Grinding of WC–Co hardmetals

J.B.J.W. Hegeman a, J.Th.M. De Hosson a,⇑, G. de With b

⇑ Laboratory of Applied Physics, Materials Science Center and The Netherlands Institute for Metals Research, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

b Laboratory of Solid State and Materials Chemistry, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Received 24 November 2000; accepted 24 November 2000

Abstract

This paper concentrates on the morphology of the ground surface of cobalt tungsten carbide (WC) composite materials that belong to the category of so-called hardmetals. A deformed and detached surface layer was found on top of the specimens after surface grinding with a diamond wheel. In order to determine aspects of material removal, various routes were followed. Etching the surface layer revealed WC grains in the subsurface of the machined samples. Most of these grains were plastically deformed by prismatic slip in the hexagonal lattice of WC. Also cracks were found in these grains. Further, the increase in residual stress due to the grinding process was examined by X-ray diffraction (XRD). The stress increases to a maximum stress in the carbide grains before the relaxation occurs by slip and cracking. The surface roughness after grinding was measured by scanning confocal microscopy. Roughness exponents were calculated from the 3D profiles and the values of this process were in good comparison with values for grinding ceramics. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Grinding; Hardmetals; Abrasive machining; Roughness; Residual stress

1. Introduction

Tungsten carbide (WC) hardmetals are often used as a wear resistant material, e.g. for cutting tools, drilling tools, dies, etc. The high hardness of the WC grains combined with the relative ductile binder leads to excellent mechanical properties. Because the wear rate can be related to the mechanical properties of the materials such as hardness, ductility and fracture toughness, various researchers studied the relation between the microstructure and hardness of the WCs. It was found that the hardness depends on the cobalt content as well as on the grain size of the carbides [1,2].

Also the wear of the hardmetals was studied using carbides with various cobalt contents and hence various microstructures were found [3,4]. In some studies wear was simulated by scratching the surface in a controlled way [5,6]. From the scratch tests it was shown that the size ratio between the abrasive particles (the sliding indenter) and the WC grains determines the material removal behavior. It was also found that for increasing grain size or increasing cobalt content, the hardness decreases. Grinding experiments were performed on cemented carbides under various conditions such as dry grinding, wet grinding or even electrochemical grinding [7,8,9]. Here, we focus on the grinding of WCs with a fixed amount of cobalt with various grain sizes. Therefore, different wear behavior is predicted for the hard metals with the small grain sizes than for those with the large grain sizes.

In earlier research, plastic deformation of the hardmetal was entirely explained by plastic deformation of the binder phase. Later, it was shown that the anisotropic ($c/a < 1$) WC could also exhibit plastic deformation under certain conditions [10]. In this study, we show some new results on the wear behavior of WC–Co during the grinding process. In particular, we will show that the WC is mainly plastically deformed by slip but cracks were also found in the carbide phase.

Many researchers studied residual stress inside the carbide grains and inside the cobalt phase. It is important to differentiate between the macroscopic residual stresses and the microscopic residual stresses between the individual phases due to differences in expansion coefficients. The first is usually measured by X-ray diffraction (XRD) by determining the peak shift using the sin$^2$ψ method, where the latter is measured by peak broadening [11,12]. In the present study, the macroscopic residual stresses that are induced by the grinding process are measured. Stress relief by heat treatments was studied by Mari et al., [13] and Krawitz [11] using neutron diffraction. The increase in compressive residual stress after grinding was studied using XRD.
[12–15]. Most of the scientists found an increase in residual stress with a decrease in cobalt content or an increase in abrasive grit size. Only a few researchers pointed out that the penetration depth of Cu Kα radiation in WC is very low compared to the average grain size for Cu Kα radiation [13,16]. Here, we will show that the penetration depth becomes even more important when there is a deformed layer on top of the ground surface.

2. Experimental procedures

2.1. Materials and sample preparation

The materials used for the grinding experiments were various kinds of liquid phase sintered hard metals with WC grain sizes of 3, 5, 10 and 20 μm and cobalt contents of 6, 10 and 20 wt.% (Boart Longyear), which lead in principle to 12 different kinds of Co–WCs. However, here we mainly focus on the WC with 10 wt.% cobalt and occasionally the other systems are used. The samples (Ø = 12 mm, h ≈ 3 mm) were polished with 60, 30 and 10 μm paste, respectively, to obtain a surface as flat as possible. Diamond paste of 1 μm was not employed for finishing in order to avoid preferential polishing of the cobalt phase, as is observed during polishing with 1 μm diamond paste. After each sequential polishing step, the surface was cleaned with acetone. Then, the samples were heat-treated at 700°C for 4 h in high vacuum (P < 2.6 × 10⁻⁴ Pa) with subsequent slow cooling. The second heat-treatment was performed at 900°C for 8 h in high vacuum to relieve the macroscopic residual stress and the damage that was induced in the surface by the polishing process. The relevant material properties were measured using SEM and the line-intersection method. The equations of Lee and Gurland [1] were applied to determine the mean intercept diameter \( \delta_{\text{WC}} \), the mean free path in the binder phase \( \lambda_{\text{Co}} \), assuming the presence of a cobalt layer between the WCs grains and the contiguity \( C_{\text{aa}} \). The hardness \( H_v \) was measured using a micro hardness tester (Vickers). All the properties are listed in Table 1 versus their grain size (as given by Boart Longyear) and cobalt content.

2.2. Grinding procedure

The grinding experiments were performed using a Jung JF 415 grinding machine for plane surface grinding. The abrasive wheel used was a Technodiamant D91 C75 MN 790 with diamond abrasives and a metal binder (brass). The wheel had a diameter of \( d_w = 25 \text{ cm} \). The average size of the abrasive grains on the wheel is 91 μm with a standard deviation of 15 μm, which means that approximately 34 μm of the grain is protruding from the binder of the grinding wheel [17]. Water–oil emulsion was used as a coolant during the grinding process to avoid burn out and thermal damage. During the grinding experiments, various parameters were used as listed in Table 2.

The specimens were glued on a steel plate with hot wax (dissolvable in acetone). Then, the steel plate was fixed on the grinding machine as parallel as possible with the abrasive wheel to avoid a variation of depth of cut over the surface of the specimen. The specimens were ground within one single pass. After grinding, the samples were ultrasonically cleaned with acetone (to dissolve the wax) and alcohol.

2.3. Analysis of the ground surfaces

The surfaces were analyzed using a Philips XL30 FEG SEM equipped with a secondary electron detector, a backscatter detector and also an X-ray microanalysis system. 3D profiles were recorded using a confocal microscope (Surf of NanoFocus) with four different objectives, i.e. different lateral and vertical resolutions. Residual stress measurements were performed on a Philips X’pert PW 3040 X-ray diffractometer with a \( \psi \) goniometer.

3. Results and discussion

3.1. Morphology of the ground WC–Co surface

The morphology and microstructure of the specimens were studied before and after grinding using SEM with a backscatter detector and a secondary electron detector. EDS
measurements were employed to check the average cobalt contents of the samples. The characteristic microstructures of the polished and heat-treated WC-10 wt.% Co samples with various WC grain sizes are shown in Fig. 1. After grinding, the specimens were studied using the backscatter detector to increase the contrast between the cobalt phase and the WC grains in order to reveal the cracks inside the WC grains. In Fig. 2, the typical morphology of the ground surface is shown. Comparing the micrographs with the polished and heat-treated samples, one can clearly see that the microstructure and morphology at the ground surfaces was changed, as also observed by Zelwer and Malkin [7] and Jia and Fischer [3].

More detailed studies of the ground surfaces show that during grinding the WC grains are cracked and pulverised by the high-applied (tensile) stresses of the diamond abrasive grains. It is also shown that part of the carbide grains are pulled-out, leaving some pits, or they are plastically deformed by the compressive stresses in front of the abrasive grains. The relatively soft metal binder will be smeared out over the surface with the pulverised WC grains and is partly removed from the surface together with the WC grains and fragments.

In Fig. 2 it is shown that the ratio between the grain size of the work piece and the abrasive grain size on the wheel determines the detailed material removal behavior. Deforming

---

Table 2
The grinding parameters used during the grinding experiments on the Jung grinding machine for plane surface grinding

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Grinding parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC-10 wt.% Co, 3, 5, 10, 20 μm WC grains</td>
<td>Wheel speed $V_s = 30$ m/s</td>
</tr>
<tr>
<td></td>
<td>Table speed (workpiece) $V_w = 12.2$ m/min</td>
</tr>
<tr>
<td></td>
<td>Depth of cut $d = 4$ μm and $d = 10$ μm (for each type of sample)</td>
</tr>
<tr>
<td>WC-20 wt.% Co, 3 μm WC grains</td>
<td>Wheels speed $V_s = 30$ m/s</td>
</tr>
<tr>
<td></td>
<td>Table speed (workpiece) $V_w = 3$ m/min</td>
</tr>
<tr>
<td></td>
<td>Depth of cut $d = 2, 5$ and $9$ μm</td>
</tr>
</tbody>
</table>

---

Fig. 1. Characteristic SEM micrographs of the polished and heat-treated WC-10 wt.% Co specimens. Average tungsten carbide grain size: (a) 3 μm (b) 5 μm (c) 10 μm (d) 20 μm. The cobalt phase was partly evaporated at the surface due to the heat treatment. The white straight truncated areas are the tungsten carbide grains and the dark parts are cobalt binder.
the surface during scratch tests by diamond indenters show a similar dependence on the ratio between indenter size and WC grain size [3,18]. In hard-metals with smaller grain size more pull out, pulverization and fragmentation of WC grains were found. At the surface of those with the bigger grain sizes pull out was found at localised areas between the grains at the surface. Some of these big WC grains at the machined surface are cracked.

In order to study the subsurface, cross-sections of the cobalt WC samples were made by cooling the sample to liquid nitrogen temperature and by subsequently breaking at brittle fracture. The cross-sections were made perpendicular to the grinding direction. SEM micrographs of the fracture surface at the machined surface show that the grinding process resulted in a layer on top of the ground surface as is shown in Fig. 3. The morphology of this layer varied with...
different WC grain size and with the grinding parameters. The thickness of such a deformed layer for the sample shown in Fig. 3 with 20 \( \mu \text{m} \) grains and a cobalt contents of 10 wt.\% was approximately 1.5 \( \mu \text{m} \) and varied along the surface. It was found that the thickness of the layer is smaller at the ridges of the ground surface and thicker in the valleys. The content of the layer was studied at larger magnification and it was found that the layer consists of pulverised and fragmented WC particles bonded by some cobalt. From X-ray microanalyses on the top-view of the surface, we can see that the cobalt was smeared out evenly in the deformed layer, in contrast to the original bulk material where the cobalt is concentrated between the WC grains.

The average thickness of the deformed surface layer was studied for the WC-20 wt.% Co with the 3 \( \mu \text{m} \) WC grain size for different depth of cut during the grinding process \( d_{\text{cut}} = 2, 5 \) and 9 \( \mu \text{m} \) and also for the cemented carbides with different grain sizes. No relation between the layer thickness and the depth of cut (hence no relation with the grinding force) was found. In addition, no relation has been observed between the average thickness of the deformed layer and the microstructural parameters of the material, i.e. no relation with the hardness was noticed. A difference in layer thickness with hardness and forces is expected based on the analyses of cracks during the normal indentation of indenters with various shapes [19,20]. However, the measurement of the layer thickness is complicated because of the large variation in thickness along the ground surface due to the in-homogeneity of the cemented carbides and the size distribution of abrasive grains on the grinding wheel.

In contrast to the layer thickness, a difference in morphology of the deformed surface layer with different cobalt content and different carbide grain size was observed. The deformed layer of the ground surface of the hardmetals with the larger WC grains also contained larger fragments of WC [21].

The ground surface was etched for the cobalt phase. The etchant contained a solution of 15 ml demineralised water, 15 ml glacial acetic acid, 60 ml hydrochloric acid 32% and 15 ml nitric acid 65% [22]. After 30 s of etching, the surface was cleaned using alcohol and subsequently acetone. The etched surface was examined using SEM. In Fig. 4, one can clearly see that parts of the deformed surface layer were removed by the etching procedure leaving a pit in the deformed surface layer. However, still many parts of this layer are present on the surface. The morphology and size of the deformed layer could be studied by changing the angle of inclination of the specimen relative to the electron beam in the SEM to 45\(^\circ\) as is shown in Fig. 5. As is depicted in the picture, there is a gap between the layer and the surface. This may indicate that the etchant removed the cobalt between the deformed layer and the subsurface and thus pointing out that there is less cobalt in the deformed surface layer than in the bulk otherwise the layer would be removed first. Here, we also can see that the layer is homogeneous but varying in thickness at protruding WC grains.

The WC grains at the bottom of the pit were studied at higher magnifications. From Fig. 6, we can conclude that most of the subsurface WC grains at the machined surface were plastically deformed by slip (no. 1 in Fig. 6a). Some of the carbide grains contained three different slip planes as is indicated in Fig. 6b. Since \( c/a \) ratio of the hexagonal lattice of WC is very small \( c/a \approx 0.97 \) compared to the ideal of 1.633, the preferred slip system may differ from slip in the basal plane as observed in most hexagonal systems. Here, three-fold symmetry was observed, which indicates that the WC was deformed by \( \{1010\} \) prism slip. Other researches did also report slip in the WC grains in cemented carbides using indentations, transverse rupture tests and scratch tests, respectively [1,3,6,23]. Cracks (no. 2 in Fig. 6) were found in some of the WC grains. Engqvist [6] showed that cracking

---

**Fig. 4.** Top view of the ground surface after etching, showing a pit in the surface layer with the plastically deformed WC grains. Only parts of the surface layer are dissolved which indicates that there is only little cobalt in the smeared layer.
might appear for scratching WC in different crystallographic directions.

3.2. Surface roughness of ground WC–Co

The surface roughness of the ground cobalt WCs was examined by scanning confocal microscopy. Using this technique, 3D profiles can be recorded of ground surfaces at different magnifications. In principle, the lateral resolution is limited by the wavelength of light. Here, the lateral resolution is limited by the field of view of the objective and the number of pixels of the CCD camera and therefore the lateral resolution lies between 0.27 and 2.7 \( \mu \text{m} \) for the 0.95/100\( \times \) and the 0.30/10\( \times \) objectives, respectively [24]. The vertical resolution is limited by the step-size of stepper motor or piezo element and the numerical method to fit the depth response curve (\( \Delta z \approx 50 \text{ nm} \)).

From the 3D profiles obtained by the confocal microscope measurements, the surface roughness values, such as \( R_a, R_z \), and the Hurst exponent were calculated. The Hurst exponent \( H (0 < H < 1) \) is a measure of the degree of surface roughness at short wavelengths. Small values of \( H (\sim 0) \) characterize the extremely irregular surfaces, while large values of \( H (\sim 1) \) delineate smooth surfaces with some hills and valleys. The Hurst exponent and the characteristic correlation length \( \xi \) can be determined from the height–height correlation function: \( G(X) = \langle [h(x) - h(0)]^2 \rangle \), where \( h(x) \) is the roughness fluctuation perpendicular to the grinding direction, with \( \langle h(x) \rangle = 0 \) (see Meakin [25]). The average of the correlation function was calculated for 150 lines on
Three different images at the same magnification perpendicular and parallel to the grinding direction (see Fig. 7) for all of the objectives. The magnification should be chosen to optimize for the correlation length and the characteristic features at the ground surface. The roughness values $R_s \perp$ and $R_s \parallel$ perpendicular to the grinding direction were calculated from 512 lines. It should be noted that the calculated $R_s$ and $R_z$ values are not according to the DIN standard because the length of the roughness lines were too short.

The roughness values for the ground WC-10 wt.% Co samples are listed in Table 3. The results show that the roughness of the ground surfaces depends on the WC grain size inside the specimens. It seems that the roughness increases for the smaller grain size although more pullout was expected on samples with the larger grain sizes and more pulverization was found on the samples with smaller grain sizes. The roughness values perpendicular to the grinding direction were on average three times higher than parallel to the grinding direction. The height distribution had a small negative skewness for all of the specimens. For the cemented carbides with the 20 $\mu$m grain size, the skewness was somewhat higher indicating the presence of pits.

In Fig. 7, the height–height correlation function is shown for all specimens at the same magnification (20×). The Hurst exponent was calculated from the least-square fit to the left part of the graph. Also the correlation length was calculated from the height–height correlation function. The Hurst exponents $H$ of ~0.75 means that the surface is not completely formed randomly although the grains on the grinding wheel are distributed randomly. However, the Hurst exponent indicates that grinding process contains some non-linear terms in the roughness formation process. The movement of the grinding wheel and the formation of the surface profile can be described by non-linear equations [17]. The Hurst exponents found are similar to the values determined for the ground surfaces of some ceramic materials [26].

The correlation length $\xi$ corresponds to the average abrasive grain size on the grinding wheel. Only the most protruding part of those grains is used for the grinding operation and hence the correlation length is larger for the higher depth of cut.

### 3.3. Residual stresses in WC–Co due to grinding

XRD was employed to examine the residual strains in the subsurface area of the ground specimens. The $\sin^2 \psi$ method was used to calculate the stress from strains in the specimens before and after grinding. The diffractometer was set up to measure the strains perpendicular to the grinding direction, i.e. $\psi = 90^\circ$.

The strains in the samples were measured using the (201) reflection of WC with Cu Kα radiation. The diffraction angle $2\theta = 84.0^\circ$ and a beam mask of 0.6 mm × 0.6 mm were chosen which resolves in a radiated area between 0.5 and 1.1 mm² for $\psi$ varying from −60 to 60°. This area contained at least 40 scratches of the abrasive grains on the

<table>
<thead>
<tr>
<th>WC-10 wt.% Co grain size (µm)</th>
<th>WC-10 wt.% Co abrasive grain size (µm)</th>
<th>WC grains 3 µm</th>
<th>WC grains 5 µm</th>
<th>WC grains 10 µm</th>
<th>WC grains 20 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$ (µm)</td>
<td>4</td>
<td>0.77 ± 0.11</td>
<td>0.78 ± 0.09</td>
<td>0.28 ± 0.03</td>
<td>0.30 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.69 ± 0.06</td>
<td>0.72 ± 0.06</td>
<td>0.28 ± 0.03</td>
<td>0.33 ± 0.04</td>
</tr>
<tr>
<td>$R_z$ (µm)</td>
<td>4</td>
<td>3.5 ± 0.3</td>
<td>3.5 ± 0.3</td>
<td>1.6 ± 0.1</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.3 ± 0.1</td>
<td>3.4 ± 0.4</td>
<td>1.6 ± 0.1</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>$H$</td>
<td>4</td>
<td>0.77 ± 0.02</td>
<td>0.82 ± 0.03</td>
<td>0.72 ± 0.02</td>
<td>0.73 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.72 ± 0.02</td>
<td>0.80 ± 0.03</td>
<td>0.74 ± 0.02</td>
<td>0.76 ± 0.02</td>
</tr>
<tr>
<td>$\xi$ (µm)</td>
<td>4</td>
<td>20 ± 1</td>
<td>19 ± 2</td>
<td>12 ± 1</td>
<td>14 ± 1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>27 ± 2</td>
<td>19 ± 2</td>
<td>17 ± 1</td>
<td>15 ± 1</td>
</tr>
</tbody>
</table>

The $10 \times 0.30$ objective was used to determine $R_s \perp$ and $R_z \perp$, the $20 \times 0.45$ objective was used to calculate the height–height correlation function ($H$ and $\xi$).
grinding wheel and therefore local stress variations were averaged out.

The penetration depth in the WC was calculated for $2\theta = 84.0^\circ$ and $\psi = 0^\circ$ from Eq. (1) of [12,27] where the reflected intensity $I(z)$ at depth $z$ can be evaluated.

$$I(z) = I_0 e^{-z/z^*}, \quad \text{where} \quad z^* = \frac{\sin \theta \cos \psi}{2\mu}$$

where $\mu$ represents the mass absorption coefficient. It was determined that 50% of the radiation comes from the first 0.9 $\mu$m and that 95% appears from a depth <3.9 $\mu$m, which is very similar to that found by Krawitz [13]. It should be realised that this penetration depth is much less than the size of the WC grains in the materials used and that most of the reflected beam (68%) comes from the plastically deformed layer as denoted in Fig. 8. This means that only the average residual stresses in the deformed surface layer and the first layer of carbide grains are measured. Note that these layers had the largest interaction with the grinding wheel and are mostly deformed as shown by the SEM micrographs, therefore, it is expected that the residual stress state at the machined surface is different from the bulk residual stress. Some researches [15,28] electro-polished the surface to obtain a depth profile of the residual stress. They found a compressive stress up to a depth of about 10 $\mu$m.

The residual stress state was calculated from the strains using the X-ray elastic constants for the (201) reflection in WC [16]: $S_1 = -2.25 \times 10^{13}$ m$^2$/N and $(1/2)S_2 = 15.69 \times 10^{13}$ m$^2$/N ($E_{WC(201)} = 744$ GPa, $v_{WC(201)} = 0.17$). The measured stresses on the polished and heat treated specimens before grinding for the 10 wt.% cobalt specimens are listed in Table 4. An increase in stress was found in the polished and heat-treated samples with an increase of grain size although they all were stress relieved at the same temperature.

Also the average stress increase due to the grinding process, i.e. the grinding residual stress, is listed in Table 4. The grinding residual stress is considered to be the difference between the total residual stress after grinding as measured with XRD and the residual stress after the heat treatment. Although the specimens were ground at different depth of cut, i.e. different grinding forces, no relation was found with the grinding residual stress. For the different grain sizes, as well as for the different depth of cut, the residual stress seems to increase to a maximum total stress of the order of 1.5 GPa for all of the specimens.

This maximum residual stress can be explained by the stress relieve due to the cracking and plastic deformation in the WC grains. Electron microscopy proved that most of the WC grains at the ground surface contained slip-planes and some of them were cracked. In earlier work researchers have noticed that the residual stress increases up to a maximum between 1 and 1.5 GPa [29]. The residual stress inside the carbide grains is of the same magnitude of the tensile

Table 4

The residual stress after heat treatment and the grinding residual stress measured by X-ray diffraction in the tungsten carbide phase using the (201) reflection of tungsten carbide and Cu Kα radiation

<table>
<thead>
<tr>
<th>WC-10 wt.% Co</th>
<th>WC grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>d$_i$ (µm)</td>
<td>3 µm</td>
</tr>
<tr>
<td>After polishing and heat treatment</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Total residual stress</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Grinding residual stress$^a$</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

$^a$ Grinding residual stress = total stress − the residual stress after heat treatment.

Fig. 8. SEM micrograph of the cross section at the ground surface and the graph of the intensity of the reflected beam as a function of depth $I(z)$ showing the small penetration depth compared to the surface layer and the average tungsten carbide grain size.
strength of WC. The strength of WC is an upper bound for the residual stress $\sigma_{\text{residual}} < \sigma_{\text{strength}}$, therefore, the measured residual stress has a limit near 1400 MPa [30,31].

4. Conclusions

The paper illustrates that the importance of the ratio between the grain size of the specimen and the grain size of the abrasives during the grinding experiments. It was shown that the grain size determines the hardness and therefore, it will influence the wear resistance of metal matrix composites. Also, here it is shown that the material removal behavior was different for the Co–WC with small grain sizes and for the larger grain sizes. In contrast, some research attributed the plastic deformation of the composite totally to the deformation of the cobalt binder material. Also, here it is shown that a major part of the plastic deformation takes part in the WC grains. The cobalt binder was partly removed together with fragmented carbides and was also partly smeared out. A deformed layer with an average size of 1.5 $\mu$m was found on top of the ground surface. This deformed surface consists of fragmented and pulverized grains and smeared out cobalt.

The relationship between the surface roughness and the grain size, i.e. the mechanical properties of the specimens was studied. It was shown that there is a relation between the correlation length and (abrasive) grain size. Part of this relation was ascribed to the pullout of WC grains during the grinding process. The Hurst exponent was found to be the same as for ground surfaces of other materials [26]. This may be attributed completely to the type of mechanical process by which the surface was formed. The minor differences in Hurst exponent and correlation length for different materials can be explained by the difference in material removal behavior of these materials during the grinding process.

In X-ray residual stress measurements, the deformed surface layer is very important because 68% of the beam strength of WC is an upper bound for the residual stress $\sigma_{\text{residual}} < \sigma_{\text{strength}}$, therefore, the measured residual stress has a limit near 1400 MPa [30,31].

- The roughness of the ground surface is depending on the size of the WC grains in the hardmetal.
- In X-ray residual stress measurements, 68% of the diffracted beam is coming from the deformed surface layer.
- The X-ray residual stress increases up to a maximum near the strength of WC because of relaxation of stress by cracking and slip in the WC grains as observed by electron microscopy.

Acknowledgements

This research project was partly funded by Priority Program for Materials (PPM) and the Foundation of Technical Science (STW Stichting Technische Wetenschappen). We wish to thank G. Palasantzas for the help with the roughness analysis. S.Y. Shulepov is gratefully acknowledged for the discussions on the grinding process of hard materials and N. Lousberg is gratefully acknowledged for performing the grinding experiments.

References