 N, the same value as the monotonic critical one of this system. Moreover, accumulated damage effect was also discerned as load was increased from 1000 N to 1500 N. Thus, the result confirmed that these two systems are fatigue sensitive.

Regarding the cohesive failure, it was suggested that droplets on top surface of the coating are responsible for the cohesive failure. They are typical microstructural heterogeneities in films deposited by cathodic evaporation. From a mechanical perspective, they are weakly bonded to the bulk coating and

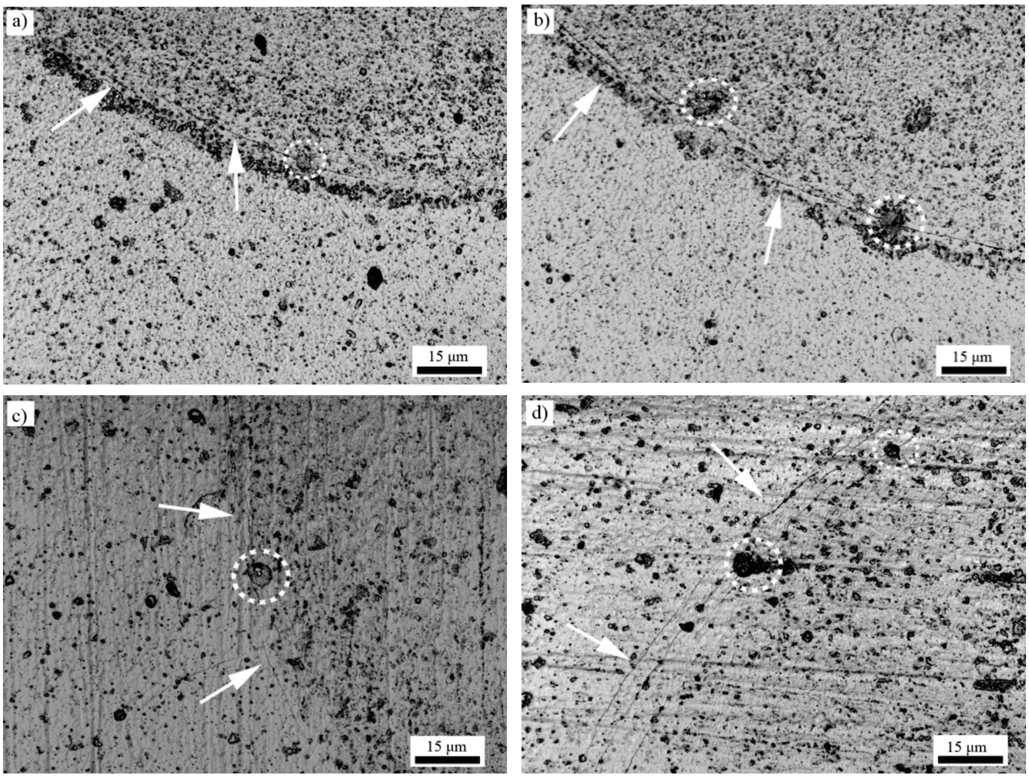

Figure 3. Damage evolution under cyclic spherical indentation on the studied systems: WC-Co+AlCrN for applied P_{max} of a) 1000 N and b) 1500 N; as well as Tool Steel+AlCrN for applied P_{max} of c) 1000 N and d) 1500 N. Circular cracks and cohesive failures are indicated by white arrows and dotted circles, respectively.

prompted to drop out from the surface under tribomechanical service conditions. Following the above ideas, cohesive failure maybe explained on the basis of progressive degradation under cyclic loading of the flawed interfaces between the droplets and bulk coatings [11].

As indicated before, the above experimental facts definitely revealed the existence of real fatigue sensitivity for both coated systems. However, it should be highlighted here that the two systems showed different damage modes under the same condition. For instance, at 1000 N during 10^5 cycles, Tool Steel+AlCrN system presented more successive multi-cracks than the WC-Co+AlCrN system. Similar trend was even intensified at 1500 N.

Considering that for both systems, coating intrinsic properties (hardness, toughness and residual stresses) were the same, relative mechanical response as a function of the substrate should be expected on the basis of the different contact strength under both monotonic and cyclic loading, in terms of the damage scenario. In some studies by other authors [15,16], it was postulated that for hard coating exhibiting columnar structure, sliding along intercolumnar cracks is the principle deformation mechanism in the coating. Thus, the system response is a combination of an elastic film that undergoes shear cracking at a critical stress and an underlying elastic–plastic substrate. Then it seems rational to speculate that WC-Co with higher stiffness and hardness than the tool steel implies less deformation, which finally renders the upward coating easier to follow and results in less shear cracks.

3.3 Subsurface indentation damage

Spherical indentation tests are especially attractive because, different from more conventional techniques involving sharp-like indenters, they allow to monitor damage evolution within an otherwise uncracked microstructure as a function of increasing either applied load (monotonic tests) or number of cycles (cyclic tests). This is particularly interesting in the case of coated systems due to the fact that here it is important to evaluate not only the intrinsic competition between deformation and fracture mechanisms but also where they are first developing, i.e. within the coating or the substrate, or even at the interface. Within this context, the damage resulting from contact loading was inspected by focused ion beam (FIB) cross section observation (figure 4).

In figure 4, it can be seen that for the WC-Co+AlCrN system, damage within the coating starts by circular crack nucleation at the periphery of the contact and at the coating surface, and subsequently advances through the thin film up to the interface, finally leading to substrate cracking either through carbides or along the metallic binder surrounding the ceramic particles. This result was consistent with previous findings of this research group [10] on degradation of TiN coated cemented carbides under cyclic loads. Abdul-Baqi and Van der Giessen [17] studied the cracking of hard coating during indentation using the finite element method. They support the idea that primary potential locations for the initiation of coating cracks are the coating surface close to the contact edge and the coating side of the interface in the contact region, where high values of tensile radial stress are found. Circumferential cracks are found to initiate from the coating surface and to propagate towards the interface. On the other hand, for the Tool Steel+AlCrN system, findings were not the same as the previous system. Cracks were observed to grow and stop at the interface rather than propagating into the substrate. Considering this special feature, it is clear the relevant role played by the tougher character of the tool steel substrate. Lawn [9] indicated that from the standpoint of substrate design, the principal requirement is to maximize hardness in order to prevent crack nucleation. But on the other hand, once cracks do initiate, softer (and generally tougher) substrates are better suited to arrest or inhibit any penetrant cracks within the sublayer through plastic deformation, so that design once more depends on whether crack prevention or crack containment is the more pressing goal.

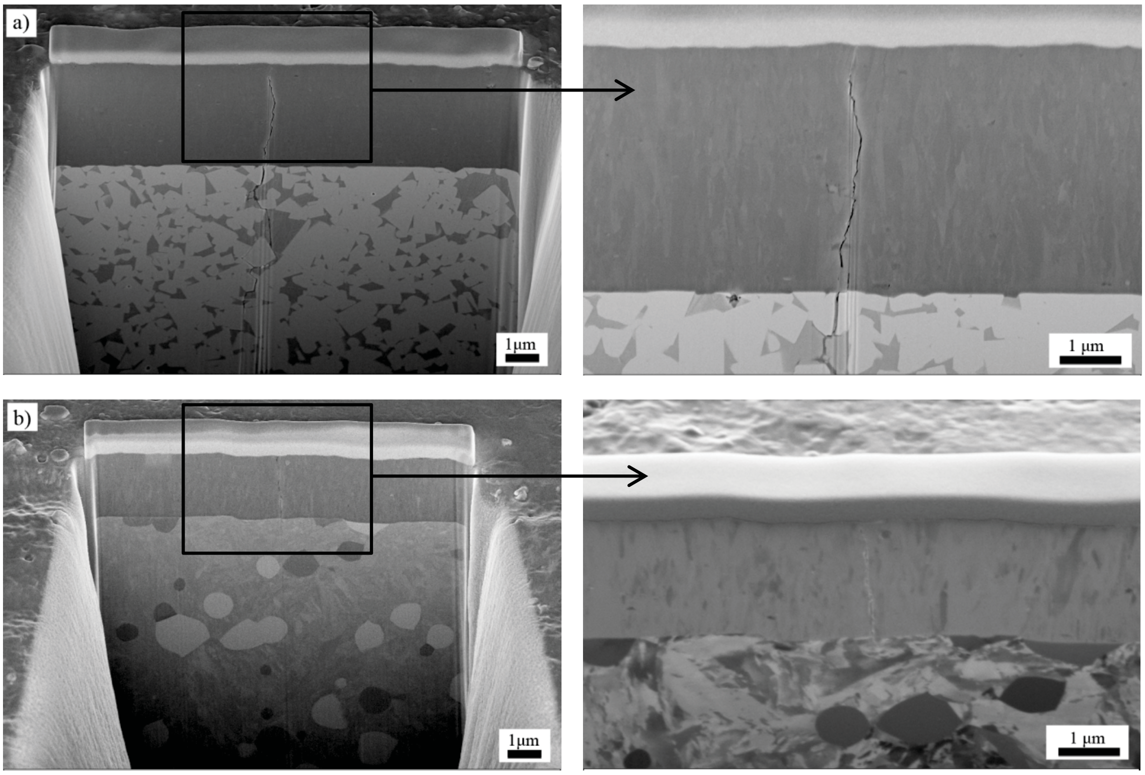

Figure 4. Typical contact damage scenario for the coated systems studied, as assessed from FIB cross-section observation: a) WC-Co+AlCrN; and b) Tool Steel+AlCrN.

Here, it should be noted that, (1) the absence of any intermediate interfacial delamination stage (at substrate/coating level) for both systems, and (2) the role of coating circular fissures as precursors of crack nucleation in the underlying brittle hardmetal. Both experimental facts are quite significant, within the context of the investigation conducted here, because they sustain the choice of early circular cracking at the coating as the critical damage event, mainly because it induces a loss of mechanical integrity of the hardmetal substrate before any adhesive failure takes place. Moreover, they also point out the relevant influence of the substrate nature on the contact response of the coated system, on the basis that such final damage evolution stage (substrate cracking) is not evidenced for the tougher substrate.

4. Conclusion

Based on the experimental study of the mechanical contact behavior, under monotonic and cyclic spherical indentation, of an AlCrN film coated onto two distinct hard tool substrates: cemented carbides and tool steel, the following conclusion can be drawn:

1. Circular cracking at the coating is a more appropriate choice than interfacial delamination for defining critical damage under spherical indentation for the coated hardmetal studied here. Such a statement is based on the fact that it not only emerges as the first failure feature observed with increasing load but also leads to the substrate cracking without any intermediate failure at the interface.

2. Coated systems studied here are susceptible to “real” contact fatigue. However, the substrate plays an important role in the failure-related contact response of the coated system. Cemented carbides

represents a harder and stiffer substrate than tool steel, hence, it deforms less and enables the upward coating easier to follow its deformation before the coating experiencing brittle rupture. On the other hand, once crack initiate, tool steel represents a tougher substrate, thus better equipped to arrest or inhibit any penetrating cracks.

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References

[1] Mo J L, Zhu M H, Lei B, Leng Y X and Huang N 2007 *Wear* **263** 1423

[2] Mo J L, Zhu M H, Leyland A and Matthews A 2013 *Surf. Coat. Technol.* **215** 170

[3] Mitterer C, Holler F, Reitberger D, Badisch E, Stoiber M, Lugmair C, Nobauer R and Kullmer R. 2003 *Surf. Coat. Technol.* **163-164** 716

[4] Fox V, Jones a, Renevier N and Teer D 2000 *Surf. Coat. Technol.* **125** 347

[5] Podgornik B, Hogmark S and Sandberg O 2004 *Surf. Coat. Technol.***184** 338

[6] Carlsson P and Olsson M 2006 *Surf. Coat. Technol.* **200** 4654

[7] Taylor P and Guiberteau F 1993 *Philos. Mag.* **68** 37

[8] Lawn B R 1998 *J. Am. Ceram. Soc.* **94** 1977

[9] Lawn B R, Deng Y, Miranda P, Pajares A, Chai H and Kim D K 2002 *J. Mater. Res.* **17** 3019

[10] Tarrés E, Ramírez G, Gaillard Y, Jiménez-Piqué E and Llanes L 2009 *Int. J. Refract. Met. Hard Mater.***27** 323

[11] Ramírez G, Mestra A, Casas B, Valls I, Martínez R, Bueno R, Góez A, Mateo A and Llanes L 2012 *Surf. Coat. Technol.* **206** 3069

[12] Góez A, Coureaux D, Ingebrand A, Reig B, Tarrés E, Mestra A, Mateo A, Jiménez-Piqué E and Llanes L 2012 *Int. J. Refract. Met. Hard Mater.* **30** 121

[13] Hogmark S, Jacobson S and Larsson M 2000 *Wear* **246** 20

[14] Bantle R and Matthews A 1995 *Surf. Coat. Technol.* **74-75** 857

[15] Jayaram V, Bhowmick S, Xie Z-H, Math S, Hoffman M and Biswas S K 2006 *Mater. Sci. Eng.* A **423** 8

[16] Cairney J, Tsukano R, Hoffman M and Yang M 2004 *Acta Mater.***52** 3229

[17] Abdul-Baqi A and Van der Giessen E 2002 *Int. J. Solids Struct.* **39** 1427