Influence of binder metal on wear initiation of cemented carbides in sliding contact with granite

J. Heinrichs a,*, S. Norgren a, b, S. Jacobson a, K. Yvell c, M. Olsson c

a Applied Materials Science, Uppsala University, Sweden
b Sandvik AB, Stockholm, Sweden
c Materials Science, Dalarna University, Sweden

ARTICLE INFO

Keywords:
Cemented carbides
Alternative binder
Sliding
Wear
Rock drilling

ABSTRACT

Drill bits equipped with WC-Co cemented carbide buttons offer great performance in many rock drilling applications. Generally, the wear of these buttons against the rock is gradual and moderate, or even slow depending on the rock conditions. However, the Co binder has recently been found to cause health issues and an alternative binder, which does not compromise the performance of the cemented carbide, is needed. In the present work, the performance of WC-Fe and WC-Ni is investigated and compared to the common WC-Co in a sliding test against granite.

The results show immediate scrape-off of granite against protruding WC grain edges. Some WC grains crack and fragments are subsequently removed, adding up to loss of entire WC grains. A nanoscale pattern gradually evolves on other WC grains, implying also nanoscale wear. Both WC-Fe and WC-Ni show significantly faster wear initiation and early propagation compared to WC-Co, although the wear characteristics are similar.

1. Introduction

Cemented carbides are composite materials consisting of hard carbide particles in a more ductile binder phase. The result is a material that is both hard and tough, sought for in many tribological applications. It is commonly produced by sintering from raw material powder to near net-shape, to minimize the post-treatment to obtain the desired geometry. The ratio between hardness and toughness can be tuned by varying the carbide grain size and composition as well as the binder volume fraction and composition.

In rotary percussive drilling these types of materials are used for the drill bit buttons, constituting the part of the drill that comes first into contact with the rock. The hardness prevents macroscopic plastic deformation while toughness prevents brittle fracture during the impact. The most common cemented carbide is composed of WC grains in a Co binder (WC-Co), often resulting in slow or moderate wear in the rock drilling application [1,2]. When drilling in granite the wear is gradual and shallow resulting in a macroscopically, and microscopically, smooth worn surface. The surface becomes partly covered by layers of rock, and where not covered by rock it is characterized by fractured and plastically deformed WC grains, intermixed with granite. The affected depth is often limited to a few microns into the drill bit button [1,2].

WC-Co is a well-functioning combination in rock drilling. However, in recent years Co has proven to be harmful and a replacement is sought for. Alternative binder metals including Ni and Fe are commonly suggested to be promising candidates. There are several aspects to consider when preparing cemented carbides with alternative binders. Depending on the binder composition, the WC grain growth will either be inhibited or promoted during sintering, compared to when using Co. Further, the shape will be directed towards more rounded or prismatic grains [3–8]. The resulting microstructure will strongly affect the properties of the cemented carbide. The influence from WC grain size on wear resistance has been thoroughly investigated for WC-Co grades. Wear resistance and impact resistance are dependent on the hardness and fracture toughness of cemented carbides. The relation between the hardness of the cemented carbide composite and the grain size of WC is given by the Hall-Petch relation where the hardness increases with decreasing grain size [9,10]. Generally, keeping the Co content constant, larger grains result in lower composite hardness as well as lower wear resistance [11–14] and a more prismatic grain shape increase the risk of local stress concentrations [15]. The use of Fe binder tends to inhibit WC grain growth and promote rounder grains, while Ni is a grain growth promoter, generally resulting in a microstructure with larger and more prismatic grains [3–6]. To compensate for the behaviour during

---

* Corresponding author.
E-mail address: Jannica.heinrichs@angstrom.uu.se (J. Heinrichs).

https://doi.org/10.1016/j.wear.2021.203645
Received 14 September 2020; Received in revised form 22 January 2021; Accepted 25 January 2021
Available online 1 February 2021
sintering, the WC raw material could be adjusted [8,16], and small amounts of grain growth inhibitors could be added [5,8]. Also the reduced hardness can be addressed by adding alloying elements [5,7, 17–20].

The performance of cemented carbides with alternative binders is so far inconclusive. In Ref. [7] the abrasive wear resistance of cemented carbides with pure Co, Fe and Ni binders were reported to be poor, while a mixture of the three performed better. It was suggested that a proper choice of Co/Fe/Ni composition, combined with suitable alloying additions and heat treatment procedure, could be a good, or even superior, alternative to Co. Similar conclusions are drawn in Refs [21,22], where different sintering routes for mixtures of Co/Fe/Ni are investigated and a proper route result in superior mechanical properties over Co. In Ref. [6] Ni was added to a Co binder, which improved the tribochemical wear resistance against mild steel. Also stainless steel binder has shown promising results, and improved the wear resistance in a ball cratering test, although it was owing to the presence of eta phase [23]. However, in Ref. [24] it was concluded that the use of Co is preferable over alternative binders Fe/Ni and Co/Fe/Ni/Mo, when drilling in Red Lepidite. In Ref. [25] cemented carbides with pure Co, Fe and Ni binders were tested in sliding contact with iron ore, and the wear initiation was found significantly slower with the Co binder. However, also the influence from the almost inevitable difference in microstructure, WC grain size and shape, is included in the comparison, since it is hard to separate from the influence from binder composition.

In this work the mechanisms of wear initiation were studied, rather than the wear resistance, to get an insight into how the alternative binders influence the performance of the cemented carbide. To exaggerate the influence from the binder, relatively large amounts (20 vol%) of pure Co, Fe and Ni were used. A crossed cylinder sliding test, that has previously proven useful to study the early wear events for different combinations of cemented carbides and rock [25,26], was utilized to study their interactions with granite. The sliding length was kept short, and the surfaces were repeatedly studied at certain short intervals, allowing for careful monitoring of the very initiation of wear.

2. Materials and methods

2.1. Materials

Cemented carbide cylinders (Ø 10 mm, L 20 mm), comprising small WC grains in 20 vol% binder, were used to represent drill bit buttons. The binder was either Co, Fe or Ni, where Co is commonly used in rock drilling and Fe and Ni represents two alternative binders that are promising in replacing or in reducing the amount of Co. The amount of binder is considered large for the rock drilling application, however it was used to exaggerate the influence from the binder phase on the wear initiation. The grain size of the WC phase after sintering was influenced by the binder composition, although the WC raw material powder and milling conditions were the same for all cemented carbides. The final WC grain size was measured using Electron Backscatter Diffraction (EBSD) to 1.14 μm, 0.88 μm and 1.22 μm for the sintered WC-Co, WC-Fe and WC-Ni, respectively [25]. The WC grain size influences also, as is well known, the binder mean free path. Here it is given as the size of the binder phase pockets, also measured using EBSD. The size distribution for both WC grains and binder pockets is illustrated in Figs. 1 and 2. The dominating smaller grain size in WC-Fe result in considerably smaller binder pockets, while WC-Ni shows several exceptionally large WC grains and hence large binder pockets. The EBSD analysis was performed in equally sized areas (4000 μm²) for all cemented carbide grades. However, due to the difference in grain size, the number of analysed WC grains and binder pockets differs between the grades, see Fig. 2.

The crystal structure of the binders was analysed using X-ray diffraction (XRD) after sintering. The Co and Ni were both identified as fcc, while the Fe was bcc, Fig. 3. The cemented carbides were analysed also after sliding against granite and no changes in crystal structure were noticed.

Each cylinder was prepared by polishing, using 1 μm diamond particles in the last polishing step, to a surface roughness value of Sa 0.01 μm and Sq < 0.02 μm (average of 5 interference profilometry measurements, 40 μm x 40 μm). The polished surface is not representative for the application, however was necessary to observe minor changes to the microstructure. The counter material was granite rock, comprising mainly the minerals quartz (25–40%), feldspar (40–50%) and mica (15–20%), with a grain size in the sub-millimetre range. It was in the shape of a cylinder (Ø 42 mm, L 148 mm) and the surface was roughened using 120 grit SiC grinding paper.

The hardness of the respective constituents in the cemented carbide and the rock was measured in previous work by the authors [13,15,25], using nanoindentation to an indentation depth of 100 nm, Table 1. To minimize contributions from the WC phase when measuring the hardness of the binders, and vice versa, Scanning Electron Microscopy (SEM) was used to confirm the position of the indent and ensure that the distance from binder/WC interfaces was sufficient.

The Vickers microindentation hardness was measured at a load of 100 g, resulting in indents large enough to include several WC grains and binder, Table 2 and Fig. 4. The WC-Co and WC-Fe show similar hardness, while WC-Ni is significantly softer. Extrusion and smearing of binder, plastic deformation and fracturing of WC grains and ridging is common in the indents, Fig. 4. Comparing the three grades it is observed that the number of plastically deformed and fractured WC grains is larger in WC-Ni, Fig. 5. Besides fractured WC grains, formation of pores and extrusion

---

Fig. 1. Band contrast maps from EBSD, with binder phase colored blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2
of binder is observed in the cross sections of all grades.

2.2. Crossed cylinders sliding test

A sliding test rig, with a crossed cylinders geometry, was used for the tribological evaluation, see Fig. 6. The use of this test method results in similar wear surfaces as observed on field worn drill bit buttons, and the early wear stages can be studied in detail [27]. The rock cylinder was mounted as the work piece in a lathe and rotated in contact with a spring-loaded (50 N) cemented carbide cylinder, while the contact was flushed by deionized water. The load and friction force were monitored and was high enough to fracture the rock in the micro scale. The sliding speed was 0.1 m/s and fresh rock was continuously introduced by feeding the cemented carbide in the lateral direction. Both micro scale fracturing of the rock and introduction of fresh rock into the contact are key factors to mimic rock drilling.

The test was performed both in continuous mode, with 1 m and 5 m sliding length, and in an interrupted mode with a total sliding length of 1 m. During the interrupted mode, several pre-defined areas close to the middle of the wear mark on the cemented carbide cylinder was analysed after every 0.1 m sliding to document the wear initiation process. The analysis was performed while the cemented carbide sample was still mounted in the holder, allowing for very accurate repositioning. The test was then continued at the exact same position on the cemented carbide. Both sliding lengths, 1 m and 5 m, correspond to very initial contact between a drill bit button and rock.

2.3. Post test surface characterization

All cemented carbide samples were analysed using FEG-SEM (Zeiss Merlin) and Energy Dispersive X-ray Spectroscopy (EDS; Oxford X-max) after each sub-test during the interrupted testing mode, and after finishing the continuous tests. The analysis was preceded by flushing each sample with ethanol and drying in compressed air. Each sample was analysed also in cross section, prepared by Focused Ion Beam (FIB; FEI Strata DB235), after finishing the interrupted sliding tests.

3. Results

3.1. Friction

The friction coefficient is calculated from the normal load and friction force, monitored during the continuous tests and each sub-test, Fig. 7. Initially, the friction rapidly rises to about 0.35, followed by a decrease to about 0.3, irrespective of testing mode and cemented carbide grade. The interrupted tests additionally show dips when the test is halted and restarted. Besides these discontinuities, the friction is quite constant at about 0.3 and rather similar between the cemented carbide grades. The continuous tests show similar behaviour during the 1 m test and during the first meter of the longer 5 m test. However, the friction starts to increase slightly already during the first meter for WC-Ni, and later also for WC-Fe, and reaches 0.4 and 0.35, respectively, when the test is finished.

3.2. Wear surface appearance

The worn cemented carbide surfaces were studied after each test, Figs. 8–10. Already after 1 m continuous sliding they were significantly modified, Fig. 8. The worn WC-Co surface is characterized by smooth WC grains, where however many grains show cracks and single grains also show a slight waviness (e.g. top row, right column, grain in the center). Areas of transferred material, appearing dark in the SEM, are spread over the surface, filling the pits between WC grains. Further, sub-micron wide scratches are occasionally observed. The wear of the WC-Fe is more severe, with a large amount of fractured WC grains, WC grain fragments and larger scale scratches. Transferred rock material is
present both as particles and as smoother areas between WC grains. WC-Ni is generally similar to WC-Fe, but differs in showing several plastically deformed WC grains, fewer WC fragments and particles of transferred rock, and no large scratches.

After continuous sliding for 5 m, all the wear marks have grown, but the surface characteristics are very similar, Fig. 9. However, more rock has been incorporated into the cemented carbide surfaces, indicating that it is not only a larger worn area, but also locally deeper wear between the remaining, still polished, WC grains. In addition to the transfer between WC grains, larger transfer particles are observed on the surface of WC-Fe.

After finishing the interrupted test, Fig. 10, the surface appearance differs slightly from the continuous tests. Although the sliding distance is similar to the continuous 1 m test, the wear is less severe. The scattered areas with transfer are fewer on the WC-Co, and so is the number of fractured grains. Again, the WC-Fe shows a large amount of transferred material mixed into the surface, but the WC grains are still smooth from the preceding polishing and the larger scale scratches are absent. The WC-Ni also has a smoother appearance, where the WC grains have kept their polished appearance, implying less wear.

However, the general character of the surfaces complies with the continuous tests. The wavy pattern on the WC grains is again present, single grains have cracked and fractured, and rock material has become

Table 1
Nanoindentation hardness of the cemented carbide binders [25], hard phase [15] and granite minerals [13] (Berkovich tip, 100 nm indentation depth). The number of indentations is given in brackets.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Nanoindentation hardness [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cemented carbide binder</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>8.7 ± 1.1 (11)</td>
</tr>
<tr>
<td>Fe</td>
<td>4.6 ± 1.5 (20)</td>
</tr>
<tr>
<td>Ni</td>
<td>6.0 ± 1.0 (17)</td>
</tr>
<tr>
<td>Cemented carbide hard phase</td>
<td></td>
</tr>
<tr>
<td>WC</td>
<td>28.0 ± 2.4 (23)</td>
</tr>
<tr>
<td>Granite minerals</td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>12.8 ± 1.0 (133)</td>
</tr>
<tr>
<td>Feldspar</td>
<td>10.5 ± 1.3 (80)</td>
</tr>
<tr>
<td>Mica</td>
<td>3.4 ± 1.3 (28)</td>
</tr>
</tbody>
</table>

Table 2
Microindentation hardness of the cemented carbides (Vickers diamond tip, 100 g load). Average of 5 indentations.

<table>
<thead>
<tr>
<th>Cemented carbide</th>
<th>Micro-hardness [HV0.01]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC-Co</td>
<td>1295 ± 40</td>
</tr>
<tr>
<td>WC-Fe</td>
<td>1329 ± 65</td>
</tr>
<tr>
<td>WC-Ni</td>
<td>1135 ± 30</td>
</tr>
</tbody>
</table>

Fig. 3. XRD analysis of the binder phase in a) WC-Co and WC-Ni and b) WC-Fe, before and after sliding against granite. The marked peaks correspond to binder and unmarked peaks correspond to WC.
transferred. Higher magnification micrographs, Fig. 11, unveil that the wavy pattern has a periodicity and direction, normal to the sliding direction. Further, it becomes apparent that sub-micron wear fragments of WC and rock are common, and that rock transfer give a slight smoothening effect by filling the gaps in the worn microstructure. Although the wear was limited after finishing the interrupted test, the surfaces were undoubtedly modified. To understand more about the initiation, each incremental step of 0.1 m sliding was evaluated.

For WC-Co, Fig. 12, the immediate observation is that small movements of the WC grains embedded in the binder have made the grain boundaries more prominent. Some grain edges protrude from the polished surface, causing scrape-off of granite, seen as black lines along the edges. Besides that, some single WC grains show cracks, and WC grain fragments have been removed and replaced by transferred material.

---

**Fig. 4.** Microindentations (Vickers diamond tip, 100 g) of the three grades. Bottom row; the area indicated in the top row imaged in higher magnification. (SEM, 3 kV).

**Fig. 5.** Cross section images of microindentations (Vickers diamond tip, 100 g) in the cemented carbide grade indicated in the left column. Right column; the area indicated in left column imaged in higher magnification. The preparation technique by FIB includes protecting the surface by depositing a μm thick platinum layer, visible as a light grey film on top of the cemented carbide. (SEM, 3 kV).

**Fig. 6.** Sketch showing the crossed cylinder geometry, including rotation and lateral feed, in the sliding test rig. The larger cylinder (ø 42 mm, L 148 mm) is the granite and the smaller cylinder (ø 10 mm, L 20 mm) is the cemented carbide.
seen as larger black areas. When the test continues, some WC grains move slightly in the sliding direction. As more rock becomes trapped behind these WC grains, the areas with transfer grow. Single WC grains or fragments are also removed and replaced by granite, and new cracks are generated, during the continuation of the test. Wear, and the subsequent transfer of granite, reduces the amount of Co visible in top view. Single sub-micron scratches in the composite appear early on and subsequently become polished in the contact. The small-scale waviness of WC grains is also initiated quite early, and then evolves during the test.

The WC-Fe, Fig. 13, shows a similar behavior, but with more extensive cracking of the WC grains. The subsequent sliding removes WC grain fragments, and occasionally also small WC grains. It is commonly observed that neighboring WC grains or fragments preferentially become removed together, including also the binder. This results in larger, and gradually growing, areas with transferred material. Also larger WC grain movements are observed; single grains and fragments

Fig. 7. The friction coefficient trends during each test. a) Tests run in interrupted mode (friction dips correspond to the engagement and disengagement when the test is interrupted) and b) continuous mode.

Fig. 8. Surface appearance of all cemented carbides after 1 m continuous sliding against the granite cylinder. Sliding direction of the granite from bottom to top. Increasing magnification from left to right column. Rows from the top; WC-Co, WC-Fe, WC-Ni. Tilt 41°. (SEM, 3 kV).
Fig. 9. Surface appearance of all cemented carbides after 5 m continuous sliding against the granite cylinder. Sliding direction of the granite from bottom to top. Increasing magnification from left to right column. Rows from the top; WC-Co, WC-Fe, WC-Ni. Tilt 41°. (SEM, 3 kV).

Fig. 10. Surface appearance of all cemented carbides after 1 m accumulated sliding in the interrupted testing mode. Sliding direction of the granite from bottom to top. Increasing magnification from left to right column. Rows from the top; WC-Co, WC-Fe, WC-Ni. Tilt 41°. (SEM, 3 kV).
move over a micron in the sliding direction. After the test is finished, the surface is dominated by WC fragments and cracked WC grains, some of which have a wavy appearance. These grains and fragments sit in a granite matrix rather than in an Fe binder.

The WC-Ni shows several cracked grains already after the first contact, Fig. 14. These cracks propagate, sometimes gradually over several
sub-tests, and fragments are eventually lost. Also here neighboring grain fragments tend to be removed together and replaced by granite, resulting in larger and slightly rougher areas containing a mixture of rock and WC grains. In areas where less wear has occurred, Ni binder seems to be still present, and cements the still smooth, but often slightly wavy, WC grains together.

The presence of binder and transferred granite was further studied using EDS, with settings adjusted to give surface sensitive elemental analysis (low acceleration voltage, 3 kV, and tilt angle of 41°). From Fig. 15 and Table 3 it is clear that the rock coverage is higher on WC-Fe and WC-Ni than on WC-Co, and that the individual covered areas are also larger. The presence of binder on the surface is still substantial for the WC-Co and the WC-Ni, but much less so for the WC-Fe.

By increasing the acceleration voltage in an SEM, the interaction depth in the imaged sample increases. Here, this results in that thin transferred rock layers on top of a cemented carbide become transparent for the electrons, which better reveals the depth to which the WC has been lost and replaced. This effect is used to compare the thickness of the rock layers and to study the microstructure modifications, in Fig. 16.

At the higher acceleration voltage, the layers on WC-Co become completely transparent, and the binder underneath visible. The only exception is that the thicker transfer associated to the sharp WC grain edges is still visible. For WC-Fe, the layers become just partly transparent, and both binder and WC grains are revealed, along with numerous WC grain fragments that are trapped in the transfer layer. WC-Ni also shows minor areas with trapped WC fragments, as well as areas with both thicker and thinner transfer films.

The depth to which the cemented carbide is affected was further studied using FIB cross sectioning, Fig. 17. The WC-Co indeed shows a very limited wear depth, and the transferred material is barely visible in the cross section. The WC-Fe shows large presence of transferred material, but the affected depth is still very limited, and not even a single WC grain layer has been removed. WC-Ni is similar to WC-Fe, however with a larger presence of fractured grains and binder in the surface. All cemented carbide grades are visually unaffected below the topmost layer of WC grains, indicating that the wear and deformation mechanisms are operating at very shallow depths.

4. Discussion

The friction rapidly increases in the very start of each test, and thereafter decreases slightly. The friction behavior and level during (almost) the first meter is similar for all three cemented carbide grades. This implies that the larger amount of transferred granite and the increased roughness of the WC-Fe and WC-Ni surfaces, observed in Fig. 8, do not result in higher friction. After the full 5 m though, while the friction for WC-Co has kept almost unchanged, the effect of the more substantial surface modification of WC-Ni and WC-Fe has become significant and a friction rise is observed.

Granite is transferred already at the first contact, primarily scraped-off against protruding WC grain edges. The areas with transferred material then grow during the test. The small shift and tilt of a WC grain that result in a protruding edge requires substantial plastic deformation of the adjacent binder material. The displacement of the WC grain continues until the load from the sliding contact against the granite is balanced, typically involving the grain coming into close contact with its
neighbors. This contact will however also lead to high stress concentrations between the WC grains, resulting in plastic deformation and cracking of the WC, as observed in Refs. [15, 25]. The difference in binder hardness and WC grain sizes will result in different support of the load from the passing granite.

Once a WC grain has cracked, the granite might grip into the crack, similar to the protruding WC grain edges. This will cause crack propagation, or further shift and tilt of the fragment. Eventually, the fragment can be lost, i.e. wear has occurred. When a fragment or grain has been removed, the support in that area is undermined and it is easier to access the next WC grain or fragment, causing the observed preferential removal in areas where grains or fragments have already been removed. Loose WC fragments or grains may become trapped in the rock surface and can then be forced to slide over the cemented carbide along with the rock. This is a probable cause to the scratches found on some surfaces.

The waviness observed on the surface of some WC grains, which then evolves during the test, indicates that the described mechanism acting on the sub-micron scale is not the only active mechanism. Rather, either chemical or mechanical wear, acting on the nanoscale, is likely occurring in parallel. No similar observations, from field use or laboratory tests, are found in the published literature. Unlike most wear studies, here the initial wear taking place in the very first layer of WC is studied. However, this has either not been previously observed in similar wear initiation studies by the present authors, neither in dry contact using the same material combination [26] nor in water lubricated contact with magnetite [25]. Not all WC grains show this wavy appearance, but when present it has a directionality and periodicity indicating that the WC grain orientation might be of importance. Possibly the pattern results from plastic deformation that generates sharp slip steps in the WC grain surface, which subsequently become further deformed and polished into the smooth wavy pattern. This process has however not been studied in detail here, which would be needed to draw any firm conclusions.

The surface appearance differs slightly between the continuous and the interrupted tests, where continuous tests result in more granite transfer. One explanation to this might be the cleaning procedure between sub-tests in the interrupted testing mode. Before SEM imaging, loose wear fragments are removed by flushing with ethanol followed by drying in compressed air. In this way, the presence of WC grains and fragments that can scratch the surfaces, and loose rock fragments that can adhere to the surface, will be limited. Their contribution to the wear in the subsequent test will be eliminated.

The elemental analysis of the worn WC-Co surface (Fig. 15) showed evenly spread areas of Co, and only minor scattered areas with rock transfer. Complementary analysis using different acceleration voltages, Fig. 16, and cross sectioning, Fig. 17, revealed that the transferred rock layers were not only few, but also very thin. Larger, interconnected rock covered areas were more frequent on WC-Ni and WC-Fe. This is explained by the higher tendency of these materials to lose neighboring grains or opening up gaps between grains, events that form depressions that subsequently become replaced by granite. This larger scale wear mechanism thereby results in much thicker transfer layers, as evident from Figs. 16 and 17. The amount of binder visible on the surface differs between the WC-Fe and WC-Ni grades. For the WC-Fe, the large displacements of WC grains (allowed by the smaller grain size) and the subsequent transfer of rock that fills the pits, promote both removal of and concealment of the Fe binder. This leaves very little binder visible in
For the WC-Ni, more binder is visible. This is due to that the WC-Ni grade shows less pronounced WC grain displacement, which keep the binder better protected, combined with a rougher surface where rock does not fill the deeper grooves (where Ni is revealed).

The traditional Co binder material shows much slower wear initiation than the two alternative binder versions, which may be disappointing in the work towards finding a replacement for Co. However, not only the binder composition but also the almost inevitable difference in microstructure influences the wear behaviour. The difference in WC grain shape is of importance, since rounder grains result in less severe stress concentrations between neighboring WC grains. This would give WC-Fe an advantage over WC-Ni, and agrees to the observed lower cracking tendency of WC grains in WC-Fe. Also the significantly lower composite hardness of WC-Ni, due to the larger WC grain size, speak in favor of WC-Fe. However, some of the smallest grains in the WC-Fe microstructure seem to be removed as they are, without preceding cracking, which could be presumed to be harmful to the wear resistance. In the WC-Ni the WC grains are large enough to avoid complete removal, but the material also includes several abnormally large grains, which are more easily cracked, resulting in fragments that subsequently can be removed. The larger grain size will also result in larger binder regions, which further weakens the microstructure by facilitating shifts and tilts of the WC grains. It should be noted that in the present paper, the binder fraction is rather large compared to typical rock drill grades. A lower amount would improve the WC support for all tested grades, which would improve their wear resistance provided that they do not become too brittle for the rock drilling application.

The present paper has been entirely focused on the initiation of wear, taking place in the topmost WC grain layers, and no tests long enough to estimate a steady state wear resistance have been included. However, previous investigations of the presently tested cemented carbide grades in sliding against magnetite (rather than granite), have in fact shown a superior performance of the WC-Fe over the WC-Ni [25]. The wear initiation and propagation are similar, including tilting, deformation and fracturing of WC grains, followed by removal of fragments. However, magnetite shows a significantly higher tendency to transfer, which levels the worn surfaces by filling all gaps in the cemented carbide microstructures. This stronger tendency to penetrate the microstructure showed to be a disadvantage for WC-Ni, where large binder pockets are easily accessed from the surface. As a result, a large share of the binder very soon becomes exchanged for magnetite, to a greater depth. Magnetite is softer (8.5 GPa measured by nanoindentation [25]) than the binder.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Binder surface area fraction [%]</th>
<th>Rock surface area fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unworn</td>
<td>worn</td>
</tr>
<tr>
<td>WC-Co</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>WC-Fe</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>WC-Ni</td>
<td>19</td>
<td>15</td>
</tr>
</tbody>
</table>

Fig. 15. Elemental analysis showing the presence of binder and rock (represented by O) in the wear tracks (close to the middle) after 1 m accumulated sliding in the interrupted sliding mode. Rows from the top; WC-Co (from Fig. 12), WC-Fe (from Fig. 13) and WC-Ni (from Fig. 14). Tilt 41°. (SEM/EDS, 3 kV).
the main constituents in granite and can be plastically deformed at high strains or temperatures [28], which probably explains the deeper penetration and the smoothening effect.

Interestingly, the microhardness of WC-Fe is close to that of WC-Co despite the smaller average grain size. This is partly due to the advantage of small grain size in WC-Fe is compensated by the softer binder, but could also be an effect of the wider grain size distribution in WC-Fe. A wide WC size distribution leads to a wider distribution of binder region sizes, where larger regions reduce the hardness. Another contributing mechanism to the deviation from the expected may be the differences in stacking fault energies between the binder metals. Stacking faults play an important role, as their energy influences the deformation hardening of the binders.

Fcc-Ni and fcc-Fe have high stacking fault energies, ~200 mJ/m² [29,30]. Contrastingly, ferromagnetic Co has a very low stacking fault energy, ~20 mJ/m² [29], and easily transforms to hcp on deformation by planar slip, and subsequently deformation hardens [31]. In Ref. [31] the authors showed that beyond 2.1% strain, partial dislocations begin to nucleate at the Co grain boundaries and WC/Co phase boundaries, and thereafter slip occurs in the Co binder, leaving stacking faults behind. This deformation hardening effect could contribute to gradually restrict the WC grain movements with increasing plastic deformation. Ni on the other hand does not deformation harden. Thus, the restriction to WC grain displacement may be less changed during the wear process. The Fe binder is more complicated, as its microstructure depends on its carbon content and the cooling rate. The presently used manufacturing process resulted in a soft ferritic phase, giving less support to the WC grains and due to the bcc structure it will not deformation harden by stacking faults.

Is the wear resistance of the binders themselves important? For all grades, the binder is much softer than the WC grains. Hence, in any wear situation against rock, the binder will deform plastically and allow displacement of the WC grains. The binders are also all softer than the hardest phases of granite (quarts and feldspar), which means that they cannot avoid scratching from these.

However, the abrasion resistance of the binder itself is probably not the important part. After very short use, the highest areas of the surface are strongly dominated by WC, and especially so for the Ni and Fe binder materials. On the remaining surface area, at a somewhat lower level, we find binder, or transferred rock, or a mixture of rock fragments, WC fragments and binder. After the initial wear, the binder will therefore have very little direct contact against the passing rock surface. Even so, it may influence the wear resistance in several ways, as illustrated in Fig. 18.

Fig. 16. The same wear marks as in Figs. 12-14, after 1 m accumulated sliding in interrupted mode, imaged using different imaging depths (acceleration voltages). Sliding direction of the granite from bottom to top. Rows from the top; WC-Co, WC-Fe and WC-Ni, first column 3 kV and second column 10 kV. Tilt 41°. (SEM).

- If the binder is hard, at the prevailing temperature, this helps to restrict the displacement and tilting of the WC grains.
- If it binds strongly to the WC grains and WC fragments, this helps to avoid that these – the primary wear protectors – become lost from the surface.
- If it binds well to the transferred rock fragments, this helps to avoid that WC fragments inside the transferred layer are lost, and it also means that it retains the extra wear resistant cover.
- If it has a high cohesion, this helps to avoid losing larger clusters of the newly formed surface composite of WC grains/WC fragments/rock fragments/binder.

Regarding the binder hardness point, the two alternative single
element binders included are clearly softer than Co, but were here primarily selected to increase the fundamental understanding. However, in an industrial application they would be used as alloys. By combining Fe, Ni and Co, it is likely possible to improve both the binder hardness and to form a cemented carbide with competitive wear performance, allowing reduced use of Co [7, 21, 22].

5. Conclusions

With the goal to better understand the influence of the binder metal on the wear initiation of cemented carbides in sliding contact with granite, the present paper has used a short sliding test, both in continuous mode and in interrupted mode with very short sliding cycles.

- In the sliding contact with the granite, the friction coefficient varied with binder type, as Ni > Fe > Co.
- Granite was transferred to the cemented carbide already at the first contact (within 10 cm sliding), primarily scraped-off against protruding WC grain edges, but also found as particles on top of the surface.
- The transferred granite particles are removed and replaced during the test, while the granite transferred to areas between grains mainly stays, resulting in growth of these transfer patches.
- WC grains crack, and are sometimes plastically deformed, during the test. The generated WC fragments are more easily removed than the intact grain.
- The worn surfaces of WC grains gradually achieve a smooth wavy appearance, indicating that a second wear process operating on nanoscale is also active.
- After testing, the cemented carbide surfaces are dominated by grains still close to their original size. Other than these grains, the surface is characterized by fragments of WC intermixed with granite. The larger grains are still relatively flat from the preceding polishing.
- The WC-Fe and WC-Ni both show significantly quicker wear initiation and earlier propagation, compared to the WC-Co.

CRediT author statement

Jannica Heinrichs: Conceptualization, Investigation, Analysis, Writing.
Susanne Norgren: Conceptualization, Resources, Writing.
Staffan Jacobson: Conceptualization, Funding acquisition, Writing.
Karin Yvell: Analysis, Writing.
Mikael Olsson: Conceptualization, Funding acquisition, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge Dr Mikael Kritikos at Sandvik Coromant for performing the XRD analysis and interpreting the results thereof. The financial support from the Swedish Knowledge Foundation (Dnr 20150193) and EIT Raw Materials via the project Upscaling of Co-free solutions for cemented carbides (CoFree) is gratefully acknowledged.

References


