Grinding effects on surface integrity and mechanical strength of WC-Co cemented carbides

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Abstract

In this study, the correlation existing among grinding, surface integrity, and flexural strength is investigated for WC-Co cemented carbides (hardmetals). A fine-grained WC-13 wt % Co grade and three different surface conditions: (1) ground, (2) mirror-like polished (reference), and (3) ground plus high-temperature annealed, are investigated. Surface integrity and mechanical characterization is complemented with fractography. The grinding strongly affects both surface integrity and flexural strength. During grinding, a damaged thin layer together with high compressive residual stresses is introduced. The layer results in considerable strength enhancement compared to the reference polished surface condition. Fractography reveals that the improved strength mainly stems from grinding-induced changes on effective location, from surface into subsurface levels, of the strength-controlling flaw.

Keywords: Grinding; Surface integrity; Cemented Carbides

1. Introduction

WC-Co cemented carbides, often simply termed as hardmetals, represent one of the most successful composite materials ever developed. Due to their two distinct constituents: hard carbide particles embedded in a tough metallic binder, they exhibit an excellent combination of hardness, strength, and fracture toughness together with unique wear and abrasion resistance. As a result, they are frontrunner candidates as tool materials for many cutting and forming operations of metal alloys (e.g. Refs. [1-3]).

Diamond wheel grinding of hardmetals is well established as a primary process used to achieve a particular tool geometry and/or close tolerances prescribed by its design. However, as it is also the case for other hard and brittle materials (e.g. Refs. [4,5]), surface integrity of ground cemented carbides commonly becomes altered. Grinding-induced changes include deformation, microcracking, phase transformation, and residual stresses at both surface and subsurface levels [6-11]. On the other hand, it is also known that strength of hardmetals is controlled by the effective loading condition, microstructure, flaws and their interrelation [12-15]. In this regard, literature information about grinding effects on fracture behavior of these materials is not only scarce but also limited to reports on strength enhancement associated with induced compressive residual stresses [16-18]. It seems necessary and essential to extend the knowledge in this area if the performance and reliability associated with tool and structural applications of hardmetals are to be improved.

Following the above ideas, it is the objective of this study to explore the correlation existing among grinding, surface integrity, and flexural strength for a WC-Co grade. In doing so, surface integrity and mechanical characterization is complemented by a detailed fractographic analysis of the broken samples.
2. Materials and experimental procedure

The material studied is a fine-grained WC-13wt%Co experimental grade. It was supplied as rectangular bars with dimensions 4×4×53 mm. Three different surface conditions (on the 4×53 longitudinal section) were investigated: ground (G), mirror-like polished (P) and ground followed by high temperature annealing (G+TT). Plane surface grinding was performed using commercial diamond abrasive wheel and coolant, the latter for preventing heat generation. On the other hand, P optical finish condition (reference) was produced by a three-step grinding sequence using diamond-containing disks, followed by another three-step polishing sequence employing initially diamond suspension and finally a silica colloidal one. Aiming to investigate a damaged-like ground condition without residual stresses, some of the originally ground specimens were heat-treated at 920 °C for 1h in vacuum [14,15,19-21].

Surface integrity characterization for each investigated condition was conducted in terms of roughness and residual stress assessment as well as damage inspection. Surface roughness was measured by employing a stylus type, surface texture measuring system (Model SurfTest SV512, Mitutoyo). Five measurements were performed per sample. Roughness parameters \( R_a \) (arithmetic deviation from the mean line through the complete profile) and \( R_y \) (maximum profile depth) were recorded.

Subsurface deformation and microcracking were inspected by means of focused ion beam (FIB). Cross-section preparation and microscope investigation was conducted using a dual beam Workstation (Zeiss Neon 40) within a FIB – field emission scanning electron microscope (FESEM).

Surface residual stresses were determined by X-ray diffraction (XRD) with a Panalytical Empyrean four-circle diffractometer using a Cu-K\textalpha\ radiation. Under these conditions, the X-ray penetration depth was approximately 1.1 \( \mu \)m with 50% of the diffracted intensity scattered from a layer extending to the penetration depth. Accordingly, aiming to evaluate the grinding-induced residual stress profile, measurements were performed at different depths (in 2-micron steps approximately down to about 12 \( \mu \)m) below the surface. The different depths were achieved by systematic layer removal by mechanical polishing using 1 \( \mu \)m diamond suspension. The residual stress measurements were performed in \( \psi \)-geometry and point focus mode. Stresses were only determined in the WC phase due to a relative low amount of the binder phase, mainly cobalt, resulting in too weak and broad diffraction peaks and hence inconclusive stress measurements. The WC 211-peak position (20=117°) was recorded for 4-8 \( \psi \)-angles between 0 and 57° by fitting a Gauss or Pseudo-Voigt function to the diffraction data. The stresses were then calculated by applying the \( \sin \psi \)-d method using X-ray elastic constants for WC 211-peak from Eigenmann and Macherauch [22] (\( E=491 \) GPa and \( v=0.20 \)). At this stage, it must be noticed that effective grinding effects from the residual stress values determined for the WC phase should take into consideration the intrinsic microscopic residual stresses existing between the ceramic and metallic phases due to differences in expansion coefficients and processing route for these materials (i.e. sintering at high temperatures and subsequent cooling). In this regard, and according to literature reports using both XRD and neutron diffraction [20, 23-25], baseline values in the range from -100 to -500 MPa are expected for the WC phase in a reference surface condition where machining-induced residual stresses could be disregarded.

Flexural strength was measured to evaluate grinding-induced effects on the fracture resistance of the studied material. It was assessed under four-point bending with inner and outer spans of 20 and 40 mm, respectively. For all the surface conditions, the longitudinal section shaped was the one subjected to the maximum stress in bending. Before testing, the longitudinal edges of all the specimens were chamfered. Flexure tests were conducted using a universal testing machine (Model 8511, Instron, Ltd.) in a room-air environment. At least twelve specimens were tested for each surface condition.

Extensive and discriminative fractography of all the broken samples was conducted by FESEM (Model JSM7001F, JEOL) to identify the sites of fracture origin as well as to characterize, when it was possible, the critical flaws. Experimental data were finally used for evaluating the correlation between surface integrity resulting from grinding (i.e. subsurface damage and residual stresses state) and fracture resistance for the hardmetal studied.

3. Results and discussions

3.1. Surface integrity characterization

Grinding is well-established as the primary abrasive machining process for hardmetals. It involves abrasive grits (diamond particles with sharp edges) bonded into a wheel that rotates at high speed. The mechanism of material removal caused by the abrasive cutting edges on the wheel surface is basically the same as that with cutting tools. During grinding, the WC grains are either cracked by the high-applied (tensile) stresses of the diamond abrasive grains, or plastically deformed by the compressive stresses in front of the referred grains. The relatively soft metal binder is smeared out over the surface with the pulverized WC grains and may be partly
removed from the surface together with the WC grain fragments [8,26]. Roughness features for the ground and polished conditions studied are intimately related to the resulting surface texture. Average and mean roughness values are given in Table 1. From the results, it can be seen that grinding yields roughness values one order of magnitude higher than those achieved for the optical finish condition.

Fig. 1 shows the subsurface features associated with G and P surface conditions. Transverse-sections were made perpendicular to the grinding direction by FIB milling. Microstructural changes as well as cracking are clearly discerned for the G condition. Grinding-induced damage is intense within a thin subsurface layer (around 400 nm) where fragmented WC particles are the main features. Moreover, damage is also evidenced in terms of carbide microcracks, following either transgranular or intergranular (between contiguous particles) paths, up to depths of approximately 0.1 μm. These findings are in agreement with those reported by Hegeman et al. [8]. Such scenario is completely different from that observed for the P surface condition, tagged as reference, where any surface damage is hardly observed. Finally, G+TT condition showed similar surface texture and subsurface damage features to those described for the G condition. As heat treatment does not imply any mechanical action or crack healing, such inheritance from G condition was expected.

The residual stresses measured at the surface level for the three different surface conditions are presented in Fig. 2. The grinding process leads to compressive residual stresses of about -1.8 GPa (± 0.2 GPa). It is one magnitude higher than those assessed at the surface of the reference P condition, approximately -0.1 GPa (± 0.1 GPa). On the other hand, similar deformation-free state is discerned for the G+TT condition, validating then the effectiveness of 920 ºC / 1 h (i.e. temperatures above 800 ºC [19]), as high temperature annealing for relieving mechanically induced residual stresses in hardmetals.

In general, residual stress levels measured at the surface of ground specimens are in satisfactory agreement with those reported in previous studies [8,16,27]. Although mechanical and thermal loads both exist during grinding, the former predominates as thermal effects are suppressed by the coolant [28]. The origin of these residual stresses can then be understood by regarding the irreversible deformation, as well as fracture, induced by a large number of isolated sharp particle contact events during the grinding. Each isolated elastic/plastic contact gives rise to a radially compressive field with tangential tension outside the plastic zone which surrounds the contact site. As a result, cracks form on median planes within the tensile field, and overlap of residual fields from neighboring damage sites in the machined surface gives rise to a layer of compressive residual stresses [29]. This is exactly the surface integrity scenario discerned for ground hardmetals in this investigation. On the other

Table 1. Nomenclature, involved machining operations, and roughness parameters associated with the surface conditions studied.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Machining operations</th>
<th>Ra (μm)</th>
<th>Ry (μm)</th>
</tr>
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<tbody>
<tr>
<td>G</td>
<td>Diamond wheel grinding</td>
<td>0.19±0.07</td>
<td>1.05±0.35</td>
</tr>
<tr>
<td>P</td>
<td>Polishing up to optical finish</td>
<td>0.01±0.01</td>
<td>0.11±0.04</td>
</tr>
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hand, sequential removal of material (beyond the damaged/deformed layer) by soft abrasion, i.e. gentle polishing employing finer, looser abrasives in fluid suspensions, yields an ideal undamaged and unstressed reference surface condition. Similar deformation-free state is attained by annealing at 920 °C for 1 h, which is above the temperature (about 800 °C) when the binder phase becomes too soft to carry any load and residual stresses are relieved by local creep [20]. However, as neither mechanical action takes place nor temperatures are extremely high for any possible crack healing, the damage inherited from grinding is retained.

As changes in the stress state at the surface may also induce variations in nature and site of the strength-controlling damage, assessment of residual stresses was extended to subsurface levels. Indeed, reliable experimental information on this key issue is scarce [30], possibly because the quite limited penetration depth of Cu-Kα radiation in WC (about 1-3 μm) requires sequential material removal and corresponding XRD analysis for attaining a depth profile of the residual stress. This was performed here by mechanical (and quite gentle) polishing using 1 μm diamond suspension.

The depth resolved residual stress profile for the G surface condition is given in Fig. 3. Very interesting, a ground-related compressive stress state (i.e. above -300 MPa) is assessed to persist at the subsurface down to depths as large as 12 μm, i.e. well beyond the thickness estimated for the deformed/damaged layer. Such a finding is in agreement with results recently published by Denkena et al. [30]. The compressive stress profile describes a rather smooth variation (30% lessening) in the first 6 μm depth, pointing out an overcompensating effect to the undesirable damage concentrated in the layer just below the surface. On the other hand, it exhibits a rather rapid change from about -1.3 GPa to baseline values (-0.3 GPa approximately) within the next 6 μm depth range. The effective influence of this compressive layer, regarding magnitude and depth profile, on the strength of ground specimens will be discussed below.

3.2. Grinding effects on flexural strength

Mean and standard deviation values (σf), as well as Weibull parameters (characteristic strength σ0 and modulus m) for the flexural strength of the surface conditions investigated are shown in Fig. 4. It may be stated that strength of the hardmetal studied is enhanced by grinding, as compared to the intrinsic one measured for the P reference condition. On the other hand, such strength increase is completely lost after annealing the ground specimens. Hence, measured flexural strength for the G+TT condition yields strength values even lower than those determined for the P condition, although differences between both surface conditions may not be accounted as statistically significant. Considering that grinding has been found to induce relevant compressive stresses at the surface (where maximum stress is applied in bending tests), a strength increase was somehow expected. However, and in agreement with previous findings by other authors [16, 17], it should be noticed that improved behavior is relatively lower than the one estimated by assuming simple superposition of residual stresses to the applied stress, on the basis that critical flaws are linked to induced surface damage.

Regarding Weibull analysis of the experimental data, as expected, σ0 (stress value for a failure probability of 63.2%) values are higher than those corresponding to σf, (failure probability of 50%). More interesting is the finding of a significantly higher m value for the G+TT condition (close to 30) as compared to those determined for G (12.7) and P (5.4) conditions. Higher m values are the result of less scattered data, and this is directly

Fig. 2. Residual stresses at the surface for G, P and G+TT conditions, measured by X-ray diffraction in the tungsten carbide phase using the (211) reflection and Cu Ka radiation.

Fig. 3. Depth resolved residual stresses profile measured (in WC phase) for the G surface condition.
related to how narrowly the failure scenarios among the tested specimens vary.

Aiming to provide additional information for analyzing surface integrity - strength correlation, extensive fractographic analysis of all the broken specimens was conducted. The main goal behind this was to identify the type and location of flaws governing the strength of the cemented carbides for each of the surface conditions studied. FESEM micrographs showing typical examples of failure initiation sites for G, P and G+TT surface conditions are given in Fig. 5. Several observations may be listed. First, for both G and P specimens fracture initiation sites are always associated with intrinsic processing flaws (pores or large carbides) with sizes of about 10-20 μm. Second, while flaw location for the P condition is rather undefined (i.e. at the surface or close to it at variable depths), for the G specimens it is always at the subsurface. Third, subsurface critical defects in G specimens are usually located deeper (always beyond 10 μm and in some cases even down to 300 μm from the surface) than in P samples. Fourth, identification of discrete critical flaws for G+TT specimens is scarcely achieved, although its location is clearly discerned at the surface and affiliated to grinding-induced damage. Moreover, this fractographic analysis is quite compelling as they reveal that enhanced strength measured for ground specimens is not a direct effect of the induced compressive stresses (i.e. simple superposition of stress fields acting on generated surface damage) but rather an indirect one associated with changes promoted by them on the effective location of the strength controlling flaw (from surface into subsurface levels). This statement is supported by the results documented for the G+TT condition, where it is evidenced that grinding-induced surface damage becomes critical if compressive residual stresses are relieved by heat treatment.

Finally, it should be underlined that fractographic findings just described are also basic for understanding the statistical (Weibull) behavior presented above. In general, Weibull modulus is directly associated with how variable nature, size, geometry and location of critical defects are. Hence, the relatively high m value for the G+TT condition is clearly associated with well-defined and uniform (from specimen to specimen) grinding-induced damage features being always

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Fig. 4. Flexural strength σf, characteristic Weibull parameters: σ0 and m for surface conditions studied.

Fig. 5. FESEM micrographs of failure initiation sites: intrinsic processing defects at depth around 260 μm for G specimen (a) and at near the surface for P sample (b); and grinding-induced surface damage for G+TT specimen (c).
responsible for failure. On the other hand, the rather low Weibull modulus exhibited by the P condition is the result of the intrinsic variability on microstructural heterogeneities for the hardmetal studied, including their nature, geometry and location (e.g. elongated versus rounded pores, the former randomly oriented, located either at the surface or in the bulk). Such dispersion is decreased for the G surface condition (higher m value than for P condition) as the high compressive residual stresses induced by the grinding process not only impose all strength-controlling flaws to be uniformly located (in the bulk) but also rise the mean strength value used as reference for evaluation of relative variability of the determined data.

4. Conclusions

The present study focused on the assessment and understanding of grinding effects on surface integrity and flexural strength of a fine-grained WC-13%Co hardmetal grade. The main findings are summarized as follows:

1. Surface integrity of the hardmetal studied is strongly affected by grinding: generation of a thin deformed/damaged layer containing fragmented carbides and microcracking; and introduction of a relevant compressive stress field with maximum levels close to -2 GPa at the surface and extended (although decreasing with depth) until subsurface levels of about 12 μm. Subsequent annealing at 920 ºC for 1 h effectively relieves the machining-induced compressive residual stresses but without any beneficial effects on the damaged surface layer.

2. Ground specimens exhibit a noticeable strength enhancement, as compared to the values determined for the reference P condition. However, improved mechanical behavior is relatively lower than the one estimated by assuming simple superposition of residual damage and externally applied stresses on generated surface. On the other hand, the experimentally measured strength increase is lost after relieving the surface compressive residual stresses by heat treating the ground samples.

3. Extensive inspections of fractured specimens reveals that enhanced strength measured for ground specimens mainly results from grinding-induced changes on effective location, from surface into subsurface levels, of the strength controlling flaw.

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References


