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Adaptation of Laboratory tests for the assessment of wear resistance of drill-bit inserts for rotary-percussive drilling of hard rocks

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ABSTRACT

The development of wear resistant materials for drill-bit inserts are of primary importance for efficient percussive drilling in hard abrasive rock. To speed up the development of enhanced wear resistance materials, the laboratory tests are fundamental to evaluate the material performance before proceeding to the in-field drilling test which is labor-intensive and costly in time and resources.

The current work aims to perform a comparative study of the wear resistances of drill-bit inserts intended for rotary-percussive drilling. Three laboratory testing methods were adapted to evaluate the abrasive sliding wear and abrasive impact wear which are the main wear components in rotary-percussive drilling. The standard abrasion value (AV) test and the standard LCPC (Laboratoire Central des Ponts et Chaussées) test which were originally developed to study the rock abrasivity, are adapted to study, respectively, the abrasive sliding wear and abrasive impact wear of drill-bit inserts. The disintegrator abrasive impact wear test was adapted to study the effect of impact velocity on impact abrasive wear. The testing setups were modified to enable testing drill-bit inserts as specimens. The drill-bit insert materials were selected to represent various cemented carbide microstructures including five WC-Co grades which differ by the volume fraction of Co and the grain size of WC, and one diamond enhanced insert. All drill-bit inserts were tested in dry condition against Kuru grey granite which is a homogenous rock and well suited as a reference in connection with hard rock testing. The wear measurements were evaluated with respect to the effects of drill-bit insert material and microstructure.

The abrasive sliding wear test and abrasive impact wear tests exhibit similar behavior related to the effects of average grain size of WC and volume fraction of Co on the wear measurements for the investigated WC-Co inserts. In all performed tests, the weight losses of WC-Co inserts increased with the volume fraction of Co and average grain size of WC. The abrasive impact wear tests performed on diamond enhanced insert showed a significant improvement of the impact wear resistance by adding diamond particles. Though the removal of the composite matrix between diamond particles was observed, the diamonds particles were providing an additional protection for the composite matrix which explain the lower mass losses of diamond enhanced insert compared to WC-Co inserts. However, an initial stage of decohesion at the diamond/WC-metallic binder interface were observed indicating possibilities of diamond removal at more higher impact energy.

1. Introduction

The rotary-percussion drilling has demonstrated higher rate of penetration in hard rock compared to other conventional drilling methods [1,2]. The hammer breaks and penetrates the rock by continual percussion and rotation of the drill-bit. When the hammer piston impacts the top end of the drill-bit, the impact energy is converted into a shock wave that travel the drill-bit at speed of sound and generates a high percussion force in the contact area between the drill-bit and the rock. The drill-bit is rotated after each impact to cut into fresh rock. The penetration rate in hard rock might be increased by increasing the force on bit and rotation speed. However, this entails exigent requirements on

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the material of drill-bit, specifically the drill-bit inserts which are the main component operating during the rock breaking process. The insert materials must ensure high strength and high wear resistance to extend the life of drill-bit.

Materials such as cemented tungsten carbide composites were used for manufacturing of drill-bit inserts due to their improved fracture and wear resistances. They consist of high fraction of tungsten carbide grains embedded in a metallic binder. The cobalt is mainly used as a binder to bond the tungsten carbide grains and to enhance the composite toughness [3,4]. Alternative materials such as iron and nickel alloys were also investigated to substitute the cobalt [5,6]. The addition of polycrystalline diamond compact particles was adopted to enhance the wear resistance. Although the diamond enhanced inserts (DEI) demonstrated a great improvement of abrasive wear resistance in rotary drilling, a short life time was observed for DEI in presence of impacts with high frequency vibrations [7–11]; and [12]. The use of diamond enhanced composites for hard rock percussive drilling requires fundamental understanding of the effects of DEI material on impact and wear resistances [13]; Gant et al., 2018].

To support the development of more enhanced materials for rotary-percussive drilling, the laboratory tests are key to evaluate the performance of insert material before proceeding to the in-field drilling test which is labor-intensive and costly in time and resources. The strengthen of insert material can be assessed using standard testing methods defined for hard materials, e.g. the standard testing method based on ultrasonic measurements system for the assessment of elastic properties [3,14] and the standard testing methods based on indentation test for the assessment of hardness and Palmqvist fracture toughness (International Standard IOS 28079:2009E-hard metals). Non-standard testing methods based on three-point bending test were also proposed as alternative to assess the elastic properties and fracture toughness [3,14, 15]. When it comes to the assessment of wear resistance, this might be a challenging task. The assessment of wear resistance by laboratory tests is based on the measurement of the wear rate. This measurement do not depend only on the specimen material, but on the full conditions of the tribological system such as contact conditions, specimen geometry, and rock type [5,16–18]; and [6]. Therefore, the assessment of materials performance will not provide a qualification of the inherent material properties but will rather allow for comparative analyses under identical and well controlled testing procedures.

Most of the abrasive wear testing methods are not adapted for testing insert materials or involve kinematics and tribological systems that are not originally designed for rotary percussive drilling applications. For example, three-body abrasion tests such as crushing pin-on-disc wear test [18,19]; and [20] and rotating steel wheel tests [ASTM B611 and modified ASTM G65] were mainly developed to mimic the wear generated in sliding contact with the abrasive particles (see Fig. 1). To approach the contact conditions in rotary drilling, the rotating wheel testing set up was modified to enable the use of a rock cylinder instead of the rotating steel wheel [21]; and [22]. With such testing set-up, it was difficult to correlate the wear measurement with the applied load due to the vibration induced by the rough surface of the rock [16]. Another type of abrasive wear testing method was proposed to mimic the wear generated by impacting abrasive particles, e.g. impeller-tumbler abrasive impact wear test [34] and disintegrator abrasive impact wear test [23]. The kinematics systems were designed to provide the rock particles with high velocities to impact the composites specimens. The impact energy was controlled by the rotation speed of the impeller and the size of the rock particles. For impeller-tumbler test, the particle size of rock specimens was reduced during the test due to the fragmentation of rock specimen by crashing. This changes the impact conditions during the test and makes it difficult to estimate the impact energy. To enables the estimation of impact energy, the rock specimen was constantly renewed during the disintegrator abrasive impact wear test [23]. The effect of particles size and impact speed on the wear measurement was evaluated in term of the total kinetic energy of all particles attacking the specimen surface. There are few testing methods in which the kinematics system combines sliding and impact contact, e.g. the hammer-mill impact tests [24] and impact wear rig [25]; Zhang et al., 2015. However, by combining sliding and impact wear, it might be difficult to relate the wear measurement to the fundamental wear mechanisms.

In the present work, three testing methods were adapted to perform a comparative study of the wear resistance of drill-bit inserts for percussive drilling of hard rock. The standard Abrasion Value (AV) [26] and LCPC (Laboratoire Central des Ponts et Chaussées) [27,28] tests which were originally developed to classify the rock abrasivity, were adapted to study the abrasive sliding wear and the abrasive impact wear of insert materials, respectively. The disintegrator abrasive impact wear test [23] was also adapted to study the effect impact speed on wear measurements. The testing setups and procedures were modified to enable testing drill-bit inserts as specimens. The modified tests will be referred to by abrasive sliding wear test, LCPC abrasive impact wear test and disintegrator abrasive impact wear test.

The comparative study involves drill-bit inserts representing cemented tungsten carbide-cobalt composites with varied volume fraction of cobalt and average grain size of WC, and one diamond enhanced composite newly developed for rotary-percussive drilling. All inserts were tested in dry condition against Kuru Grey granite rock which is used as a reference in connection with hard rock testing [26]. The Kuru granite rocks were crushed and sieved to obtain homogenous particles with specific particle size for each test. The rock particles were constantly renewed during the abrasive sliding wear test and disintegrator abrasive impact wear test and was cyclically renewed during the LCPC abrasive impact wear test. The wear measurements of WC-Co inserts were evaluated with respect to the effects of volume fraction of Co and average grain size of WC. The wear measurements of DEI were compared to the wear measurements of WC-Co inserts. Secondary-electron microscope (SEM) observations of worn surface of

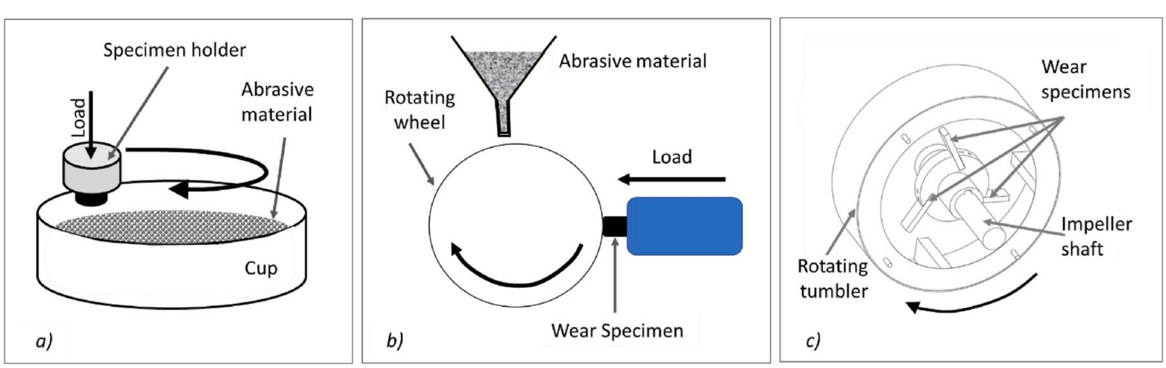

Fig. 1. Schematic representation of kinematics systems in selected laboratory wear tests used for hard materials: a) crushing pin-on-disc test, b) rotating wheel test, and c) impeller-tumbler impact abrasive test.

DEI after LCPC abrasive impact wear tests were performed to support understanding the effect of DEI microstructure on wear mechanisms.

2. Materials

2.1. Drill-bit inserts materials

To enable the study of the effect of volume fraction of Co and average grains size of WC on wear measurements, five WC-Co inserts which differ by the volume fraction of Co and grain size of WC were selected. The nominal composition, microstructural characteristics and Vickers hardness of the inserts are presented in Table 1. The WC-Co inserts were divided into two groups to enable the study of separate effects of Co and WC:

1. Group of grades having similar volume fraction of Co and different WC gain size. It includes WC (2.5)-6 Co, WC (5.0)-6 Co and WC (7.5)-6 Co,
2. Group of grades having small variations in WC gain size compared to the large variation in volume fraction of Co. It includes WC (2.5)-6 Co and WC (3.5)-9.5 Co, and WC (2.0)-15 Co

In addition to WC-Co inserts in Table 1, a diamond enhanced insert developed for rotary-percussive drilling was selected. The insert material contains a homogeneous distribution of diamond particles with approximately 10 μm average diameter in a composite matrix composed of WC and metallic binder. The nominal compositions of the composite matrix (composition of metallic binder and fractions of diamond and metallic binder) are subject to non-disclosure agreements. The wear measurements of diamond enhanced inserts were compared to a reference WC-Co insert, which is a standard rock drilling drill-bit insert with 6% of cobalt. It will be referred to by standard WC-Co insert. The microstructure of standard WC-Co insert and DEI are illustrated in Figs. 7 and 8 respectively. The standard WC-Co insert has large variation in WC grain sizes.

2.2. Hard rock sample

All inserts were tested against a granite rock commercially known as Kuru Grey granite which is homogenous rock and hence well suited as a reference in connection with hard rock drilling. The rock density is 2630 kg/m3 and the mineral grain size varies from 0.5 to 1.5 mm. The mineralogical compositions of the rock specimen obtained by X-ray diffraction analysis are 35.3% Quartz, 30.4% Albite intermediate, 28% Microcline, 2.9% Biotite, 1.3% Chlorite and 2.1% Diopside. The uniaxial compressive strength and Vickers hardness of the rock specimens were determined by Tkalich et al. [29], and are respectively 236 MPa and 850HV. The quartz in this rock is regarded as the mineral which can cause the highest degree of wear on drill-bit insert due to its hardness (Vickers Hardness VHN 1060). The albite (plagioclase feldspar VHN 800) and microcline (alkali feldspar VHN 730) are also known to be hard mineral which cause a high degree of wear.

Table 1
Nominal composition, microstructural characteristics and Vickers hardness of the investigated WC-Co inserts. In the insert designation, the number in brackets define the average grain size of WC and the number in front of Co define the volume fraction of cobalt.

Grade designation	Average grain size of WC (μm)	Vol. fraction of Co (%)	Vickers Hardness [HV20]
WC (2.0)-15 Co	2.0	15	1150
WC (2.5)-6 Co	2.5	6	1400
WC (3.5)-9.5 Co	3.5	9.5	1220
WC (5.0)-6 Co	5.0	6	1270
WC (7.5)-6 Co	7.5	6	1190

To classify the abrasivity of Kuru Grey granite compared to other hard rocks, the standard AV test methods [26] and the standard LCPC impact abrasion test method [27,28] were performed. The rock classification by the standard AV test is determined for sliding abrasion. It is based on the wear index which measure the mass loss (in mg) of a standardized WC-Co specimen tested against various rock specimens in dry condition. The wear index measured by standard AV test for Kuru Grey granite was 23 which indicates according to Dahl et al. [26] that the rock specimen is medium abrasive. The rock classification by the standard LCPC test is determined for impact abrasion. It is based on the Abrasivity Coefficient which is defined by the mass loss of the impeller (in mg) divided by the mass of the rock specimen in tonne (0.0005t). The impeller material used for the rock classification by LCPC test is a standardized steel with a Rockwell hardness of B 60–75 [28,30]. The LCPC Abrasivity Coefficient for Kuru Grey granite was 1489 mg/tonne which indicates according to the Käsling and Thuro [28] classification that the rock is extremely abrasive. It should be noted here that the classifications given by the standard AV and LCPC tests cannot be directly compared since the tests involve different kinematics systems and use different wear specimens.

3. Wear testing methods

3.1. Abrasive sliding wear test

The testing set-up is illustrated in Fig. 2. The specimen is abraded by rock particles homogenously distributed over a disk rotating at a speed of 20 rev/min. The linear velocity of the specimen hitting the rock particles on the disk is 0.35 m/s.

The rock specimens for the tests were prepared from a Kuru granite block using the procedure given in Ref. [26]. They contain 99% of particles being < 1 mm and 70% of particles being <0.5 mm. The rock particles are continuously renewed after passing beneath the carbide specimen. A dead weight is applied on the top of the specimen to press it against the rock particles.

The drill-bit insert specimen was prepared from two inserts, which have been reshaped to approach the geometry of standard AV test specimen (see Fig. 2). First, the head and the bottom of two inserts were removed. The resulting cylinders were then used side by side to obtain a total length of 20 mm which is 2/3 of the length of standard AV test specimen. The insert's sides were ground until a curve of 15 mm radius is obtained. Fig. 2 shows the geometry of the reshaped insert specimen compared to the standard AV test specimen. To ensure that the same pressure is applied on both standard specimen and reshaped insert specimen, the dead weight for the reshaped insert specimens was adjusted by the ratio of reshaped specimen length to standard specimen length (i.e. 2/3).

The weight loss of the specimen was measured after 5 min of testing which corresponds to 100 m of travelled distance over the abrasive disk. The measurements of the reshaped insert specimens were normalized by the ratio of reshaped specimen length to standard specimen length (2/3) to obtain comparable measurements. It was verified that both standard AV test specimen and reshaped insert specimen provide the same normalized measurements and the difference in the specimen's length has negligible effects on the normalized wear results.

3.2. Abrasive impact wear tests

Two abrasive impact wear tests were adapted: LCPC abrasive impact wear test and disintegrator abrasive impact wear test. The setup for each test is illustrated in Fig. 3.

The standard LCPC specimen used for rock classification is a rectangular impeller which is rotated at high speed in a cylindrical container filled with rock particles. Such a rectangular geometry of the impeller cannot be used for testing the brittle cemented carbide composites. Preliminary tests with rectangular impeller showed breakage of the

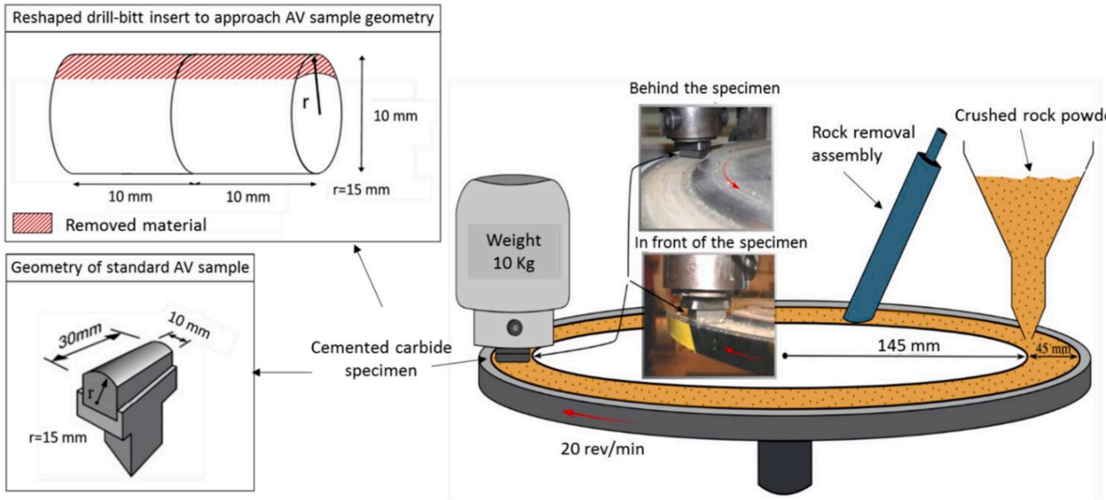

Fig. 2. Schematic illustration of the abrasive sliding wear test and the geometries of reshaped insert specimen compared to the standard AV test specimen.

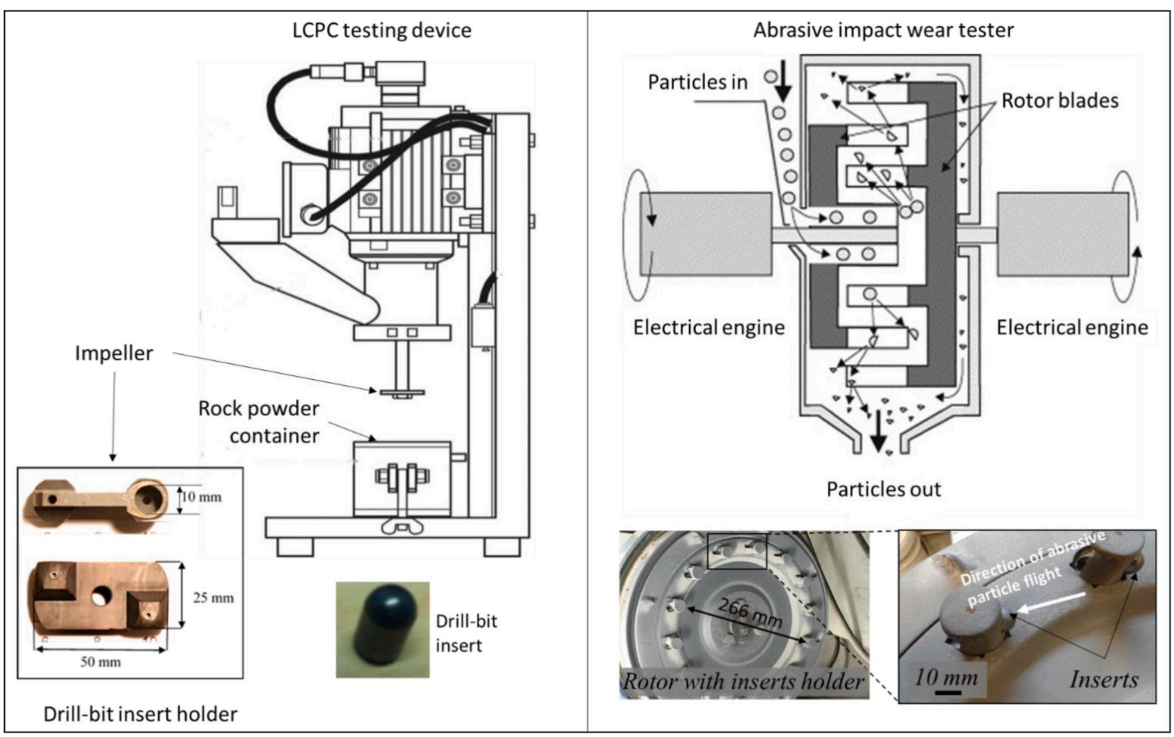

Fig. 3. Schematic illustration of the LCPC testing device (left side) and disintegrator impact wear tester (right side) with the corresponding inserts holders.

corners and edges of the WC-Co specimen after impacting the rock particles [6]. In the current study, the impeller is replaced by a holder designed to grab two drill-bit inserts placed at its extremities (see Fig. 3). This holder was fixed on the device's rotation axe and rotated at a speed of 4500 rev/min in the rock particles container. The holder rotation resulted in a theoretical linear velocity of 6.716 m/s at which the inserts hit the rock particles. The rock specimens for LCPC abrasive impact wear tests were prepared from Kuru grey granite using the preparation procedure given in Ref. [28]. The weight loss of the inserts was measured after each testing cycle corresponding to 5 min of rotation in 500 g of rock. The rock specimen was renewed after each cycle.

Flat specimens are usually used with the disintegrator abrasive impact wear tests. To enable testing drill-bit inserts, new holders were designed. These holders (see Fig. 3) have slots for inserts with additional stoppers to avoid inserts from falling out during the test. The diameter of the sample holder is 22 mm and the diameter at which the holders are positioned is 266 mm. The impact angle is adjusted by rotating the insert holder with respect to the horizontal axis. For the current tests, it was set as perpendicular to the tip of the insert (the direction of particle flight was coaxial with the axis of symmetry of insert). Three impact velocities: 40 m/s, 80 m/s and 100 m/s were applied. The rock quantity utilized for the disintegrator abrasive impact wear tests was the same for all testing velocities (30 kg).

4. Results and discussion

The abrasive sliding wear test was performed on WC-Co inserts presented in Table 1 to study the effect of WC grain size and Co volume fraction on sliding abrasive wear. The diamond enhanced inserts could not be reshaped to obtain a specimen representative of DEI material for abrasive sliding wear test. This is due to the non-homogeneous distribution of the diamond in the investigated DEI. Therefore, only abrasive impact wear tests were performed on DEI, including LCPC abrasive impact wear test and disintegrator abrasive impact wear tests at 40 m/s, 80 m/s and 100 m/s of impact speeds. The standard WC-Co insert is utilized as a reference material for DEI and therefore was subjected to the same tests to compare the wear behavior of DEI to the wear behavior of standard WC-Co insert.

The disintegrator abrasive impact wear test was performed on all WC-Co inserts presented in Table 1 at impact velocity of 40 m/s and 80 m/s. The disintegrator abrasive impact test at 100 m/s was performed on WC (2.0)-15 Co, WC (3.5)-9.5 Co, WC (2.5)-6 Co and WC (7.5)-6 Co, while the LCPC abrasive impact wear test were performed on WC (2.0)-15 Co, WC (2.5)-6 Co and WC (7.5)-6 Co inserts due to the limited number of WC (5.0) - 6 Co and WC (3.5)-9.5 Co inserts.

The weight losses of the specimens were measured after 5 min of testing for abrasive sliding wear test and after 10 min of testing (2 cycle) for LCPC abrasive impact wear test. The weight losses for the disintegrator abrasive impact wear test were measured at the end of the tests when the rock specimen is passed through the testing device (see Fig. 3). The rock quantity utilized in the disintegrator abrasive impact test was 30 kg for all impact velocities (40 m/s, 80 m/s and 100 m/s).

4.1. Tests repeatability and measurement uncertainty

The standard AV test are normally performed on 2–4 specimens; and the weight loss is determined by the average measurement. Based on previous experience with more than 2600 tested samples [26], it has been demonstrated that the variation of the test results for standard WC-Co materials is very low. This variation should not exceed 5 units (milligrams of weight loss) if the testing is correctly performed. In this work, two abrasive sliding wear tests were performed on each WC-Co inserts presented in Table 1. Each test involve 2 drill-bit inserts as described in Section 3.1. The average weight loss of the tests and the standard error of the mean value are given in Table 2. As can be observed, the variation of the measurements for all inserts does not exceed the limit defined by Dahl et al. [26].

In a previous study, the scatter of testing results by disintegrator abrasive impact wear test was determined for various WC-Co drill-bit inserts (grades with 6%, 8% and 15% Co) and found to be in the range of ±15% [23]. In this study, the impact wear tests performed on drill-bit inserts were repeated. The average weight losses are given in Table 3 for each material together with the measurement uncertainties. As can be observed, the scatter of the results for WC-Co inserts is within the range of ±10% and the scatter of results for diamond enhanced inserts is within the range of 14%. The scatter of the impact wear test results still within the range defined by Antonov et al. [23].

The wear measurements by LCPC abrasive impact wear tests were determined for each material as the sum of measurements performed on two drill bit inserts after 2 cycles (corresponding to 10 min of total testing time). The average value of the weight loss and the measurement uncertainties are given in Table 4 for each tested material. The time dependent wear measurements and the standard error of the mean value for the LCPC abrasive impact wear tests performed on diamond enhanced insert and standard WC-Co insert are represented in Fig. 5.

Table 2
Average weight losses and uncertainties for sliding abrasion tests performed on WC-Co inserts.

Drill-Bit inserts	Weight loss in mg (Mean value)	Standard error of the mean value
WC (2.0)-15 Co	104.23	±1.6%
WC (2.5)-6 Co	27.15	±1.3%
WC (3.5)-9.5 Co	73.00	±2.1%
WC (5.0)-6 Co	42.78	±0,1%
WC (7.5)-6 Co	55.00	±0.1%

Table 3
Average weight losses and uncertainties for disintegrator abrasive impact wear tests.

Drill-Bit inserts	Weight loss in mg (Mean value)			Standard error
	40 m/s	80 m/s	100 m/s	
WC (2.0)-15 Co	7.15	40.07	65.87	±0.1%
WC (2.5)-6 Co	1.07	6.23	8.20	±3.1%
WC (3.5)-9.5 Co	2.86	17.11	24.10	±9.4%
WC (5.0)-6 Co	1.91	10.15	–	±7.2%
WC (7.5)-6 Co	3.51	15.20	18.93	±4.1%
Standard WC-Co	1.25	7.31	10.23	±6.6%
DEI	0.36	1.72	2.50	±13.3%

Table 4
Average weight loss and standard error of the mean value obtained by modified LCPC abrasive impact wear tests.

Drill-Bit inserts	Weight loss in mg (Mean value)	Standard error
WC (2.0)-15 Co	57.76	±1.9%
WC (2.5)-6 Co	7.34	±1.4%
WC (7.5)-6 Co	37.08	±2.6%
Standard WC-Co	11.32	±2.5%
Diamond Enhanced insert	3.62	±9.9%

By comparing the standard error for the three tests, it can be observed that the abrasive impact wear tests have in general higher standard error compared to abrasive sliding wear tests. This might be related to the influence of spherical shape of inserts that is attacked by the rock particles in abrasive impact wear tests. The testing conditions in abrasive sliding wear tests involves continuous contact between the inserts and the rock particles. It can be also observed that the highest standard error was associated to DEI measurement by disintegrator abrasive wear test. However, this errors still within the range defined by Antonov et al. [23].

4.2. Wear measurements of WC-Co inserts and diamond enhanced inserts

The weight losses of WC (2.5)-6 Co, WC (5.0)-6 Co and WC (7.5)-6 Co inserts which have similar volume fraction of Co were plotted in Fig. 4-a as a function of the average grain size of WC. The weight losses of WC (2.5)-6 Co, WC (3.5)-9.5 Co, and WC (2.0)-15 Co which have small variation in the average grain size of WC were plotted in Fig. 4-b as a function of the volume fraction of cobalt. Fig. 4-a and 4-b show that the volume fraction of Co and the average grain size of WC have similar effects on the weight loss measurements by abrasive sliding wear test, LCPC abrasive impact wear test and disintegrator abrasive impact wear test. The wear measurements were proportionally increased with the average grain size of WC and the amount of Co. However, the steepness of the weight loss as a function of volume fraction of Co and average grain size of WC depends on the performed test. The impact speed amplifies the effects of Co volume fraction on wear measurements. The steepness of the weight losses measured by disintegrator abrasive impact wear test increases with the impact speed (see Fig. 4-b). The difference between the weight losses of WC (2)-15Co and WC (2.5)-6Co inserts obtained by disintegrator abrasive impact wear test at 100 m/s is 57 mg which is nine times the difference of weight losses obtained at impact velocity of 40 m/s. The highest effect of volume fraction of cobalt on wear measurements is obtained by abrasive sliding wear test. The difference between the weight losses of WC (2)-15Co and WC (2.5)-6Co inserts measured by abrasive sliding wear test is 77 mg.

The abrasive sliding wear test and LCPC abrasive impact wear test demonstrates higher effect of WC grains size on weight loss measurements compared to disintegrator impact wear tests. The difference between the weight losses of WC (7.5)-6Co and WC (2.5)-6Co inserts obtained by abrasive sliding wear test and LCPC abrasive impact wear

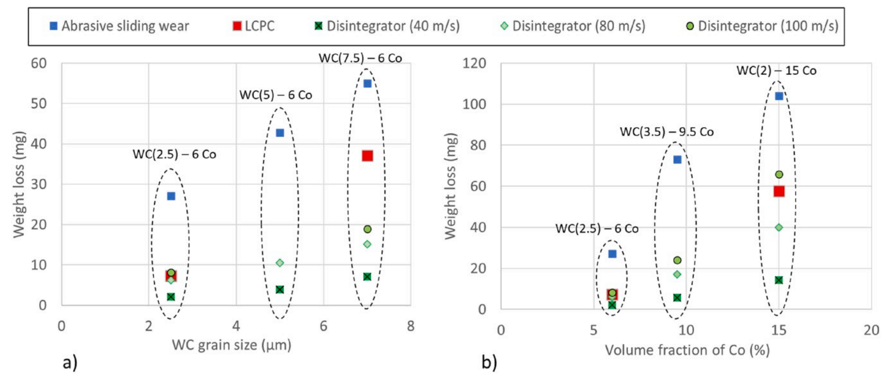

Fig. 4. Influences of WC grain size (a) and Co volume fraction (b) on the weight loss measurements by abrasive sliding wear tests, LCPC abrasive impact wear tests and disintegrator abrasive impact wear tests at 40 m/s, 80 m/s and 100 m/s.

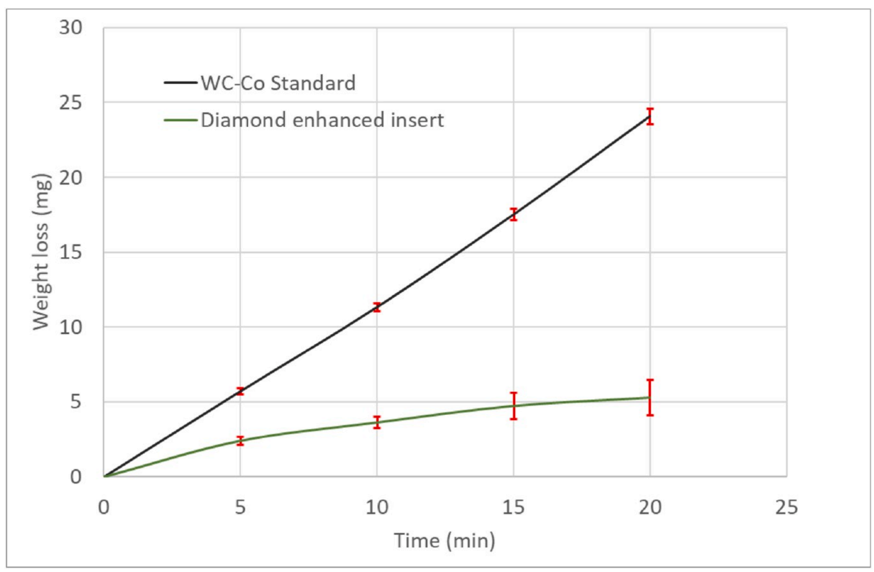

Fig. 5. Time dependent measurements of DEI by LCPC abrasive impact wear test compared to time dependent measurements of standard WC-Co insert. The error bars represent measurements deviation around the mean values.

test is approximately 2.5 times the difference of weight losses obtained by disintegrator impact wear test.

The weight losses measured by LCPC impact wear test for the diamond enhanced insert are compared in Fig. 5 to the weight loss measurements for the standard WC-Co insert. The diamond enhanced insert exhibits non-linear weight loss compared to the standard WC-Co

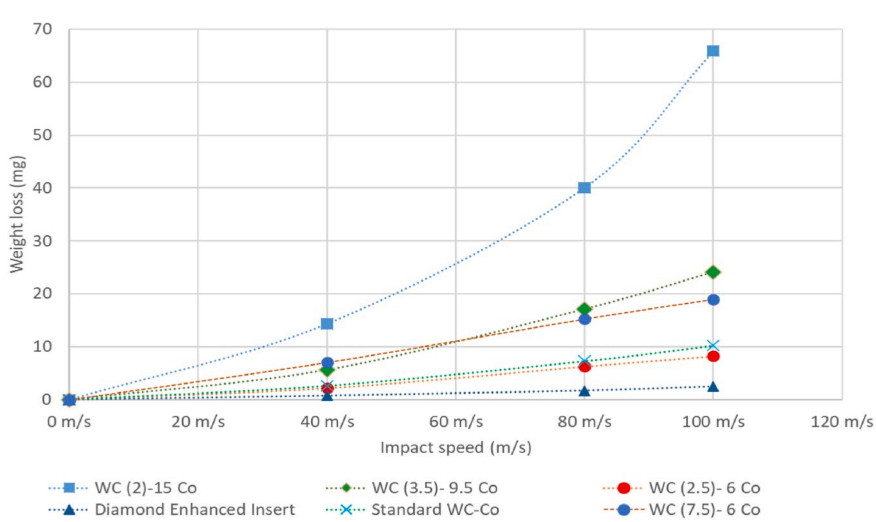

Fig. 6. Effect of impact speed on weight loss measurements by disintegrator abrasive impact wear tests.

insert. The wear rate (mass loss divided by the testing time) of diamond enhanced inserts after 5 min of testing is almost 2 times higher than the wear rate after 20 min of testing. This might indicate surface effects of diamond enhanced insert where a certain time is needed to access the bulk properties. However, the DEI demonstrate a significant reduction in the wear rate at 20 min (steady-state) compared to the standard WC-Co insert. The weight loss of the standard WC-Co insert is approximately three time the weight loss of DEI.

The impact speed increases the weight loss measurements by disintegrator abrasive impact wear tests as illustrated in Fig. 6. The relationship between the impact speed and the wear measurements for WC-Co inserts clearly depends on the microstructure. The WC (2.5)-6 Co and WC (7.5)-6 Co inserts which have the same amount of Co, show linear increasing of the weight loss with the impact speed compared to WC (2) -15 Co which has the highest amount of Co. The WC (7.5)-6 Co has higher steepness than WC (2.5)-6, which can be related to the effect of WC grain size. The wear measurements of WC (2) −15 Co exponentially increase with the impact speed. This can be related to the increased amount of cobalt in this insert. The diamond enhanced insert has the lowest weight loss at all impact speeds compared to WC-Co inserts. The maximum weight loss of DEI is 2.5 mg at impact speed of 100 m/s. An extended range of measurements is however needed to accurately describe the relation between the weight loss and the impact speed for the diamond enhanced insert.

4.3. Microstructure of diamond enhanced inserts

Microscopic observations were performed on the surface of diamond enhanced inserts before and after LCPC abrasive impact wear test and compared to the microscopic observations performed on the surface of standard WC-Co insert. The secondary-electron SEM images of WC-Co standard drill-bit insert are shown in Fig. 7 before and after the LCPC impact wear test. This figure shows a removal of Co binder after the test, where the WC grains are much more exposed given the surface a rough appearance. Also, some of the WC grains appear cracked and some contain slip bands. It is possible that some WC grains were also removed. These are the main wear mechanisms of WC-Co composites also observed by many wear studies such as Blomberry et al. [31], Gee et al. [32] and From Ref. [16]. The SEM images of the diamond-enhanced insert are shown in Fig. 8 before and after the LCPC abrasive impact wear test. EDX (energy-dispersive x-ray spectroscopy) maps taken from untested inserts are given in Fig. 9. The carbon map shows the location of the diamond particles. The tungsten map shows the areas rich in tungsten indicating the WC grains in the composite matrix. The WC grains in the composite matrix are much smaller (less than 1 μm) than in the standard insert. Before the wear test, the composite matrix (WC-metallic binder) have a smooth surface, and the dark diamond particles are partly covered by the composite matrix (Fig. 8-b).

After abrasive impact testing, the sample surface of the diamond-enhanced insert is much rougher compared with the untested condition. The facets of the WC grains are much more exposed, presumably due to removal of metallic binder. Also, the diamond particles are no longer covered by the composite matrix (Fig. 8- d). Higher magnification images in Fig. 10 reveal that some of the WC grains contain cracks. Also, the diamond particles contain holes or dimples that are often faceted. These holes were most likely filled by WC grains before the wear test, which were subsequently removed during testing. It is possible that some WC grains were also removed from the regions in between the diamond particles. Only few instances of the removal of entire diamond particles, with remaining craters, were observed (Fig. 8-d) indicating sufficient bonding between diamond and the metallic binder. However, the initial stages of decohesion at the diamond/WC-metallic binder interfaces could also be observed in some places (Fig. 10- b).

5. Discussion

The current study proposed a combination of three testing methods adapted for testing cemented carbide drill-bit inserts. These testing methods are summarized in Table 5. They have a simplified setup with repeatable testing procedure under controlled conditions. They have a great potential to assess the wear resistances of drill bit inserts for sliding and impact which are the main wear components in rotary-percussive drilling.

The LCPC and disintegrator abrasive impact wear tests have successfully enabled the use of drill-bit inserts as specimens. The drill-bit insert can now be tested without any additional mechanical

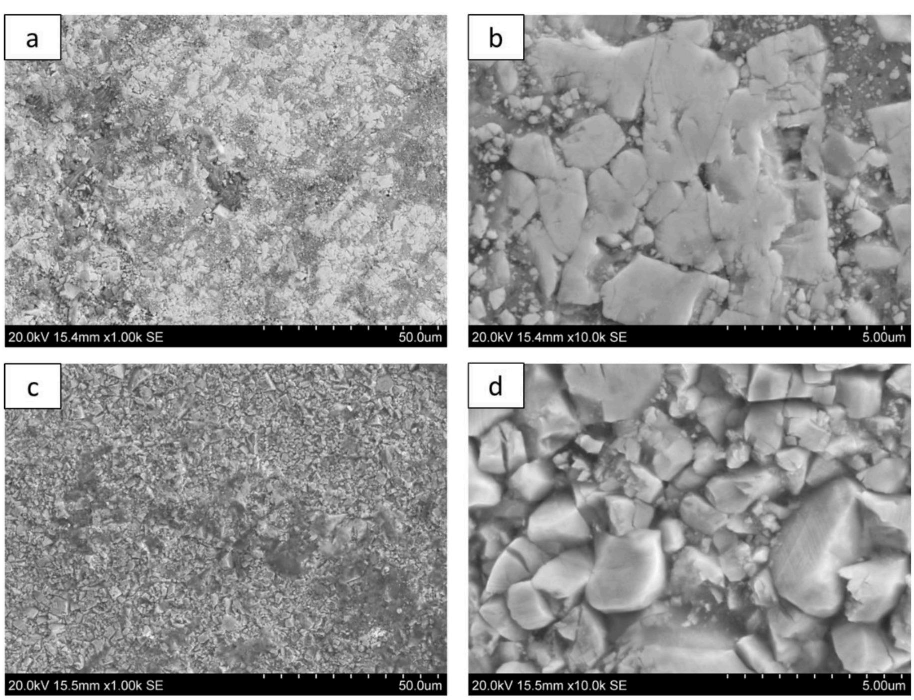

Fig. 7. Secondary-electron SEM images of standard WC-Co insert before (a and b) and after 20 min (c and d) of LCPC abrasive impact wear test (see Fig. 5).

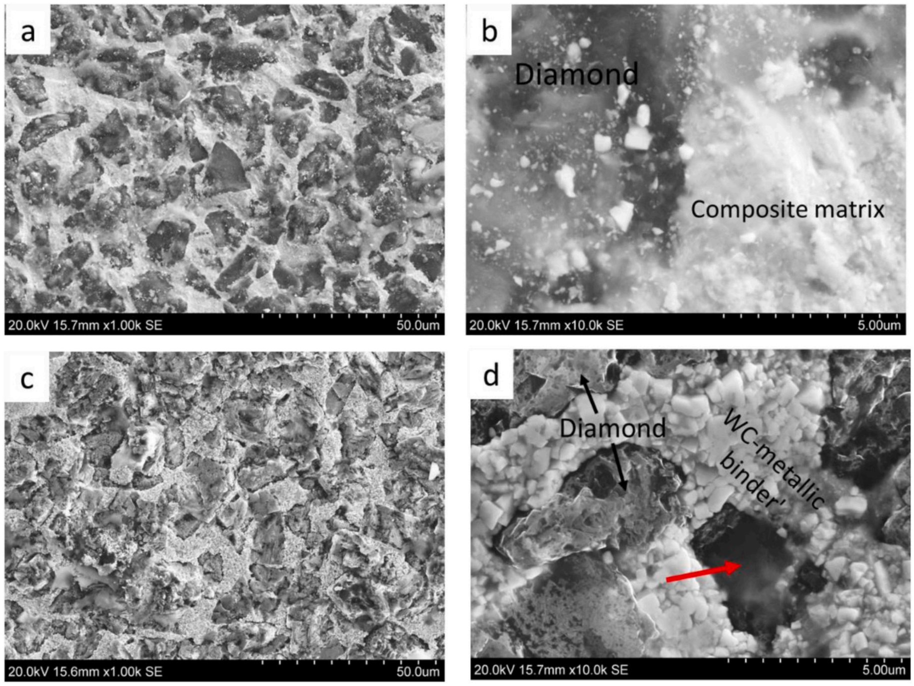

Fig. 8. Secondary-electron SEM images of diamond-enhanced material before (a–b) and after (c–d) 20 min of LCPC abrasive impact wear testing (see Fig. 5). The diamond particles appear dark, while the WC- metallic binder is bright. A hole where a diamond particle might have been removed during testing is indicated by a red arrow in (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

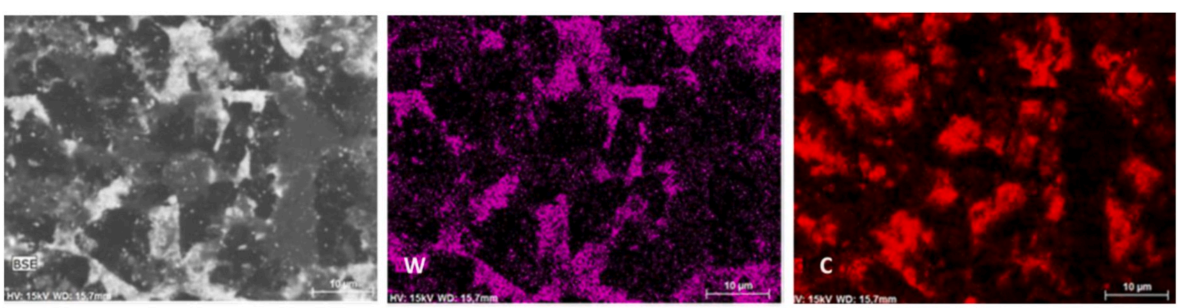

Fig. 9. Backscattered-electron SEM image and EDX (energy-dispersive x-ray spectroscopy) maps of untested diamond-enhanced insert. The carbon map (right side image) shows the location of the diamond while the tungsten map (middle image) reveals the WC grains in the composite matrix.

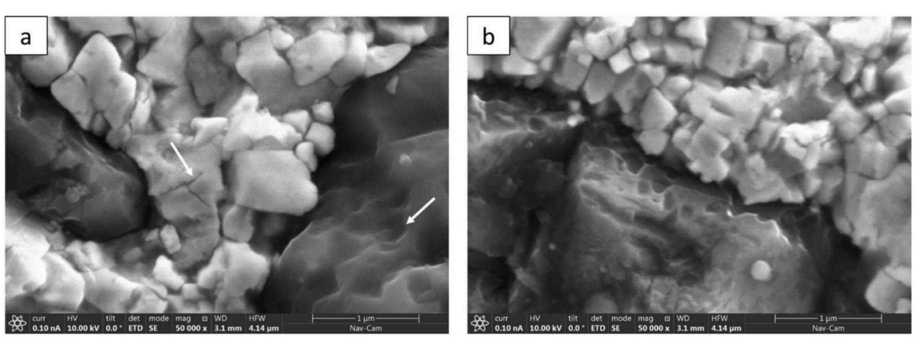

Fig. 10. Secondary-electron SEM images of diamond-enhanced composite after LCPC testing. In (a), white arrows indicate a cracked WC grain, and a faceted hole in a diamond particle.

processing. Compared to the standard impeller geometry, the drill-bit insert have a smooth semi-spherical shape which is suited for testing brittle materials such as cemented carbide composites to avoid the breakage of corners and edges. The sliding abrasion test requires reshaping of drill bit insert before testing. The reshaped geometry of the insert is needed to ensure a constant flow of rock powder beneath the specimen during the test.

For the modified LCPC test, at least 20 min of testing time was required for diamond enhanced insert to reach a steady state wear rate regime (see Fig. 5). The running-in period (prior steady state) for WC-Co

Table 5
Main parameters of the testing methods adapted for testing drill-bit inserts.

	Abrasive sliding wear test	LCPC abrasive impact wear test	Disintegrator abrasive impact wear test
Main wear mechanism	Abrasive sliding	Abrasive impact	Abrasive impact
Testing specimen	Reshaped drill-bit insert	Drill-bit insert	Drill-bit insert
Rock sample	Kuru granite	Kuru granite	Kuru granite
Particles size of rock sample	99% of particles < 1 mm 70% of particles <0.5 mm	4–6.3 mm in diameter	3–5.6 mm in diameter
Renewal of rock particles	Continuously	Cyclic (each 5 min)	Continuously
Velocity	Rotation speed = 20 rev/min. Linear velocity = 0.35 m/s.	Rotation speed = 4500 rev/min linear velocity = 6.716 m/s	Three impact velocities: 40 m/s, 80 m/s and 100 m/s
Testing duration	5 min	10 min for WC-Co inserts 20 min for DEI and standard insert	After crashing 30 kg of rock sample

grades was much shorter and test with duration of 5 min was enough to provide steady state results. The testing durations for the abrasive sliding wear test and disintegrator abrasive impact wear test (see Table 5) were selected to pass the running-in period and provide sufficient duration of test.

The three testing methods exhibit similar effects of volume fraction of cobalt and average grain size of WC on wear measurements of WC-Co inserts. The highest weight loss measurement by each test was associated to WC (2.0)-15 Co insert which has the highest volume fraction of Co. The lowest weight loss measurement by each test was associated to WC (2.5)-6 Co insert. However, the difference between the highest weight loss and lowest weight loss, which shows the effect of insert microstructure on wear measurements, was found to be dependent on the testing method. The abrasive sliding wear test and the LCPC abrasive impact wear test exhibit higher difference than the disintegrator abrasive impact wear test.

6. Conclusion

A combination of abrasive sliding wear test, LCPC abrasive impact wear test and disintegrator abrasive impact wear test is proposed to perform a comparative study of the wear resistances of drill-bit inserts. The suggested tests have a simplified testing setup with a great ability to assess the wear resistance by repeatable testing method under carefully controlled laboratory conditions. Although the conditions in the suggested tests do not reproduce all in-situ wear mechanisms representative of drilling, they demonstrate a great potential for providing good indications of expected wear rate by combining the effect of sliding and impact abrasion.

Five WC-Co drill-bit inserts with various volume fraction of cobalt and average grain size of WC, and one diamond enhanced insert were tested. The wear measurements were evaluated with respect to the effects of drill-bit insert material and microstructure. The three testing methods exhibit similar behavior related to the effects of average grain size of WC and volume fraction of Co on the wear measurements. The weight loss of WC-Co inserts increased with the volume fraction of Co and average grain size of WC. The WC-Co insert with the highest volume fraction of cobalt have the highest weight loss measurement in all performed tests. The increase of impact speed accelerates the weight loss for all tested materials. This acceleration of weight loss depends on the WC-Co microstructure, and becomes more significant when increasing Co fraction. The results of abrasive impact wear tests performed on diamond enhanced composite show a potential to improve the wear resistance at least at impact velocity up to 100 m/s. However, microstructure observations showed initial stages of decohesion at the diamond/WC-metallic binder interfaces after abrasive impact test. Such mechanism might affect the wear resistance or lead to material fail at higher impact energy and need to be further investigated.

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.

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