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Examination of wear damage to rock-mining hardmetal drill bits

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ABSTRACT

WC/Co mining bits from a drill head used for drilling holes for roof support bolts in a mine were examined using a focused ion beam scanning electron microscope (FIB-SEM). This was combined with energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) analyses to study the chemical interaction between the drill bit and the rock. It was found that at the surface of the buttons there was depletion of cobalt, change in chemistry of the remaining binder regions, and changes to the morphology of the WC grains. Tribochemistry calculations were done to understand the possible formation of silicides at the surface of the drill bits, and thus emphasise the importance of quartz content in rock on wear. The evidence of mechanical damage combined with chemical reactions is another step towards understanding the complete wear process in hardmetal mining tools.

1. Introduction

In the mining and tunnelling sector it is common practice among mining engineers, geologist and tool manufacturers to predict tool wear by to relating it to the equivalent amount of quartz in the rock [1,2]. In the case of the steel tools, this is understandable since quartz is the hardest mineral and will thus contribute most to abrasive wear. However, for hardmetal tools composed of WC/Co, this is somewhat surprising. Although the quartz is harder than the metallic cobalt binder phase, this is only a minor fraction (~10 vol%) of the composite. The major fraction is the hard WC phase with a hardness of HV1300 for the prismatic plane and HV2300 for the basal plane [3], compared to ~ HV1000 for quartz [1]. It was also shown by Gant et al. [4], comparing abrasion from SiO_2 and Al_2O_3 particles, that SiO_2 do not significantly abrade or fracture WC crystallites in the WC/Co hardmetals.

In this work, possible reasons are described why quartz or silica content is so important in predicting the tool wear, including thermodynamic calculations for the tribochemical interactions that could occur between the tool and the rock. Few papers study actual wear mechanisms of drill bit inserts directly taken from the mine [5,6] or application [7], rather they attempt to simulate the conditions in laboratory tests [4, 8,9,10,15,16,17]

Typical degradation mechanisms of hardmetals described in the literature [7–17] include loss of binder phase, crushing and fragmentation of tungsten carbide (WC) grains, as well as removal of fragments and unsupported grains. Beste [5,8,9,10] found rock material adhered to the binder phase, which formed a binder-rock mixture that locally was found to penetrate several hundred micrometres below the surface. He also found oxidation of WC grains and subsequent scraping away of the binder-rock layers. Stjernberg et al. [14] found cracks reaching ~100 μm below the worn surface, caused by large thermal fluctuations which had caused tensile stresses in the surface region that opened cracks perpendicular to the surface.

In this work, the aim was to gain a better understanding of the tribochemical wear mechanisms that lead to damage during top hammer drilling (where many of the cited works focused mainly on the mechanical wear mechanisms), and to provide a contribution to understand the chemical driving forces to the wear that contribute further to that previously reported. Improved understanding will help to determine limits on the maximum life of the bit during drilling.

A forensic examination was conducted on several of the WC/Co buttons. A focused ion beam and scanning electron microscope (FIB-SEM), energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) were used to study the mechanical damage and chemical interactions in the WC/Co buttons. The observations were compared to thermodynamic calculations of the silica (SiO_2)–Co-WC system, where investigation of these reactions gave a clearer insight into the cause of the wear mechanisms observed in the buttons. It is shown that the Co in the hardmetal reacts with the quartz and forms $CoSi_2$, enhancing the wear of the bit.

2. Experimental method

The 43 mm drill head from Sandvik Mining Rock Tools used in the analysis is shown in Fig. 1. The button geometry was GT7S100A-XT48

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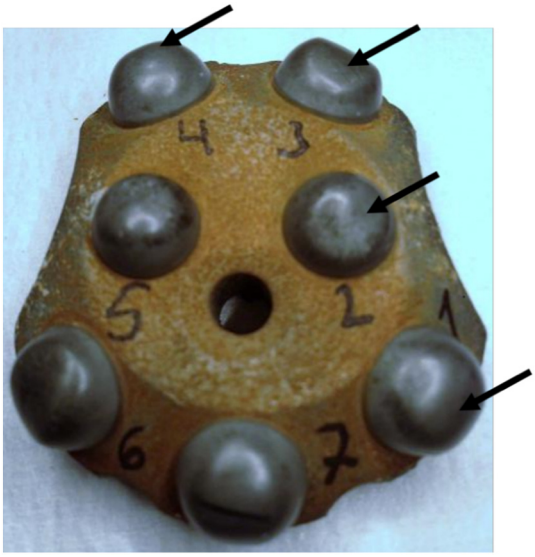

Fig. 1. The top 10 mm of the steel drill head with embedded WC/Co buttons numbered for reference. The rotating direction of the drill is anti-clockwise, as seen from this view.

thus fully spherical and 10 mm in diameter. The button composition was 10 vol% cobalt WC hardmetal with a hardness (HV30) of 1450, grain size of 1.2 μm [18], coercivity of 11.5 kAm^{-1} and relative weight specific magnetic saturation (compared to pure cobalt) of 0.90. The drill head was used for drilling holes for roof support bolts in a zinc and lead mine.

To examine the buttons, the top 10 mm of the drill head with the seven buttons was cut off (Fig. 1). It was mounted on a suitable holder with carbon glue for examination in the microscope. The buttons were numbered, where 2 and 5 are known as front buttons and the rest as gauge buttons.

A Carl Zeiss Auriga 60 FIB-SEM equipped with an Oxford Instruments X-Max EDX detector was used for microstructural characterisation. Due to the large depth of field of the electron beam, it was straightforward to locate and look at features on the domed buttons. Cross-sections were made on the buttons using the FIB with 30 kV: 1–4 nA beam conditions, and imaged at high resolution with the SEM at 3 kV accelerating voltage. Elemental mapping and line scans of the surface and some of the cross sections were carried out with EDX at higher accelerating voltages to gain understanding of the chemistry of the wear processes.

The cross-sections were made randomly on the worn surface ("wear flats") of the buttons, but as the sample was tilted in the FIB-SEM for analysis and the geometry of the buttons is domed, it was only possible to view and mill sections on certain portions of each button wear flat. As the position of the head remained the same throughout the course of the experiment (tilted along the line of symmetry through button 7, with buttons 1 to 3 uppermost), points on the surfaces nearer to the right of the buttons as viewed in Fig. 1 were most likely to have been analysed (as indicated approximately by arrows in Fig. 1). In some cases, e.g. Fig. 5, where the FIB curtaining is seen at an angle, then the cross-section was further down the side of the button. The FIB-SEM and EDX results shown in this paper are on buttons 1 and 4, which are gauge buttons, but similar surface characteristics and mechanisms were observed on the other buttons, including button 2, a front button.

XRD measurements were performed on a Bruker Discover D8 diffractometer with Davinci design equipped with a IμS Microfocus Source (CuK_α radiation, $\lambda = 1.5418$ Å), an Eulerian cradle and a Våntec-500 2D area detector. A laser-video positioning system was used for alignment of the sample. The XRD patterns were analysed with software DIFFRAC EVA (Bruker) and High Score Plus (PANalytical). XRD data were typically collected in the angular range $10° < 2\theta < 140°$. The drill bit was mounted with adhesive tape to the sample holder and XRD patterns were measured at several positions.

3. Results

Multiple wear mechanisms took place at the surface and just beneath it in the regions examined by FIB cross-sectioning and EDX. Each type of phenomenon is described in the following sections.

3.1. Surface composition

Low magnification SEM imaging of the surface of the top of a gauge button (labelled 1 in Fig. 1) showed the surface texture to be rough (compared to a polished or even fine-ground surface) with evidence of rock debris adhered to the surface (Fig. 2a). EDX analysis at 15 kV accelerating voltage of the area in Fig. 2a revealed the surface composition on a larger scale and produced a spectrum showing the presence of rock constituents including carbon, oxygen, calcium, iron, aluminium, silicon and iron, as well as zinc and lead (Fig. 2b). Oxygen and tungsten were the most abundant elements on the surface. By contrast, little cobalt was detected, despite this being a 10 vol% cobalt grade hardmetal. Distinct regions of lead and zinc, as well as oxygen and silicon from rock debris, were identified in elemental EDX maps, which were dragged across and embedded in the button surface during rotation of the drill head and this directionality is observed in Fig. 2c. Other buttons with similar surface composition and mapped at a similar magnification did not show this smearing as defined as seen in Fig. 2c.

At higher magnifications however, the button surfaces vary considerably in roughness and composition, as described in the sections below.

3.2. Carbide wear and morphology

Fig. 3a shows the position of the FIB-section on the wear flat of button 1 and Fig. 3b–d show it in higher magnification. Fig. 4 shows the same but on another position on button 1. Fig. 5 shows a milled section of button 4. In Figs. 3 and 4 there was surprisingly little cracking of the carbide grains below the wear surface (Figs. 3b and 4b), however some intergranular fracture was observed just below the top layer of carbide grains (Fig. 3c). Transgranular fracture was observed in several carbide grains where there were fine cracks through crushed and re-adhered carbide fragments at the surface (Fig. 4c) and next to binder regions where there was depletion and porosity in the binder phase (Fig. 5).

Fragmentation of the carbide grains also occurred at the surface and the crushed carbide particles were re-embedded in the surface layer and mixed with rock fragments and extruded cobalt (Figs. 3b and 4c).

There was deformation of the top layer of carbide grains such that they had lost their facets and the boundaries between carbide grains were curved. This is shown in Fig. 4c where larger fragments have been compressed together and the boundaries are deformed, and in Fig. 3b and d down to ~10 μm from the surface, the original boundaries are barely visible.

The vertical streaks and obvious "waviness" in the images are unfortunate artefacts of the FIB milling, exacerbated by the uneven surface due to omission of using a protective layer in these experiments, but the features described above are real features in the material.

3.3. Binder morphology and composition

There was significant compression of the cobalt regions between the surface and up to 10 μm in depth as revealed by FIB (Figs. 3 and 4), where cobalt binder regions of the expected size have disappeared and large number of crushed WC grains and forced-together WC-WC boundaries are present. The long thin binder region in Fig. 4d has at the top a dark region indicated by the arrow containing adhered