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# Substrate surface finish effects on scratch resistance and failure mechanisms of TiN-coated hardmetals

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ABSTRACT

In this study, the influence of substrate surface finish on scratch resistance and associated failure mechanisms is investigated in the case of a TiN-coated hardmetal. Three different surface finish conditions are studied: as-sintered (AS), ground (G), and mirror-like polished (P). For G conditioned samples, scratch tests are conducted both parallel and perpendicular to the direction of the grinding grooves. It is found that coated AS, G and P samples exhibit similar critical load for initial substrate exposure and the same brittle adhesive failure mode. However, the damage scenarios are different, i.e. the substrate exposure is discrete and localized to the scratch tracks for G samples while a more pronounced and continuous exposure is seen for AS and P ones. Aiming to understand the role played by the grinding-induced compressive residual stresses, the study is extended to coated systems where ground substrates are thermal annealed (for relieving stresses) before being ion etched and coated. It yielded lower critical loads and changes in the mechanisms for the scratch-related failure; the latter depending on the relative orientation between scratching and grinding directions.



## 1. Introduction

Physical vapor deposition (PVD) of hard coatings is a well-established surface modification route to increase the lifetime of cutting tools. The main reasons for the enhanced performance associated with hard coating deposition in terms of improved protection against mechanical and thermal loads are a lower friction and interaction between the tool and chip, and higher wear resistance across a wide range of cutting temperatures [1]. However, the tribological and mechanical behavior of coated tools depends not only on intrinsic properties of the deposited film but also on substrate surface and subsurface properties – such as topography and residual stress state – as well as on interface adhesion strength (e.g. Refs. [1–6]). It is particularly true in the case of coated tools based on WC–Co cemented carbides (backbone materials of the tool manufacturing industry and simply referred to as hardmetals in practice) as substrates. Similar to the case for other hard and brittle materials (e.g. structural ceramics [7]), geometry and/or close tolerances prescribed by the design of hardmetal tools are primarily attained by means of diamond grinding [8]. As a result of this abrasive machining route, mechanical- and thermal-induced alterations are introduced at both surface and subsurface levels [9–13], which may cause changes in the intrinsic cohesive strength of the substrate and the adhesion strength of the coating/substrate interface. Despite their importance, studies of surface integrity evolution throughout the different stages of the hardmetal coating process are scarce [6,14,15]; and knowledge on how it may affect the adhesion strength of the coated tools is even more limited. Such information is critical for further development and improved design of coated hardmetal tools for cutting applications.

In assessing the strength of a coated interface system, the scratch test is the most common method among the options described in the literature, e.g. Ref. [16]. The test is conducted such that a diamond indenter with a tip radius of between 100 and 500 μm slides over the coated surface with an increasing normal load typically between 1 to 200 N. In this context, "practical (extrinsic) adhesion" strength is evaluated in terms of critical forces associated with defined failure events. This is different from the fundamental adhesion strength which is ascribed to the bonding between coating and substrate. However, care must be taken on the quantitative analysis of the results (critical normal forces), as they are affected by various intrinsic and extrinsic parameters [17]. On the other hand, scratch testing is usually complemented by in-situ and post-failure inspection of the failure mode evolution and involved mechanisms as a function of the applied load [18,19]. Such studies have proven to be extremely useful for understanding the tribomechanical response of coated systems when subjected to sliding

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**Table 1**
Nomenclature and roughness parameters ($R_a$ and $R_y$) associated with substrate surface conditions and the coating process steps: uncoated, ion-etched and coated.

| Condition | Substrate surface finish | $R_a$ (μm) | | | $R_y$ (μm) | | |
|---|---|---|---|---|---|---|---|
| | | Uncoated | Ion-etched | Coated | Uncoated | Ion-etched | Coated |
| AS | As-sintered | 0.37 ± 0.10 | 0.36 ± 0.08 | 0.45 ± 0.08 | 2.73 ± 0.76 | 2.34 ± 0.44 | 2.95 ± 0.55 |
| G | Ground | 0.20 ± 0.07 | 0.16 ± 0.02 | 0.25 ± 0.05 | 1.05 ± 0.35 | 1.03 ± 0.12 | 1.72 ± 0.30 |
| P | Polished | 0.01 ± 0.01 | 0.09 ± 0.01 | 0.27 ± 0.05 | 0.11 ± 0.04 | 0.59 ± 0.06 | 1.54 ± 0.20 |

contacts. The individual influence of diverse factors such as the chemical nature of the contact, the hardness of both coating and substrate, and coating thickness may be separated. Recently, Sveen and coworkers used scratch testing to pinpoint the coating failure mechanisms on different hard materials used as substrate, i.e. high speed steel, cemented carbide or polycrystalline cubic boron nitride [20].

The main goal of this study was to investigate the influence of substrate surface finish on the scratch resistance and associated failure mechanisms for a TiN-coated WC–13wt.%Co hardmetal prepared with three different surface finish conditions: as-sintered, ground, and mirror-like polished. The sliding contact response of the coated systems was evaluated by the scratch test technique and characterized by focused ion beam/field emission scanning electron microscopy (FIB/FESEM) with respect to surface morphology, subsurface damage and effective residual stress state.

## 2. Materials and methods

A fine-grained hardmetal grade (WC–13wt.%Co) was used as substrate material in this study. It was supplied as rectangular bars with 4 × 4 × 53 mm dimensions. Vickers hardness and Palmqvist fracture toughness values for the cemented carbide under consideration were 14.8 GPa and 11.2 MPa √m [21], both within the range of those usually reported in the literature for WC–Co hardmetals with similar binder content and carbide grain size (e.g. Refs. [22,23]).

Three different surface finish conditions (on the 4 × 53 longitudinal section) prior to coating deposition were investigated: (i) as-sintered (AS), (ii) ground (G), and (iii) mirror-like polished (P). Plane surface grinding was performed using a commercial diamond abrasive wheel and coolant, the latter for preventing heat generation. On the other hand, polishing was sequentially done using diamond-containing disks, diamond suspensions until 3 μm, and a final step with a suspension of 45 nm colloidal silica particles. The TiN coating was deposited by means of an industrial reactive cathodic arc evaporation system MZR323. The deposition was performed from pure Ti cathodes in a $N_2$ atmosphere at a pressure of 2 Pa. A substrate bias of −50 V was used to accelerate the Ti-ions towards the substrate and the temperature was maintained at 450 °C. Before deposition, the substrates were cleaned in ultrasonic baths of an alkali solution and alcohol. The system was evacuated to a pressure of less than $2.0 \times 10^{-3}$ Pa, after which the substrates were sputter cleaned with about 500 eV Ar ions. All the substrates with the three surface finish conditions were mounted at the same height with respect to the cathodes on a rotating cylinder such that they all were deposited with the same (~3 μm) thick TiN coating in one deposition run.

Intrinsic hardness of deposited coatings, as determined by nanoindentation (MTS Nanoindenter XP), was about 28 GPa independent of substrate surface finish. Prior to nanoindentation testing, all coatings were polished using a silica colloidal suspension in order to minimize the influence from surface roughness on the obtained hardness. The indents were positioned in a 4 by 4 matrix with a closest distance between two indents of 50 μm. Each indent was made to a maximum penetration depth of 2000 nm or until reaching maximum applied load of the equipment, i.e. 650 mN. This procedure ensures no overlapping effect from neighboring indents. The recorded load–displacement curves were evaluated for hardness by assuming a constant Poisson ratio of 0.25

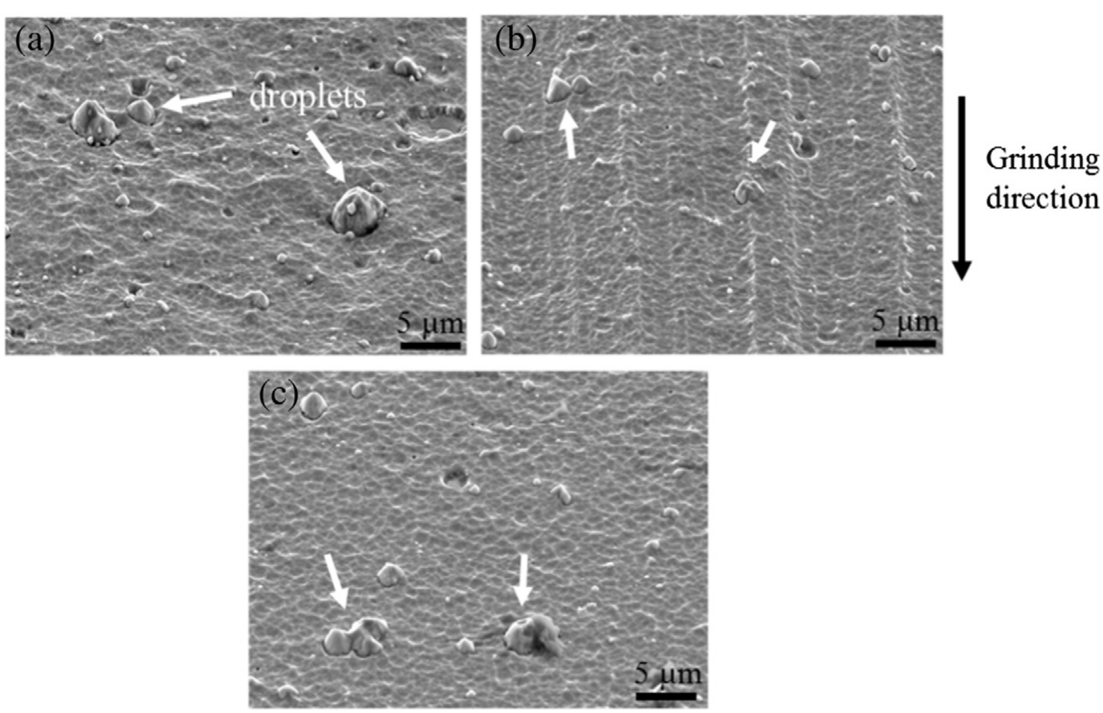


**Fig. 1.** Surface morphology of the coated systems resulting from different substrate surface finish: (a) AS, (b) G, and (c) P. Droplets are indicated by arrows, and surface texture is apparent in the G variant, which displays groove-like features following the grinding direction.