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Effect of hardfacing on wear reduction of pick cutters under mixed rock conditions

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Abstract. A pick cutter is a rock-cutting tool used in partial-face excavation machines such as roadheaders, and its quality is a key element influencing the excavation performance and efficiency of such machines. In this study, pick cutters with hardfacing deposits applied to a tungsten carbide insert were made with aim of increasing their durability and wear resistance. They were field-tested by being installed in a roadheader and compared with conventional pick cutters under the same excavation conditions for 24 hours. The hardfaced pick cutters showed much smaller weight loss after excavation, and therefore better excavation performance, than the conventional pick cutters. In particular, the damage to and detachment (loss) of tungsten carbide inserts was minimal in the hardfaced pick cutters. A detailed inspection using scanning electron microscope–energy dispersive X-ray spectrometry and three-dimensional X-ray computed tomography scanning revealed no macro- or micro-cracks in the pick cutters. The reason for the absence of cracks may be that the heads of pick cutters are mechanically worn after the tungsten carbide inserts have been worn and damaged. However, scanning revealed the presence of voids between tungsten carbide inserts and pick cutter heads. This discovery of voids indicates the need to improve production processes in order to guarantee a higher quality of pick cutters.

Keywords: pick cutter; rock cutting; partial-face machine; wear; hardfacing

1. Introduction

Partial-face machines such as roadheaders and continuous miners are mechanical excavators used for cutting rock in tunnels and mines. Such machines use a pick-laced cutting head that is much smaller in diameter than the tunnel or mining face. In particular, the cutting head, equipped with pick cutters and attached to a movable boom, excavates rock at different parts of the face at different times (Tatiya 2013). Even though partial-face machines are generally suitable for rocks of

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medium to low strength, they are much more flexible and mobile than full-face machines such as tunnel-boring machines (TBMs) as they are self-propelled and are much lighter than TBMs (Bilgin *et al*. 2014).

Pick cutters as consumable rock-cutting tools have an important influence on the cutting performance and economics of partial-face machines for given rock conditions. Therefore, it is essential to increase the life of pick cutters of partial-face machines because changing cutters is disruptive to production and reduces machine utilization time and production rates (Kim *et al*. 2012a).

Pick cutters can be classified into radial picks (or drag bits) and conical picks (or point-attack picks). Radial picks are seldom used because their durability is very low. Instead, conical picks are widely used as cutting tools for a variety of partial-face machines. Conical picks have longer lives compared with radial picks and rotate as they cut the rock, ensuring uniform wear of the tip and body, which helps to maintain the tip shape and allow the pick cutter to work efficiently for an extended period (Kim *et al*. 2012b).

A conical pick cutter consists of a tungsten carbide insert, a head holding the tungsten carbide insert, and a shaft connecting the pick cutter to a holder installed in a cutting head drum. During rock cutting, conical pick cutters are subjected to large forces (including normal forces, cutting forces, and side forces), extensive wear, and high temperatures, which together result in short pick-cutter lives and low cutting efficiencies (Bilgin *et al*. 2006, Liu *et al*. 2016a). Therefore, it is crucial to minimize the wear of and damage to tungsten carbide inserts in order to guarantee longer lives for pick cutters.

Few studies have been devoted to increasing the cutting performance of pick cutters. Most such studies have focused on the design of cutting heads for partial-face machines (Eyyuboglu and Blukbasi 2005, Hekimoglu and Fowell 1991) and on prediction of the performance of these cutting heads based on experimental, numerical, or statistical approaches (Bilgin *et al*. 2004, 2006, Comakli *et al*. 2014, Ebrahimabadi *et al*. 2015, Yimaz *et al*. 2007).

Some novel pick cutters have recently been reported; e.g., one uses water jets (Liu *et al*. 2014) and another has a diamond composite bonded into the steel body of a pick cutter (Shao *et al*. 2017), but their high costs prevent their wide use. On the other hand, hardfacing has been widely used as an economical countermeasure against wear. This involves depositing a wear-resistant alloy on the metal surface that is to be subjected to wear when in service (Gregory 1978). Although a variety of hardfaced pick cutters are produced and used commercially, few studies have considered their performance, and their field application is often neglected. While some studies have considered other types of excavating machine such as rippers and diggers (Gregory, 1978, Muro and Fukagawa 1985). Especially, field studies on pick cutters have been seldom carried out yet.

This study aimed to evaluate the field performance of conical pick cutters with hardfacing deposits applied to their heads. The hardfaced pick cutters were made particularly for excavation in a copper mine characterized by very complex and mixed rock conditions. They were tested in the mine and compared with conventional pick cutters under the same conditions to assess their durability and excavation performance when installed in a partial-face machine.

2. Field area location and conditions

The field area of interest is the Boleo Mine, located in Santa Rosalia, Baja California Sur, Mexico. The main product of the mine is copper together with cobalt, zinc, and manganese as byproducts. The mine is estimated to contain 238 million tonnes of these minerals.

The mineral deposits lie within the upper Miocene El Boleo Formation, which is characterized by fine to coarse clastic sedimentary rocks. In particular, the deposits in the Boleo Formation consist of several mineralized groups termed “Mantos,” which is a specific Spanish term used in mining for mineralized layers or strata. Mining at the Boleo Mine started in the last quarter of the nineteenth century and continued through most of the twentieth century. However, significant quantities of copper, cobalt, and zinc resources remain in the extensively mined Mantos and overlying breccia, and these resources are currently the main targets for underground re-mining in the Boleo Mine (Agapito Associates 2007). Mantos and brecciated zones vary in thickness, but the main mining areas generally have a minimum thickness of 1.8 m. The Mantos are overlain by massive and relatively soft sandstone, and underlain by relatively hard conglomerate layers with cobbles (Fig. 1). Mantos, the main target layers for underground mining, are very soft with a

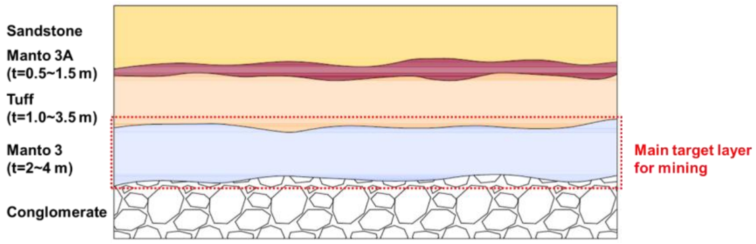


Fig. 1 Simplified lithologic section view of the Boleo Mine (Agapito Associates 2012)

Fig. 2 Mixed rock conditions typically observed in a mine face of the Boleo Mine

(a) Mixed rock conditions (b) Wear of pick cutters

Fig. 3 Mixed rock mining face conditions and excessive wear of pick cutters installed in a continuous miner uniaxial compressive strength of 2 MPa. However, it is difficult to excavate a mine face in the Boleo Mine using roadheaders and continuous miners because the underlying conglomerate with large cobbles offers very high resistance to cutting (Fig. 2), which results in excessive wear of conical pick cutters and damage to or loss of their tungsten carbide inserts (Fig. 3).

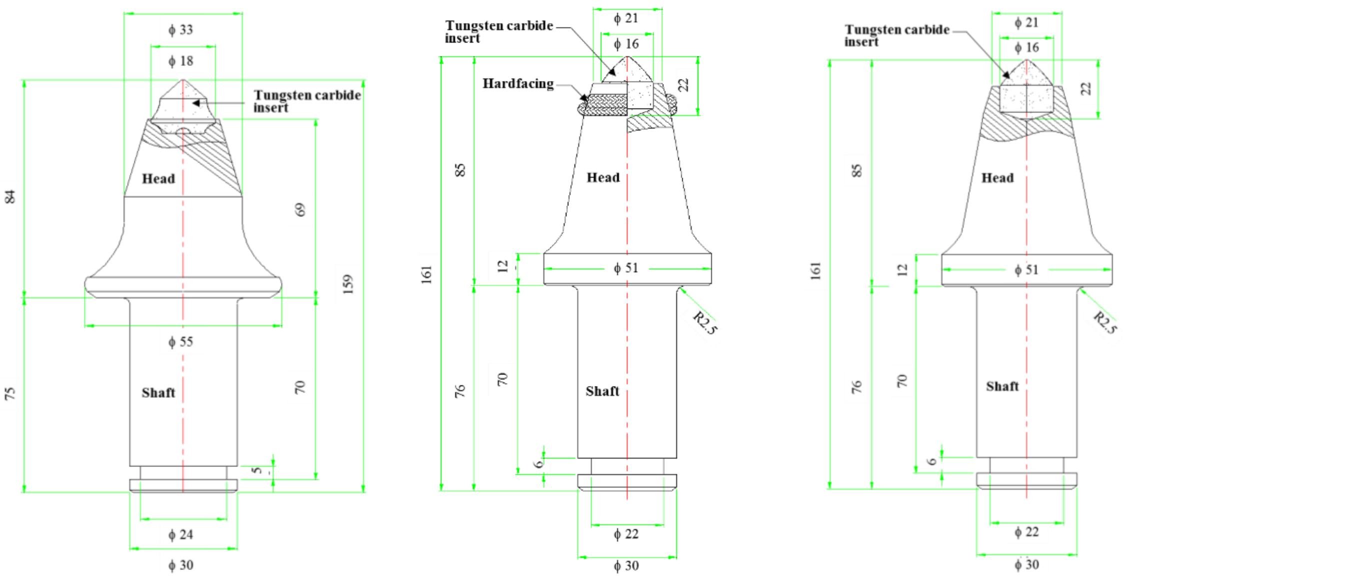
3. Design and production of pick cutters with hardfacing deposits

Conventional conical pick cutters used in the Boleo Mine are designed for soft-rock excavation and have a length of 159 mm (Fig. 4(a)). Wear of the heads, and damage to and loss of tungsten carbide inserts often occur after roadheaders and continuous miners have mechanically excavated mixed rocks (Mantos and conglomerates). The tungsten carbide insert is the key part of a conical pick cutter because it directly contacts and cuts the rock surface. As a result, it is important to ensure a high quality of tungsten carbide and to properly fix the insert to the head of a conical pick cutter in order to successfully cut rock. In addition, the wear of a pick head results in the loss of the tungsten carbide insert and frequent cutter changes).

The present study aimed to produce a hardfaced pick cutter that is much more resistant to wear during rock cutting than existing conventional pick cutters.

Applying hardfacing is an effective way to improve wear-resistance performance, and is achieved by placing a wear-resistant coating on the surface of an inner material (Liu *et al*. 2016b). Compared with alternative metal-coating preparation methods such as spraying, electroplating, magnetron sputtering, and laser coating, hardfacing (hard-surface welding) is more widely used owing to its convenience and performance (Yang *et al*. 2016).

Martin and Fowell (1997) reported that materials need to be developed for cutting tools that can retain high indentation hardness at temperatures above 800℃. The high chromium content of



(a) Conventional pick cutter (b) Prototype A with hardfacing (c) Prototype B without hardfacing

Fig. 4 Schematic diagrams of the conical pick cutters investigated in this study (unit: mm) hardfacing alloys imparts good corrosion and oxidation resistance at temperatures as high as 1000℃. Therefore, hardfacing alloys can maintained wear resistance at high temperatures, because the chromium carbide remains stable to beyond 1000℃ (Svensson *et al*. 1986).

Hardfacing deposits usually include two layers, which lead to a significant dilution effect and potentially cracking as a result of welding contraction strain. To minimize performance losses due to dilution, it is often necessary to apply a buffer layer before the hard layer is applied (Chatterjee and Pal 2003). Therefore, a three-layer hardfacing was applied in this study between the tungsten carbide insert and the top of the pick head to ensure that the insert is held tightly even in mixed-rock-cutting conditions and to minimize the mechanical wear of the pick head (Fig. 4(b)). For comparison with the pick cutter with hardfacing deposits (hereinafter “Prototype A”), a prototype of a conical pick cutter without hardfacing (hereinafter “Prototype B”) but with the same dimensions as Prototype A was also designed, as shown in Fig. 4(c).

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Table 1 lists the main specifications of the tungsten carbides used as inserts for the two pick cutter prototypes. High toughness of the tungsten carbide inserts was achieved by controlling the quantities of tungsten (W) as a hard phase and cobalt (Co) as a binder phase. The quality of the tungsten carbides was checked by measuring their Rockwell hardness and transverse rupture strength, which are widely used as index properties for the toughness of tungsten carbide (Cha *et al*. 2008). The values of Rockwell hardness, grain size, cobalt content, and transverse rupture strength of tungsten carbides for the pick cutter prototypes showed that the tungsten carbide inserts produced in this study have physical and mechanical properties suitable for use in mining and civil engineering cutting tools (Muthuraja and Senthilvelan 2015, Sandvik 2005). For example, Sandvik (2005) proposed that tungsten carbide with a cobalt content of 7%-15% and a grain size of 2-20 m should have a transverse rupture strength ranging from 1000 to 3000 MPa, suitable for use in a rock-cutting tool. The corresponding properties of tungsten carbides used in the present study and summarized in Table 1 are within the ranges proposed by Sandvik (2005).

Powders with the compositions of tungsten and cobalt described in Table 1 were prepared and sintered to make tungsten carbide inserts. They were inserted and then welded onto the prefabricated grooves at the top of the pick cutter head by sintering.

A three-layered hardfacing was applied to the interface between the tungsten carbide insert and the head of Prototype A by using martensite-based welding rods. Hardfacing with the chemical composition as summarized in Table 2 can be classified as 0.2C 12Cr 1Mo steel (Beres *et al*. 2005).

The heads and shafts of the pick cutter prototypes were made of SCM 440 steel, which is

Table 1 Specifications of tungsten carbides for the two kinds of pick cutter prototypes used in this study

Type	Rockwell hardness (HRA)	Grain size (μm)	Components (weight %)		Transverse rupture strength (MPa)
			W	Co	
Prototype A (with hardfacing)	86.5	3-9	89	11	2,600
Prototype B (without hardfacing)	88.5	3-6	92	8	2,600

Table 2 Chemical composition of the hardfacing used for Prototype A (unit: weight %)

Cobalt (C)	Manganese (Mn)	Silicon (Si)	Chromium (Cr)	Nickel (Ni)	Molybdenum (Mo)
0.26	0.72	0.50	13.2	0.89	1.05

Table 3 Chemical composition of SCM 440 steel (unit: weight %)

Cobalt (C)	Silicon (Si)	Manganese (Mn)	Phosphorus (P)	Sulfur (S)	Chromium (Cr)	Molybdenum (Mo)
0.38-0.43	0.15-0.35	0.6-0.85	Max. 0.03	Max. 0.03	0.9-1.2	1.05

Table 4 Physical and mechanical properties of SCM 440 steel

Heat treatment (℃)		Yielding strength (MPa)	Tensile strength (MPa)	Percentage of elongation (%)	Charpy impact value (kgfm/cm^2)	Brinell Hardness (HB)
Quenching	Tempering					
830–880	530–630	Min. 834	Max. 980	Max. 12	Max. 6	285–352

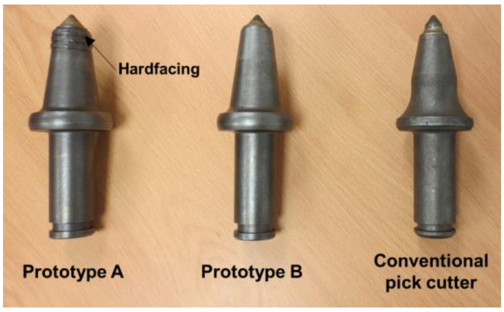


Fig. 5 Conical pick cutters tested in this study

classified as a tool steel. The chemical composition and physical–mechanical properties of SCM 440 steel are summarized in Tables 3 and 4, respectively.

Sample specimens of the two prototypes manufactured using the procedure described above, as well as a sample specimen of the conventional pick cutter used, are shown in Fig. 5.

4. Field testing of pick cutters and performance assessment

4.1 Mechanical excavation conditions

Specimens of two conical pick cutter prototypes and of the conventional pick cutter used were installed into an AQM 150-H roadheader manufactured by Antraquip Company. The cutting head of this roadheader is a transverse cutting head type with a total of 78 pick cutter holders arranged in a spiral array. Left and right cutting drums are perfectly symmetric, with each accepting 39 pick cutter holders.

(a) Prototype A (pink)

(b) Prototype B (yellow)

Fig. 6 The prototype pick cutters before being installed in the AQM 150-H cutting head

To easily identify each pick cutter after testing, white, pink, and yellow paint was sprayed on the shafts of the conventional, Prototype A, and Prototype B pick cutters, respectively, prior to installation in the cutting head (Fig. 6).

Twenty conventional pick cutters and 19 Prototype A pick cutters were installed in the right cutting drum to compare their wear resistance under the same conditions (Fig. 7(a)). Similarly, 20 conventional pick cutters and 19 Prototype B pick cutters were installed in the left cutting drum (Fig. 7(b)).

The AQM 150-H roadheader installed with both prototype pick cutters and conventional pick cutters (Fig. 7(c)) was operated in Mine M303C where the Manto 3 layer and the conglomerate are mixed (Figs. 1 and 2). The operating time of the machine was set to 24 hours.

(a) Right cutting drum
(Prototype A + Conventional)

(b) Left cutting drum
(Prototype B + Conventional)

(c) Head assembly showing the left and right cutting drums

Fig. 7 AQM 150-H cutting head after the installation of conical pick cutters

4.2 Visual inspection of worn pick cutters

After the 24-hour excavation period, all pick cutters were removed from the cutting head and visually inspected for wear of and damage to the pick cutters. Manto tailing wastes mixed with moisture stuck to the cutting head (Fig. 8(a)) were cleaned off before removing the pick cutters (Figs. 8(b) and (c)). Some of the pick cutters were noticeably damaged and worn (Fig. 8(d)).

The collected worn cutters were visually inspected and their weight loss after field testing was measured, following Á lvarez *et al*. (2003). From visual inspection, the loss of tungsten carbide and the wear of pick cutter heads were more clearly observed in the conventional pick cutters compared with the two prototypes. Specifically, Prototype A cutters (with hardfacing deposits) were observed to be less worn than Prototype B cutters (without hardfacing deposits) (Figs. 9 and 10). Some severely worn cutter tips were observed for Prototype B cutters (Figs. 9(b) and 10(c)). However, all Prototype A cutters (apart from one) appeared to be in good condition without heavy

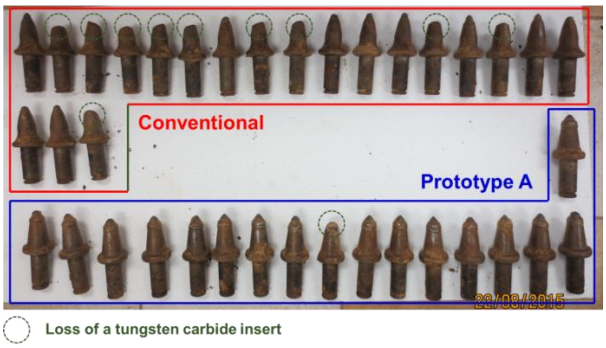
(a) Cutting head after removal of tailing wastes

(b) Left cutting drum

(c) Right cutting drum

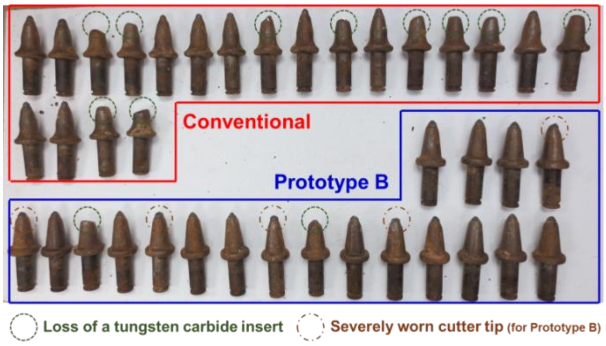
(d) Loss of tungsten carbide and excessive wear

Fig. 8 Roadheader cutting head after 24 hours of excavation



(a) Prototype A and conventional pick cutters recovered from the right cutting drum

Fig. 9 Visual inspection of conical pick cutters recovered after 24 hours of rock excavation



(b) Prototype B and conventional pick cutters recovered from the left cutting drum

Fig. 9 Continued

(a) Conventional pick cutters

(b) Prototype A (with hardfacing)

(c) Prototype B (without hardfacing)

Fig. 10 Close-up views of selected pick cutters after field testing

wear of pick cutter heads or loss of tungsten carbide inserts, even though the hardfacing deposits had started to become worn (Figs. 9(a) and 10(b)).

Table 5 summarizes the results of the visual inspection of pick cutters. The percentage of conventional pick cutters from which tungsten carbide inserts were detached is 50%, compared with 5.3% and 10.5% for the Prototype A and B cutters, respectively.

4.3 Measurement of weight loss after field testing

The weight loss of pick cutters was measured to quantitatively evaluate their wear and damage

Table 5 Results of a visual inspection of damage to conical pick cutters after field testing

Pick cutter type	Number of cutters with tungsten carbide inserts	Number of cutters without tungsten carbide inserts	Note
Conventional	20 (50.0%)	20 (50.0%)	Loss of many inserts and severe damage to the heads of cutters
Prototype A	18 (94.7%)	1 (5.3%)	Fine interfaces between inserts and cutter heads
Prototype B	17 (89.5%)	2 (10.5%)	Severely worn cutter heads for five cutters

after field testing. Weight loss was defined as the difference between cutter weights before and after field testing. The average weight loss of Prototype A cutters was minimal, 33 g, compared with that of the other cutters (Table 6). The average weight loss percentages of conventional cutters and Prototype B cutters were 2.9 times and 1.6 times greater than that of Prototype A cutters, respectively (Table 6 and Fig. 11).

The results of the visual inspection and weight loss measurements suggest that the hardfacing deposits applied to Prototype A cutters reduced the occurrence of excessive wear of the heads and prevented the tungsten carbide inserts from being detached and lost. Therefore, applying hardfacing deposits could be a highly effective way of increasing the life of a conical pick cutter by protecting its tungsten carbide insert, especially for mixed rock conditions.

Table 6 Weight loss of conical pick cutters after field testing

Pick cutter type	Average cutter weight before testing (g)	Average cutter weight after testing (g)	Average weight loss (g)	Average weight loss percentage (%)
Conventional	1,023.15	928.18	94.98 ± 33.40	9.28 ± 3.26
Prototype A	1,038.93	1,005.94	33.00 ± 29.37	3.17 ± 2.83
Prototype B	1,031.46	978.38	53.08 ± 28.92	5.14 ± 2.80

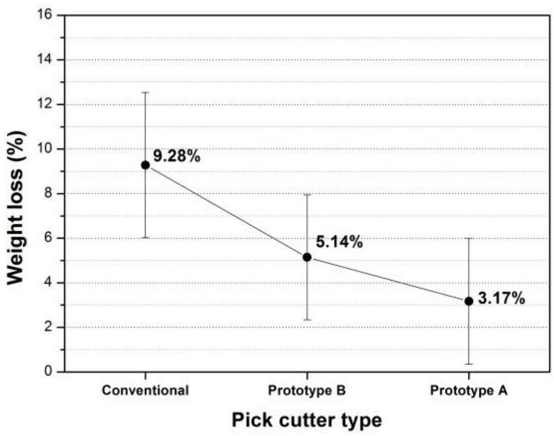
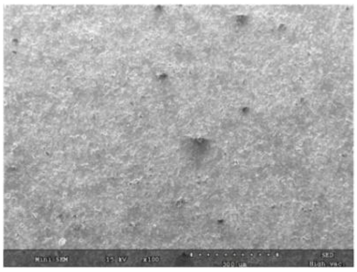


Fig. 11 Ranges and means of weight loss for the different types of conical pick cutter

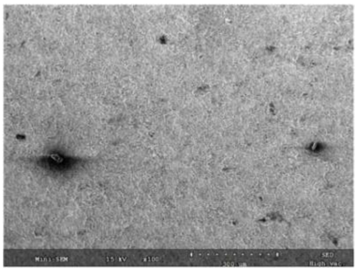
4.4 SEM analyses

Chatterjee and Pal (2003) and Gualco *et al*. (2016) carried out scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (XRD) analyses to evaluate the wear resistance of hardfacing alloys. Therefore, SEM was also conducted in the present study to investigate the presence of micro-cracks inside the conical pick cutters after field testing. Two kinds of specimens for SEM analyses were examined: tungsten carbide inserts and steel at the center of cutter heads. The specimens were sampled from fresh pick cutters and from the corresponding cutters after field testing for each cutter type (Fig. 12). SEM images were captured by an SNE-3000M system with a resolution of 1.0 nm (15 kV) and magnifications of ×100, ×300, and ×700.

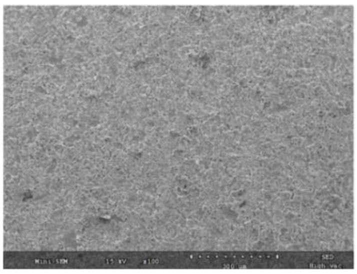
Fig. 12 Example of sampling for SEM analyses (used pick cutter)



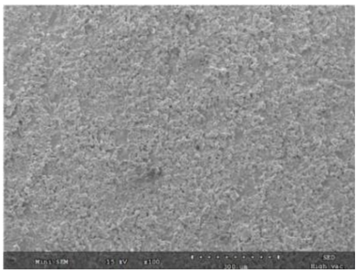
(a) Tungsten carbide (before field testing)



(b) Tungsten carbide (after field testing)

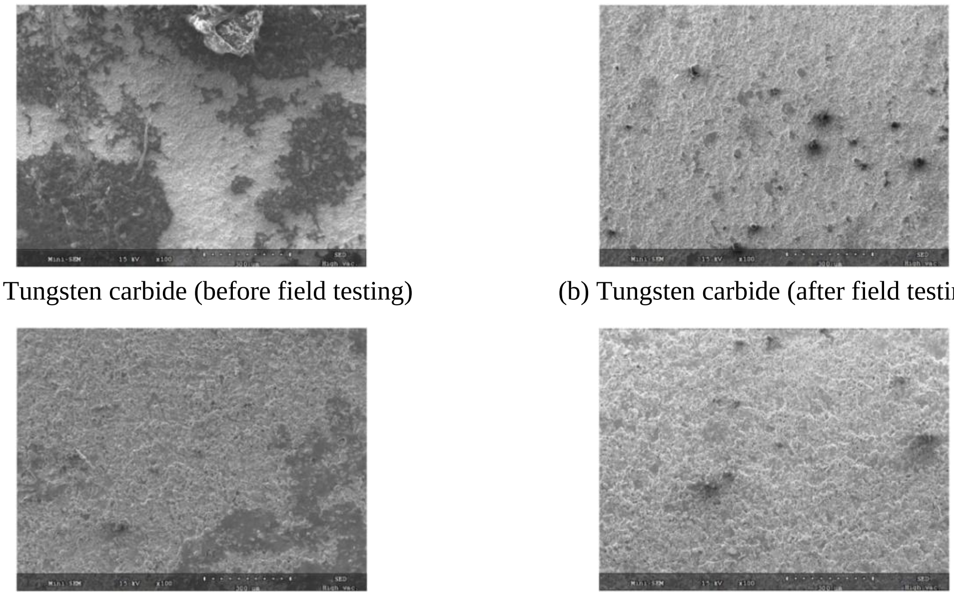


(c) Steel (before field testing)



(d) Steel (after field testing)

Fig. 13 SEM images of conventional conical pick cutters (magnification ×100)



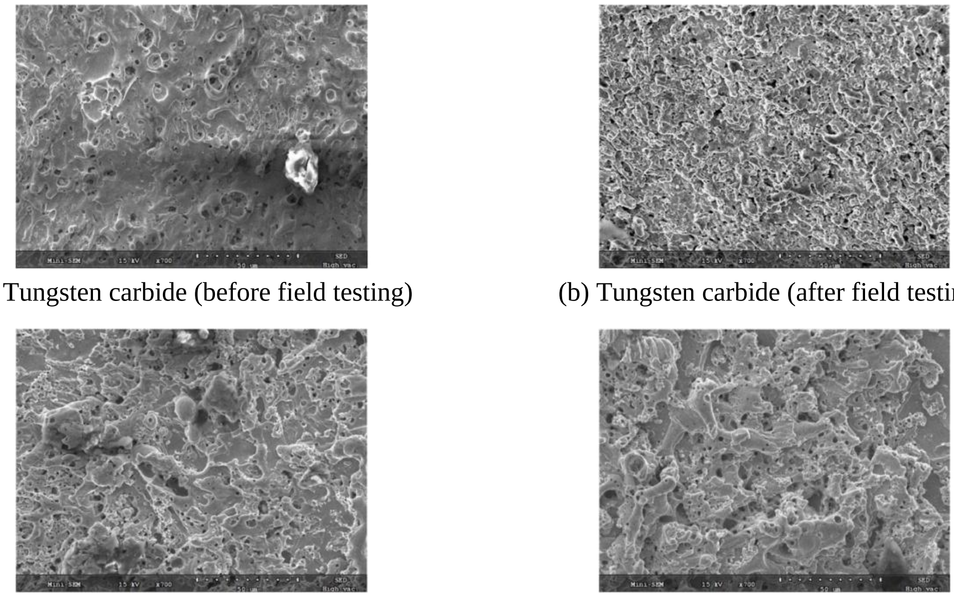
(a) Tungsten carbide (before field testing)

(b) Tungsten carbide (after field testing)

(c) Steel (before field testing)

(d) Steel (after field testing)

Fig. 14 SEM images of Prototype A conical pick cutters (magnification ×100)



(a) Tungsten carbide (before field testing)

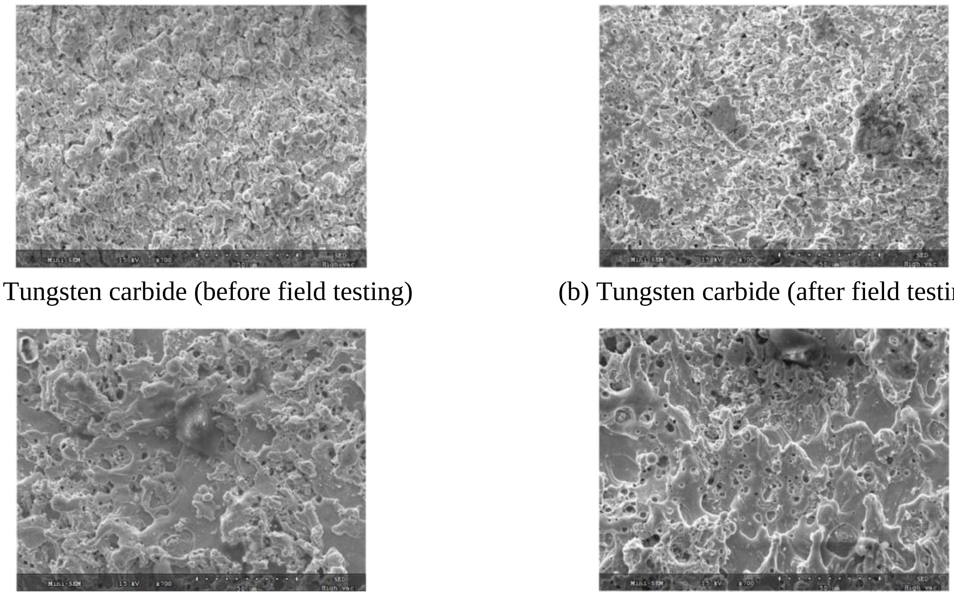
(b) Tungsten carbide (after field testing)

(c) Steel (before field testing)

(d) Steel (after field testing)

Fig. 15 SEM images of conventional conical pick cutters (magnification ×700)

Figs. 13 and 14 are examples of SEM images captured at a magnification of ×100 from conventional and Prototype A conical cutters, respectively. No observable micro-cracks were found in any SEM image, only internal voids and textures intrinsic to each material. In SEM



(a) Tungsten carbide (before field testing) (b) Tungsten carbide (after field testing)

(c) Steel (before field testing) (d) Steel (after field testing)

Fig. 16 SEM images of Prototype A conical pick cutters (magnification ×700)

images with a magnification of ×700, no micro-cracks were found in either conventional (Fig. 15) or Prototype A conical cutters (Fig. 16) or in Prototype B cutters made of the same materials as Prototype A (but without hardfacing deposits). This result suggests that the wear of and damage to a conical pick cutter does not result from internal micro-cracking but from the mechanical abrasion of tungsten carbide inserts as well as steel abrasion following the loss of the inserts. This pattern of wear and damage may be due to the high ductility intrinsic to the tungsten carbides and steels used in pick cutters.

SEM–EDX (SEM–energy dispersive X-ray spectrometer) analyses were also conducted to investigate the elemental compositions of tungsten carbide inserts and steels used for conventional and Prototype A pick cutters. Resolution and accelerating voltage were set to 4.0 nm (20 kV) and 15 kV, respectively, with a magnification of ×300. The same specimens were examined as used in the SEM analyses.

The SEM–EDX analyses reveal that the elemental compositions of steels from the conventional and Prototype A pick cutters were very close to each other, except for the contents of carbon and oxygen. The tungsten carbide compositions of the two types of pick cutter in terms of the main elements were similar to each other, but their contents were quite different. For example, the contents of tungsten (W), copper (Cu), and iron (Fe) in the Prototype A pick cutters were higher than those in the conventional pick cutters, whereas the conventional pick cutters were found to have much higher carbon (C) and Nickel (Ni) contents compared with the Prototype A pick cutters (Table 7). The percentages of cobalt in tungsten–cobalt composites were estimated to be 5.6% and 13.9% for the conventional and Prototype A pick cutters, respectively (see also Table 1). These values are within the expected range for a tungsten–cobalt composite (Acchar *et al*. 1999, Sandvik 2005). However, in the present study the geometry of the tungsten carbide inserts would have influenced their wear and loss more than did their material properties, as the conventional pick cutter was designed to have a more protruding tungsten carbide insert compared with the inserts of

Table 7 Elemental compositions of conventional and Prototype A pick cutters estimated using SEM–EDX

Elements (Average weight %)	Tungsten carbide		Head steel	
	Prototype A	Conventional	Prototype A	Conventional
C	25.1	44.1	21.5	14.7
O	16.1	18.2	12.8	15.0
P	0.5	0.8	0.3	-
Cr	-	-	0.4	-
Na	-	-	-	0.7
Mg	-	-	-	0.3
Al	-	0.3	-	0.5
Si	-	-	-	1.9
S	0.6	-	-	-
Fe	5.4	2.3	54.5	57.8
Co	3.2	0.5	-	-
Ni	0.6	5.9	-	-
Cu	23.6	13.5	7.6	7.2
Zn	2.9	6.1	2.0	2.0
Ag	2.3	-	-	-
W	19.8	8.4	0.9	-
Co/(W+Co)	13.9	5.6	-	-

the two prototype cutters (see Fig. 4). Nevertheless, further investigations of the effect of different element compositions of tungsten carbide inserts on their wear are needed, especially under conditions of highly abrasive and/or mixed rock conditions.

4.5 Three-dimensional X-ray CT scanning of pick cutters

X-ray computed tomography (CT) scanning was used to investigate the occurrence of macro- and micro-cracks in the pick cutters after field testing. X-ray CT scanning is a non-destructive method for obtaining a large number of consecutive sectional images of the internal micro-structure of specimens of interest (Kim *et al*. 2012c).

X-ray CT images were obtained for all pick cutters after field testing. The device used was an X-EYE CT System (SEC Corporation, Korea) equipped with a micro-focus X-ray tube capable of attaining high spatial resolutions of up to 6.18 μm^3. The voltage and current were set to 220 kV and 1000 μA, respectively. A CCD camera was used as a flat-panel detector to collect X-ray attenuation information after the radiation had passed through the specimen (Fig. 17). The detector measured 409.6 mm × 409.6 mm with a pixel pitch of 200 μm and a limited resolution of 2.5 lp/mm (line pairs per millimeter). The maximum wobbling allowance of the manipulator, which determines the scanning location of the rotating specimen, was 5 mm. This value lies within the range of correction ability during the reconstruction process (Kim *et al*. 2012c). Each image had a pixel size of 0.2643 mm × 0.2653 mm with 1024 × 1024 pixels.

Figs. 18, 19, and 20 show three-dimensional CT images obtained from X-ray CT scans of the

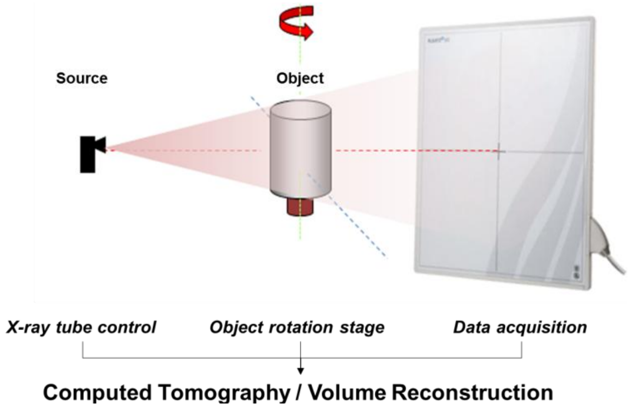


Fig. 17 Schematic diagram of the X-ray CT scanning set-up

conical pick cutters after field testing for conventional cutters, Prototype A cutters, and Prototype B cutters, respectively. The CT images revealed no macro- or micro-cracks in any of the pick cutters. This result validates the results of SEM analyses (Section 4.3), in which no micro-cracks were found in the pick cutters. Figs. 18(a) and 20(c) show CT images of pick cutters where tungsten carbide inserts had been lost, whereas the presence of worn tungsten carbide inserts at the tips of pick cutters can be seen in Figs. 18(c), 19(a), and 20(b).

The sizes of bounding boxes circumscribed onto cutter specimens were computed to quantitatively calculate cutter volumes from three-dimensional CT images (Fig. 21). The volume of a bounding box for a set of objects is a closed volume that completely contains the union of the objects in the set. From computations using bounding boxes, the average total volume of each type of pick cutter was calculated, and the results are summarized in Table 8. Even though the geometries of the three types of pick cutter were slightly different (see Fig. 4), the average total volumes of the two prototype cutters were over 9% greater than the average total volume of the conventional pick cutters. In particular, the difference between the average volumes of the two prototypes, which had the same geometric volumes except for the addition of hardfacing deposits on Prototype A, was approximately 2%, which is essentially the same as the difference between the weight loss percentages of these two prototype cutters (see Fig. 11).

Sintering using silver solder is commonly applied to attach and weld tungsten carbide inserts into the head of a conical pick cutter. Silver solder is very effective as it has high fluidity (before hardening) and high strength as well as ductility (after hardening). However, voids between a tungsten carbide insert and a steel head could be created because vapor is generated from heating silver solder in the process of sintering. Therefore, such voids were analyzed using CT images (Fig. 22 and Table 8).

Voids between tungsten carbide inserts and cutter heads were found in all pick cutters. However, the average void volumes of the two prototype cutters were much greater than the average void volume of the conventional pick cutters (Table 8). The welded part between a tungsten carbide insert and a cutter head is an important component for preventing an insert from being detached. Even though the presence of voids does not seem to influence the cutting performance of the pick cutters used in this study, particular attention needs to be paid to minimizing voids around a tungsten carbide insert in order to ensure its strong adhesion and high cutting performance, especially during the cutting of hard and/or mixed rock.

(a) Specimen No. C1 (b) Specimen No. C3 (c) Specimen No. C5

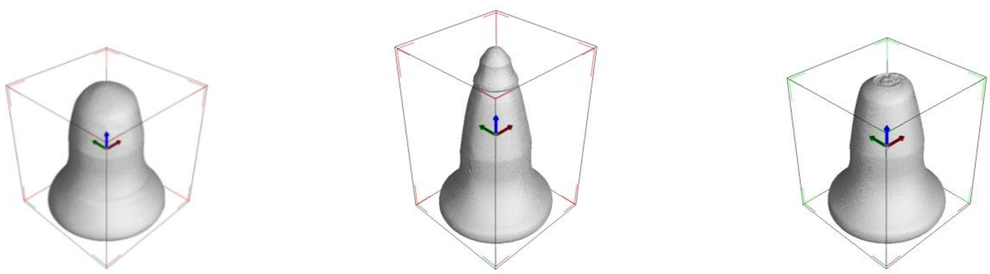
Fig. 18 Examples of three-dimensional CT images of conventional pick cutters

(a) Specimen No. A1 (b) Specimen No. A4 (c) Specimen No. A5

Fig. 19 Examples of three-dimensional CT images of Prototype A pick cutters

(a) Specimen No. B3 (b) Specimen No. B4 (c) Specimen No. B5

Fig. 20 Examples of three-dimensional CT images of Prototype B pick cutters

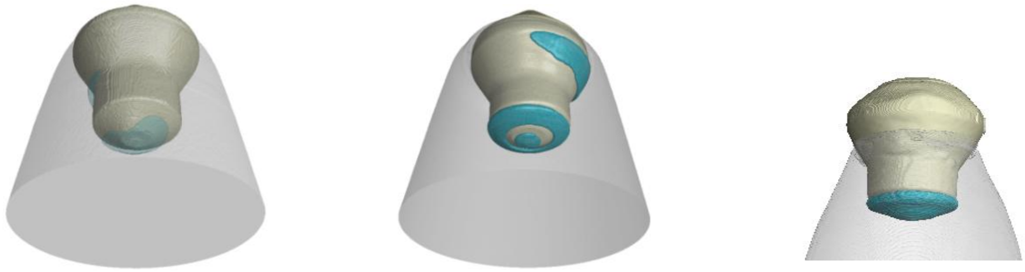


(a) Specimen No. C1 (b) Specimen No. C3 (c) Specimen No. C5

Fig. 21 Examples of bounding boxes used to calculate the volumes of pick cutters

Table 8 Average total and void volumes of the three types of pick cutter, as derived from X-ray CT analyses

Statistics	Total volume (mm^3)			Void volume (mm^3) beneath a tungsten carbide		
	Conventional	Prototype A	Prototype B	Conventional	Prototype A	Prototype B
Average	61,774	68,749	67,573	10	13	22
Percentage difference	-	+11.29%	+9.39%	-	+30.0%	+120.0%



(a) Specimen No. C3 (b) Specimen No. A5 (c) Specimen No. B3

Fig. 22 Voids around tungsten carbide inserts (blue color: voids; gold color: inserts)

5. Conclusions

Loss of tungsten carbide inserts and wear of pick cutter heads are likely to result in frequent cutter changes and thus low efficiency of mechanical excavators. Here, we made a wear-resistant pick cutter with hardfacing deposits applied to its head, and tested it in the Boleo Mine, Mexico, a mine where pick cutters are frequently damaged and changed because of mixed rock conditions at the mine face. Specimens of the hardfaced pick cutters were used on a roadheader and their performance was tested against conventional pick cutters under the same excavation conditions.

Visual inspection and weight loss measurements after 24 hours of excavation showed the improved cutters to have smaller loss of tungsten carbide inserts and the less wear of the cutter heads than the conventional conical pick cutters, which lost 50% of their tungsten carbide inserts and approximately 9% of their weight

SEM analyses and three-dimensional X-ray CT images showed that none of the pick cutters tested in the field contained macro- or micro-cracks either in the tungsten carbide inserts or in the cutter head steel. We infer that the wear of and damage to a conical pick cutter does not result from internal cracking but rather from the mechanical abrasion of cutter head steel following the wear and loss of tungsten carbide inserts. We conclude that the protection of tungsten carbide inserts is of primary importance to ensure the high cutting performance of a conical pick cutter. Therefore, applying hardfacing deposits may be an effective way of preventing the loss of tungsten carbide inserts and of reducing the excessive wear of cutter head steel.

X-ray CT scanning showed voids between tungsten carbide inserts and pick cutter heads for all pick cutters tested. We consider that such voids may be created by vapor in the process of sintering. These voids did not appear to influence the cutting performance of the pick cutters tested in this study. However, particular attention should be paid to minimizing the occurrence of voids between a tungsten carbide insert and the pick cutter to ensure its strong adhesion and high cutting performance, especially when excavating hard rocks.

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