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Surface failure and wear of cemented carbide rock drill buttons—The importance of sample preparation and optimized microscopy settings

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ABSTRACT

The combination of suitable mechanical properties and wear resistance makes cemented carbide one of the most interesting engineering composite materials for tribological applications, such as in rock drilling. Despite the fact that cemented carbide buttons have been used in rock drilling applications for a long time the detailed understanding of the prevailing wear mechanisms is far from complete and wear and breakage of rock drill buttons are still one of the lifetime-limiting factors for rock drill bits. Consequently, further research in this area, including detailed characterization of worn drill button surfaces and sub-surface regions, is needed in order to support the future development of new cemented carbide grades with improved failure and wear resistance. In the present paper, high resolution scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and Auger electron spectroscopy (AES) have been used to characterize the wear and failure mechanisms of worn drill buttons and samples exposed to well controlled impact and scratch tests performed in the laboratory. The most important mechanisms of surface failure and wear were found to be severe plastic deformation, cracking, crushing of individual WC grains and mechanical/tribochemical degradation of the Co binder phase including Co depletion. Fracture cross-sectioning under tensile stress-state was found to be the best method for achieving large and reliable sub-surface cross-sections within a short time and to a low cost. The importance of optimized microscopy and spectroscopy settings for enhanced surface sensitivity for the examination of small-scale tribological phenomena is illuminated and discussed.

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1. Introduction

In the modern society rock drilling is a vital part in e.g. mining, construction drilling and geothermal drilling. Although a lot of different techniques can be used in rock drilling, the most common applied in hard rock applications is rotary-percussive drilling. In rotary-percussive rock drilling the bit rotates and percussively impacts into the rock, the rock is crushed in the impacts and the bit is rotated to a new position before the next impact. The two most common techniques of rotary-percussive drilling are Top-Hammer (TH) and Down-The-Hole (DTH). The major difference between the techniques is the positioning of the hammer that produces the percussive chock wave. In TH the hammer is positioned above the hole in the rig while in DTH the hammer is positioned in the bit sent into the hole. The bit is equipped with several peripheral and centre buttons of cemented carbide. Depending on the application different geometries of the bit as well as different geometries and grades of the cemented carbide buttons are used to optimize the performance [1]. The combination of suitable mechanical properties and wear resistance makes cemented carbide (WC–Co) the most interesting engineering composite materials in this type of applications [2].

Despite the fact that cemented carbide buttons have been used in rock drilling applications for a long time the detailed understanding of the prevailing wear mechanisms is far from complete. In the extensive work by Beste et al. a large number of surface failure and wear mechanisms have been identified and discussed particularly the adhesion of rock material to the cemented carbide and how it may penetrate into its microstructure [3–9]. However, since wear and brakeage of rock drill buttons still are one of the lifetime-limiting factors for rock drill bits, further research in this area is needed in order to support the future development of new cemented carbide grades with improved failure and wear resistance [10,11].

Characterization and evaluation of the surface damage and wear mechanisms of cemented carbide rock drill buttons require

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well controlled testing conditions since the results obtained may strongly depend on the testing conditions, including type of rock material [3,4,7,9,12,13]. The most important wear mechanisms are plastic deformation, cracking and crushing of individual WC grains, extrusion of the Co binder and rock penetration [3,6–9,12,13]. To study these wear mechanism not only the surface of the buttons should be investigated but also the sub-surface region. The latter is preferably investigated from cross-sections obtained by fracture cross-sectioning under a tensile stress-state which gives large and reliable sub-surface cross-sections within a short time and to a low cost [14].

In the present study, a number of worn cemented carbide buttons from a drill bit used for DTH drilling in granite containing rock have been investigated with respect to surface failure and wear mechanisms. Besides, complementary model impact and scratch tests were performed in the laboratory in order to investigate the initial response of the WC–Co microstructure during impact and scratching. Post-test evaluations of the worn WC–Co surfaces were cautiously performed by scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) and Auger electron spectroscopy (AES), including the investigation of cross-sections prepared in different ways. The importance of sample preparation and optimized scanning electron microscopy settings for enhanced surface sensitivity for the examination of small-scale tribological phenomena is enlightened and considered.

2. Experimental

2.1. Rock drilling

Percussive rock drilling field test was preformed with a Down-The-Hole (DTH) hammer. The drill bit used had a diameter of 152 mm and was equipped with 8 center and 8 peripheral cylindrical (ϕ 16 mm) cemented carbide (94 wt% WC, 6 wt% Co, nominal hardness 1460 HV) buttons with a spherical top. In operation, the drill rotates at approximately 60 rpm and impacts the rock around 30 times/s with an impact energy in each impact of roughly 1000 J. One hole, with a depth of 200 m, was drilled in granite containing rock. Due to the higher wear of the peripheral buttons these were selected for an in-depth microscopy study in order to characterize the surface failure and wear mechanisms.

2.2. Laboratory model tests

The tribological characterization of the surface damage of the worn rock-drill buttons was combined with model impact and scratch tests performed in the laboratory. The aim of these complementary tests was to investigate the initial surface failure mechanisms of cemented carbide in contact with rock material under well controlled impact and scratching wear conditions. Usually, the initial stages of surface failure cannot be revealed from steady-state worn surfaces since these are commonly too distorted and sometimes covered by transferred material from the mating surface.

The impact tests were performed using an impact tester (BYK-Gardner) but instead of a steel ball commonly used in impact resistance testing of coatings on metal substrates a fine polished rock drill button was used to impact on the surface of a granite block ($80 \times 80 \times 30$ mm^3). In the present study single impact experiments using a falling weight of 1000 g and impact energy of 10 J were performed.

The scratch tests were performed using a scratch tester (CSM Instruments Revetest®) but instead of the Rockwell C diamond stylus commonly used in scratch adhesion experiments of thin PVD and CVD coated substrates a granite pin mounted in a sample holder was used to scratch the cemented carbide sample. Single pass scratch tests using a normal load of 20 N, a sliding velocity of 10 mm/min and a sliding distance of 10 mm were performed.

In both the tests cemented carbide samples were polished to a mirror like surface finish, Ra < 50 nm, by conventional metallographic techniques using 1 μm diamond in the last polishing step. The aim of this approach was to allow observation of the initial rock material transfer, surface deformation and wear mechanisms taking place between rock material and a well-defined cemented carbide surface. Before testing, the cemented carbide samples as well as the granite samples were ultrasonically cleaned in acetone and ethanol in order to ensure that no contaminants on the sample surface would affect the frictional contact.

2.3. Sample preparation of rock drill buttons

The peripheral buttons from the drill bit were carefully removed at room temperature in order to avoid any thermal effects on the buttons. Care was taken not to contaminate the tribo surfaces during the handling of the worn buttons. In the characterization of the sub-surface damage of the worn buttons, several cross-sectional sample preparations were performed and evaluated. Cross-sectional samples were prepared using both conventional metallographic techniques as well as techniques based on fracturing as described by Beste and Jacobson [8] with different modifications to achieve a repeatable and reliable metallographic preparation technique. Traditional sample preparation, i.e. cutting, grinding and polishing, was performed and the effects of mounting the sample in resin and etching on the sub-surface microstructure were analyzed. The etched samples were etched with Murakami solution ($K_3[Fe(CN)_6]$ in KOH) until the microstructure was clearly revealed.

In fracture cross-sectioning, the sample is cut from the underside toward the surface. The cut is interrupted below the top surface and the remaining material is fractured under a compressive or a tensile stress state, see Fig. 1. Cleaning was always performed after cutting but before fracturing and the cleaning procedure included ultrasonic cleaning in acetone, ethanol and water, after which the samples were blown with dry N_2 gas. The purpose of using fracture cross-sectioning is to cause a fracture through the weakest microstructural parts of the material thus revealing these features [8]. During the fracture cross-sectioning process, the button was kept in a thin copper foil in order to minimize the risk for contamination of the fresh cross-sectional surfaces. The reason for using a copper foil, instead of e.g. an aluminum foil, is due to the fact that the rock material (mineral) does not contain any copper. Thus, contamination of copper will not be mistaken for adhered rock material on the button. Contamination may occur during fracturing, i.e. rock material on the surface of the button may contaminate the fractured fresh sub-surface. Finally, in order to minimize the contamination of the fractured sub-surface the samples were carefully blown with dry nitrogen gas after the fracturing process.

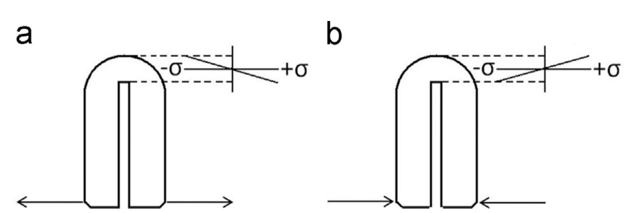

Fig. 1. Schematics illustrating the cross-sectional fracturing of the cemented carbide buttons. In (a) the worn surface is fractured under a compressive stress state while in (b) it is fractured under a tensile stress state.

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