Wear 386–387 (2017) 106–117

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Wear of cemented tungsten carbide percussive drill–bit inserts: Laboratory and field study

Dmitry Tkalich[a,c,*], Alexandre Kane[b], Afaf Saai[b], Vladislav A. Yastrebov[c], Mikko Hokka[d], Veli–Tapani Kuokkala[d], Maria Bengtsson[e], Anna From[f], Carina Oelgardt[g], Charlie C. Li[a]

[a] Norwegian University of Science and Technology (NTNU), Sem Sælands veg 1, NO-7491 Trondheim, Norway
[b] SINTEF Materials and Chemistry, Materials and Nanotechnology, Richard Birkelandsvei 2, NO-7465 Trondheim, Norway
[c] MINES ParisTech, Centre des Matériaux, PSL Research University, CNRS UMR 7633, BP 87, 91003 Evry Cedex, France
[d] Department of Materials Science, Tampere University of Technology, Tampere, Finland
[e] LKAB Wassara AB, P.O. Box 1067, SE-141 22 Huddinge, Sweden
[f] AB Sandvik Mining, Rock Tools, SE-811 81 Sandviken, Sweden
[g] H.C. Starck GmbH, Im Schleeke, D-38642 Goslar, Germany

ARTICLE INFO

Keywords:
Cemented tungsten carbide
Wear
Volume loss
Rotary–percussive drilling
Split Hopkinson pressure bar
Sliding abrasion
Impact abrasion
SEM
Surface deterioration mechanisms
Roughness
Contact area

ABSTRACT

Design of the drill–bit and selection of the Cemented Tungsten Carbide (CC) grade for drill–bit inserts are crucial for efficient percussive drilling. This study presents the results of an experimental campaign executed with the aim to identify the distinctive wear mechanisms and behaviour of different CC grades. Three laboratory and one full–scale drilling tests were performed using nine CC grades with different binder contents, binder chemical compositions, mean tungsten carbide (WC) grain sizes, and grain size distributions. Wear traces found on the drill–bit inserts after the full–scale drilling test show noticeable differences depending on their position on the drill–bit. Tensile forces present on the leading edge of the inserts due to the sliding contact with rock are suspected to play a significant role. Laboratory tests performed include: (i) single impact tests using a modified Split Hopkinson Pressure Bar (SHPB) apparatus, (ii) Abrasion Value (AV) rotating disk tests, and (iii) impact abrasion (LCPC) tests. Volume loss and shape change were used as macroscopic measures of wear. Greater volume losses were found for the grades with nickel–based binders compared to those with pure cobalt binder. The use of a narrower WC grain size distribution leads to lesser volume loss in drilling and AV tests. Surface analysis of the damaged microstructure was performed using scanning electron microscope. Distinct meso–scale (few dozens of WC grain sizes) patterns of damaged microstructure zones surrounded by the intact surface were found on the surfaces of specimens after single impact test. The pattern indicates the potential influence of a non–uniform contact due to the rock roughness and internal rock heterogeneities, which is supported by the study of the rock crater roughness. Size of such zones could be seen as a certain length–scale, which determines the insert–rock contact behaviour. A specific "peeling" mechanism of material removal was observed in the full–scale drilling test, where portion of the CC microstructure fused with the rock tribofilm gets removed when that tribofilm peels off.

1. Introduction

Rotary–percussive drilling (RPD) is a widely–recognized method for mining, tunnelling, and geothermal well applications. The rock breaking during RPD in hard rock formations relies on the rock crushing and chipping mechanisms, achieved by repetitive high speed impacts of a continuously rotating drill–bit [1]. Inserts placed at the head of the drill–bit are the main operating components directly interacting with the rock formation. Their design and wear resistance properties are crucial for rock breaking and tool performance. A composition of a hard ceramic tungsten carbide (WC) and a ductile metallic binder is the most often selected material for drill–bit inserts due to its remarkable wear and fracture resistance [2]. The wear resistance of this composite is usually estimated from its hardness and toughness characteristics together with careful considerations of each particular drilling application, such as the rock type, the environmental, and the operating conditions. However, considering a great number of possible drilling conditions combinations, it would often be a lack of available data on CC behaviour, especially if new types of drilling are employed or new CC grade is being used. Therefore, finding a

* Corresponding author at: Norwegian University of Science and Technology (NTNU), Sem Sælands veg 1, NO-7491 Trondheim, Norway.
E-mail address: dmitrii.tkalich@mines-paristech.fr (D. Tkalich).

http://dx.doi.org/10.1016/j.wear.2017.05.010
Received 10 September 2016; Received in revised form 19 May 2017; Accepted 19 May 2017
Available online 13 June 2017

laboratory test capable of reliably predicting the relative wear resistance of different CC grades is of interest and this issue is addressed in the current study.

Full–scale drilling tests can be performed in order to assess the behaviour of a Cemented Carbide grade but they are highly time and resource consuming. A large tests campaign from single impact tests to full scale fluid hammer tests, to simulate the mining and construction operations, was presented by Konyasahin et al. [3] using CC grades with different binder fractions and mean WC grain sizes.

While the laboratory tests fail to reproduce the full complexity, and coupling of forces acting during real drilling, they can be designed to reproduce some of its major features. The correlations of the CC wear with its hardness and toughness have been highlighted by many investigations (see e.g. [4]), but the question remains regarding the microstructural features' influence. For instance, wear–resistance of different WC–Co grades with similar hardness, varying in both the WC mean grain size and Co content was investigated by Konyasahin et al. [5]; while Angseryd et al. [6] studied the influence of abrasive particles type and size on wear rate. Despite hardness, friability, and size of the abrasive particles, which play a significant role [7,8] the rate of abrasion also depends critically on the CC microstructural characteristics like mean WC grain size, binder mean free path, width of the WC grain size distribution and WC skeleton contiguity [9–11].

In order to get access to the initial stages of the microstructure deterioration processes, appropriate testing procedures should be employed, where the initial degradation traces are not lost. Several examples of such approach can be found in the literature, e.g.: (i) incremental exposure of a CC specimen to a small quantities of erodent [12], and (ii) use of granite and diamond pins to cause localized contacts with CC [13], and (iii) a gradual deterioration of CC microstructure in a sliding wear test [14].

The current study employs a modified Split Hopkinson Pressure Bar (SHPB) apparatus to produce a single impact of a CC drill–bit insert with a rock sample, and capture the initial stages of CC microstructure deterioration. Two complementary abrasion tests were also performed using various CC grades and abrasives of 1–5 mm in diameter created from hard rock formations. In addition, full–scale drilling tests were performed and the results are compared with the laboratory tests' results.

2. Cemented carbide grades

Nine cemented carbide grades were used in the tests. Nominal composition of the tungsten carbide powder and the binder mixtures prior to sintering together with the mechanical properties of the sintered grades are given in Table 1. Grades in Set 1 were used in the single impact tests, whereas the grades in Set 2 were used in the full–scale drilling tests and two laboratory abrasion tests. Grades in Set 1 differ by the WC mean grain size and binder fraction, while those in Set 2 differ in WC grain size distribution and binder composition. The hardness was measured using the Vickers method and the fracture toughness was determined using the Palmqvist method in accordance with the ISO/DIS 28079 standard. Two samples of each CC grade were used with five indentations per sample.

3. Test methods

3.1. Single impact test

High–speed impact interaction of a drill–bit insert and rock was studied using a modified Split Hopkinson Pressure Bar (SHPB) testing apparatus. Transmitted bar in the original configuration was replaced by a fixed block of Kuru grey granite rock (30 × 30 × 30 cm^3), which served as the target, while the intact CC insert was fixed at the end of the incident bar facing the rock block, as illustrated in Fig. 2(a). Surface of the rock block at the place of impact was finely polished. During the test the striker bar is impacted at the free end of the incident bar at a speed of 11 m/s generating a stress wave propagating in the bar towards the end with a CC insert and the rock specimen. As the stress wave reaches the CC insert, a part of the stress wave is reflected back to the incident bar as a wave of tension, and part is transmitted into the rock causing dynamic impact damage on the rock and on the CC insert. The stress wave reflected back into the incident bar travels back and forth resulting in a succession of attenuated rebounds. High–speed camera images of the impact are shown in Fig. 2(b). Three inserts of each grade from Set 1 were tested.

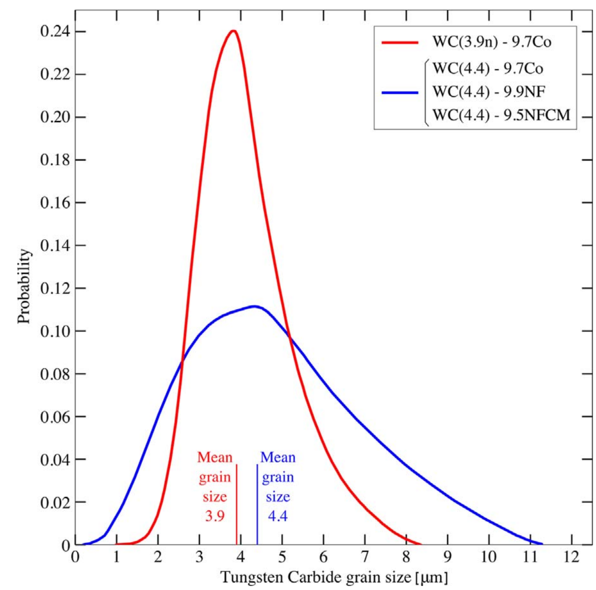

Fig. 1. WC grain size distribution for grades in Set 2.

3.2. Full–scale drilling test

Full–scale drilling (FSD) tests are performed using drill–bits of conventional size and geometry, as shown in Fig. 3(a). FSD tests were performed at underground Malmberget mine (municipality of Gällivare, Sweden) with an average rotation speed of 80 rev/min, feed force of 4.3kN, and percussion frequency of 65 Hz. Drilling paths of average length of 80 m passed predominantly through the Red Leptite rock formation with an intact strength of 184 MPa [15]. X–ray diffraction analysis of the Red Leptite's powder from the drilling site revealed the following mineral composition: 45.68% Albite, 23.83% Microcline maximum, 14.17% Quartz, 7.22% Diopside, Hornblende 5.6%, and 3.5% other.

Each drill–bit was equipped with CC inserts of identical grade, as shown in Fig. 3(b). One drill–bit for each one of four CC grades in Set 2 was tested. Inserts placed at the outer bevelled edge (positions numbered 1–10) are referred to as "peripheral inserts" and those on the flat frontal plateau (positions numbered 11–19) as "face inserts".

3.3. Sliding abrasion test

In the Abrasion Value (AV) test [16], a CC specimen is abraded by loose crushed rock particles distributed over a rotating disk surface, as illustrated in Fig. 4. Dead weight of 10 kg is used to press the specimen against the disk, which rotates at the speed of 20 rev/min. Resulting linear velocity of the specimen hitting the rock particles on the disk is of 0.35 m/s. The crushed rock is continuously renewed after it passes beneath the CC specimen. Weight loss of the specimen is measured after 5 min of testing when it travelled 100 m over the abrasive disk.

The crushed rock used in this test was Kuru grey granite (quarried in Kuru, Finland), with the density of 2630 kg/m^3 and mineral grain sizes