Comparison of laboratory wear test results with the in-service performance of cutting edges of loader buckets

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Abstract

The in-service cutting edge of a mining loader bucket was investigated and its wear behavior compared with samples tested in the laboratory to assess how well the wear testing methods correlate with the in-service conditions. The examined in-service cutting edge of a bucket had been run in an underground mine with quarry gravel and it was made of wear resistant steel. The wear behavior of the cutting edge was simulated in the laboratory scale with several application oriented abrasive and impact-abrasive wear testing methods. In addition to the contact mode, high loads, large abrasive size, abrasive type, and the comminution of the abrasive formed the basis for the design of the laboratory experiments. The wear surfaces and cross-sections of the original cutting edge and the test samples were characterized, and the wear behaviors were compared with each other. Work hardening of the steels occurred in all cases, but the amount of plastic deformation and the depth of the wear scars varied.

Keywords: Wear testing; Abrasion; Impact wear; Steel; Mining

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1. INTRODUCTION

The simulation of in-service wear environments in laboratory-scale is challenging. In the planning of the test procedures, the effect of many variables, such as the contact mode, loading energy, abrasive properties, and the environment on the active wear mechanism and the resulting wear rate must be carefully taken into consideration. The interpretation of the laboratory test results is normally easier and the repeatability of the tests is better than in the complex and expensive in-service tests [1]. In larger wear parts and complex applications, the comparison of materials using field tests is very difficult, laborious, and expensive. On the other hand, the utilization of the field test results is usually quite straightforward and the tests easily reveal the possible problems in the design or selection of materials. Thus, to select the best possible testing approach for each case, it is important to have a good understanding of the relevance of the laboratory wear tests compared to the in-service performance of the materials in high stress wear conditions.

The wear conditions are very demanding in hoisting and hauling of rocks in mining, excavation, and construction. One example of the used wear parts is the cutting edge of a mining loader bucket. The cutting edges are welded or mechanically attached to the front of the bucket and replaced when the worn-out edge restricts the loading procedure. With proper material selection, it is possible to markedly improve the life time of the wear part that affects directly on the operating costs. The part must naturally resist high stress abrasive wear. Moreover, the selected material should have high strength and sufficient ductility to withstand dynamic loading events.
Several laboratory studies have been made for the material selection of bucket tips, teeth, and cutting edges of earth moving machines [2–6]. Some studies even compare the field tests of these kinds of wear parts with laboratory tests . However, the laboratory tests have usually been conducted as standardized rubber wheel abrasive tests with low contact pressure and fine abrasives. It was also noted that the wear environment produced by the rubber wheel tests was not similar to the real conditions and that the laboratory tests did not correlate well with the field tests results [2].

The properties of the selected abrasive have a marked effect on the abrasive wear testing. For example, the very hard but also highly crushable quartz may produce an embedded quartzite powder layer on steel surfaces during testing and thus affect the wear test results [7]. The measured abrasiveness and crushability values of the natural minerals may be a basis for incorrect assumptions about the wear rates due to the different contact conditions [8].

The material selection based on laboratory tests needs test methods, which simulate as well as possible the in-service conditions, such as contact conditions and real abrasives. Consequently, careful analysis of the relevance of the laboratory test methods is essential. In this study, the wear behavior of a cutting edge was simulated in the laboratory scale using several application oriented wear testing methods. The crushing pin-on-disc, the uniaxial crusher, the impeller-tumbler, and the high-speed slurry-pot with dry abrasive bed systems produce high stress abrasive or impact-abrasive conditions with large natural rock abrasives. Thus, they simulate the harsh conditions during loading and unloading of the loader bucket. The wear behavior of the in-service cutting edge was compared with the wear tested samples by analyzing the wear rates and by characterizing the wear surfaces and microstructures.

2. MATERIALS AND METHODS

The material used in the wear testing and the in-service application was an ultra-high-strength 500 HB grade wear resistant steel. In addition, a 400 HB grade steel was used as a reference material in the wear tests. The microstructure of both steels was martensitic with some retained austenite and untempered martensite. Table 1 lists the mechanical properties and the maximum nominal compositions of the steels given by the manufacturer. The typical carbon equivalent values are determined using CEV = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.

Table 1. *Nominal properties of the studied steels.*

	400 HB	**500 HB**
Microstructure	Martensitic	Martensitic
Rp0.2 [N/mm^2]	1000	1250
Rm [N/mm^2]	1250	1600
A [%]	10	8
Hardness [HBW]	360 - 440	450 - 540
Impact toughness -40°C [J]	30	30
C [wt%] max.	0.23	0.30
Si [wt%] max.	0.80	0.80
Mn [wt%] max.	1.70	1.7
Cr [wt%] max.	1.5	1.5
Ni [wt%] max.	1.0	1.0
Mo [wt%] max.	0.5	0.5
B [wt%] max.	0.005	0.005
CEV	0.57	0.66
Density [g/cm^3]	7.85	7.85

2.1. In-service history

The cutting edge of the CAT R 2900 G underground mining loader bucket had been run for 928 hours in an underground mine with quarry gravel, including granite, chromite, and barren rock [9]. The loader was used in normal operation in various tasks. The dimensions of the cutting edge had been determined before and after the test by ATOS 3D scanner at Lapland University of Applied Sciences. Figure 1 presents a schematic of the cutting edge. The thickness of the steel plate was originally 60 mm, the width 3.354 m, and the depth 1.1 m in the middle and 0.5 m in the sides [9]. The front of the cutting edge was beveled to a 25° angle. A test piece 3.9 mm wide and 17.5 mm deep was cut from the middle area of the tip of the cutting edge for failure analysis. The heavily oxidized surfaces were cleaned with USF 175 acidic detergent in an ultrasound cleaner in order to remove the corrosion products from the wear surfaces.

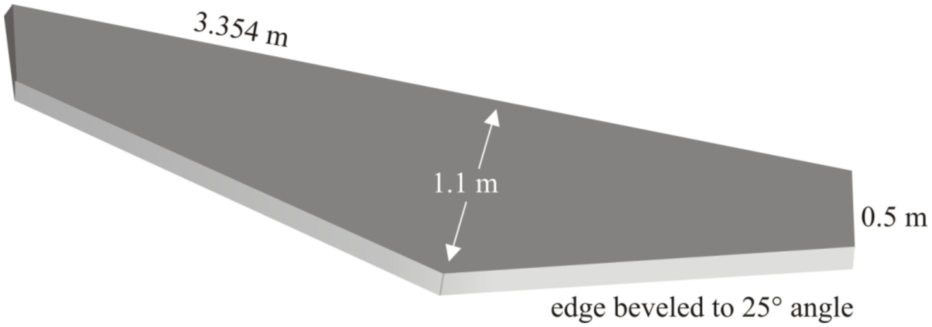


Figure 1. *Schematic of the cutting edge.*

2.2. Application oriented laboratory wear tests

Four wear testing devices built at Tampere Wear Center were used in the study: a crushing pin-on-disc, a uniaxial crusher, an impeller-tumbler, and a high-speed slurry-pot with dry abrasive bed (dry-pot). Figure 2 presents pictures of the devices that were designed to simulate the wear conditions in mining, mineral processing, and crushing with different wear mechanisms. A detailed description of the test methods has been published by Ratia et al. [10] and by Vuorinen et al. [11]. In this study, the test parameters were selected to simulate the varying conditions in a mining loader bucket. In all tests, the abrasive was highly abrasive granite rock from Sorila quarry in Finland.

In the crushing pin-on-disc tests, a sample pin with 1000 mm^2 wear area was pressed against a rotating granite gravel bed with a 240 N force. The loading was cyclic: after 5 seconds of compression, the gravel bed rotated freely for 2.5 seconds. Thus, in a 90 minute test the actual contact time was 60 minutes. The rotating speed of 28 rpm of the 160 mm diameter disc was adjusted so that the freely rotating pin landed always on the highest pile of the abrasive. The initial granite particle size was 2-10 mm, but the used 500 grams of gravel was severely comminuted during the tests. For this reason, it was changed every 30 minutes. This procedure is an in-house standard, which has been shown to produce high and stable wear rates [12]. S355 structural steel with initial hardness of 216 HV was selected for the disc material. With such a softer disc material, granite adheres to the disc and produces more sliding wear compared with harder disc materials [12]. Before the actual test cycle, a 15 minute run-in was completed to produce steady state wear in the test.

The uniaxial crusher utilized similar pin samples as the crushing pin-on-disc device. The pin crushed the 4-6.3 mm granite gravel against a tool steel counterpart in a rubber cup with a 53 kN force. After each compression, the cup was emptied and then refilled with fresh gravel. In total, 500 cycles were made with samples weighted after every 100 compressions. The compression time in each cycle was on average 1.8 seconds. Thus, the total contact time in 500 compressions was about 15 minutes.

In addition to separate tests with the crushing pin-on-disc and the uniaxial crusher, a combination test was used. In these tests, the samples were first compressed 500 times with the uniaxial crusher and then tested with the crushing pin-on-disc for 30 minutes.

In the impeller-tumbler device, the 75x25x10 mm size samples were used as impellers. The samples were attached to a 60 degree angle and then rotated at 700 rpm in the gravel-filled tumbler rotating in the same direction at a lower speed of 30 rpm. The actual wear area of the samples was 1200 mm^2. The granite was sieved to a size distribution of 8-10 mm, but the test comminuted the granite gravel efficiently. Therefore, the abrasive batch of 900 grams of granite was replaced every 15 minutes. The total test time was 360 minutes and therefore only one test for both materials was made, while three tests were made with the other methods.

The high-speed slurry-pot was modified for an abrasive wear tester (dry-pot) by filling the pot with 9 kg of dry 8-10 mm gravel. To simulate the filling of the loader bucket, two 60x40x6 mm samples were positioned at a 45° angle, as seen in Figure 2d. The actual wear area of the samples was 2540 mm^2. The rotation speed was 500 rpm, which corresponds to 5 m/s in the outer edge of the samples. The gravel and the sample position were changed after 30 minutes in the tests with a total duration of 60 minutes.

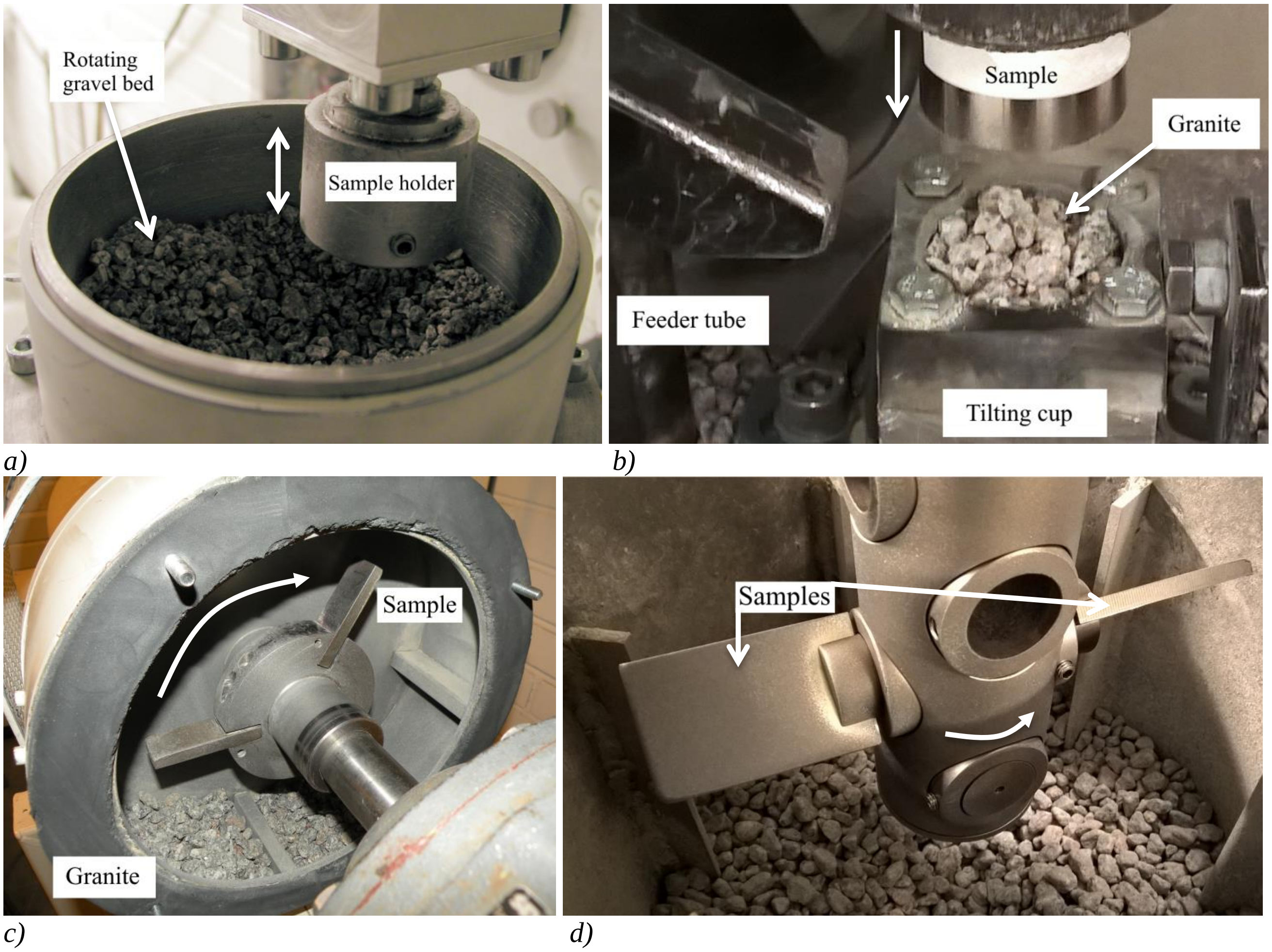


Figure 2. *Pictures of the test chambers of the wear testing devices with samples: a) crushing pin-on-disc, b) uniaxial crusher, c) impeller-tumbler, and d) dry-pot.*

2.3. Characterization

The wear surfaces were characterized using Philips XL30 scanning electron microscope (SEM), Alicona InfiniteFocus G5 optical 3D measurement system, and Leica MZ 7.5 zoom stereo microscope. The microstructures of the sample cross-sections were studied with Nikon Eclipse MA100 optical microscope. The Vickers hardness values of the wear test samples were measured with Struers Duramin-A300. For microhardness measurements, Matsuzawa microhardness tester was used.

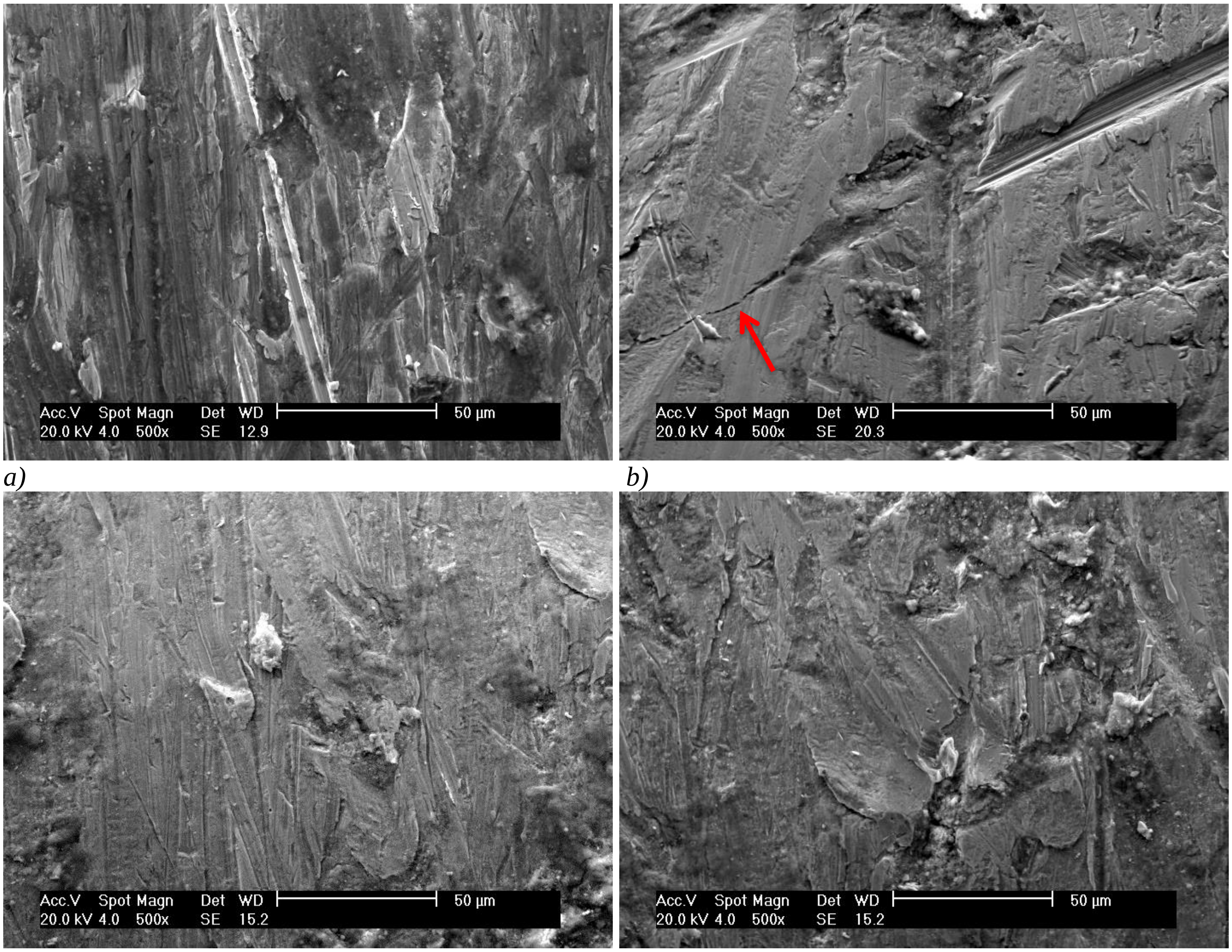
3. RESULTS

3.1. In-service cutting edge of underground mining loader bucket

The underground mining loader was used in normal operation in the Kemi mine. During 928 hours of operation, the cutting edge had lost 27.1 percent of its weight equivalent to 335 kg [9]. In the demanding conditions, the material loss had been high both in the front and on both sides. The original thickness of the steel plate was 60 mm, but in the remaining part the material thickness varied from 3 mm in the edge to 49 mm in the middle [9]. The wear rate had been highest on the underside of the bucket. The size of the handled material in mining conditions can be anything from slurry or sand to one meter wide blocks. Moreover, the loader can be used to clean or plow the bedrock in the mining tunnels.

The wear surfaces of the cutting edge were characterized by both optical and scanning electron microscopy. Figure 3 presents scanning electron micrographs of the wear surfaces taken from different parts of the sample. All surfaces showed marks of high-stress abrasion, but the top surface exhibited most clear signs of micro cutting. Both micro cutting and micro ploughing were identified on all surfaces as mechanisms of abrasive wear, with micro cutting being dominant. The tip and the underside surface were particularly heavily deformed. Figure 3c shows some surface cracks formed by surface fatigue, which may also act as starting points for delamination. Moreover, a lot of rock had embedded in the tip, completely covering the surface in some areas.

The wear surfaces were strongly work hardened, the depth of the work hardened layer varying from 150 to 300 micrometers on the underside. Figure 4 presents a white layer in the underside surface cross-section. These white layers were from a few micrometers up to 130 micrometers thick and in some cases over four millimeters wide. The microhardness of the white layers was up to 700 HV0.05. On the top surface, the depth of the hardened layer was up to 200 µm with microhardness generally below 600 HV0.05.



a) *b)*

c) *d)*

Figure 3. *Scanning electron microscope images of the cutting edge wear surfaces a) top part, b) tip on the underside, and c), d) underside. The arrow indicates a crack.*

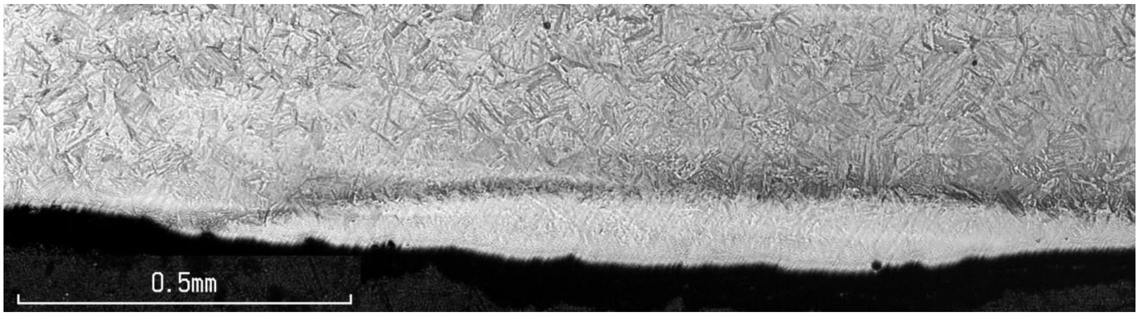


Figure 4. *Optical micrograph of the underside cross-section of the cutting edge showing a white layer.*

3.2. Application oriented wear tests

The crushing pin-on-disc (CPoD), the uniaxial crusher (UC), their combination (UC + CPoD), the impeller-tumbler, and the high-speed slurry-pot with dry abrasive bed test systems were utilized to simulate the field conditions. Figure 5 presents the wear test results as mass loss in proportion to the initial wear area for 500 HB steel samples. The wear rates were highest in the dry-pot and crushing pin-on-disc tests. However, during the tests the rock comminutes and the wear rate starts to decrease in the end of the test cycle before the gravel is renewed. This effect is seen as slight cyclic variations in the crushing pin-on-disc test results. As a general trend, the wear rate also decreased during the CPoD tests, as shown by the increasing deviation of the data points from the straight line formed by the dry-pot results in Figure 5. The wear rate in the impeller-tumbler tests was clearly the lowest in this comparison. However, compared to the other methods, the contact mechanism in the impeller-tumbler is more impacting than abrasive, which at least partly explains the different results.

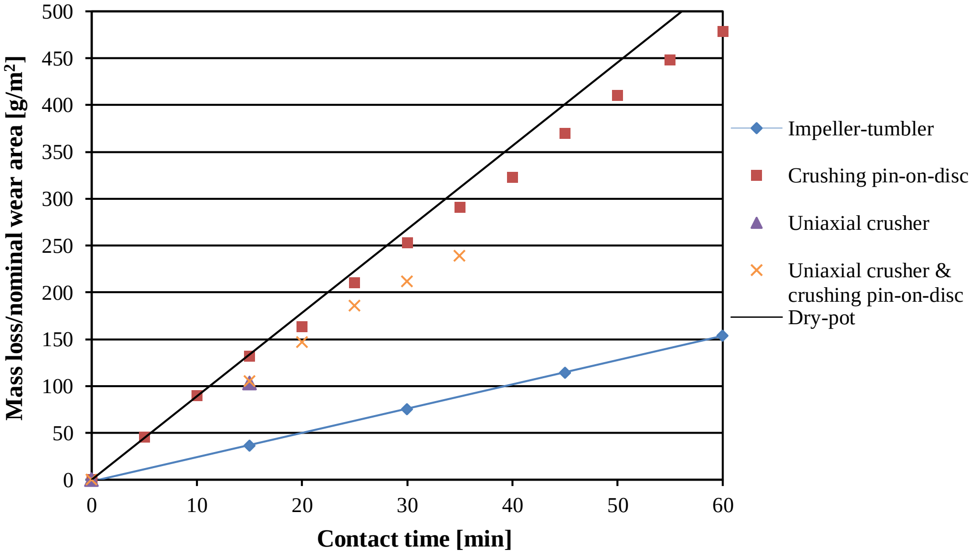
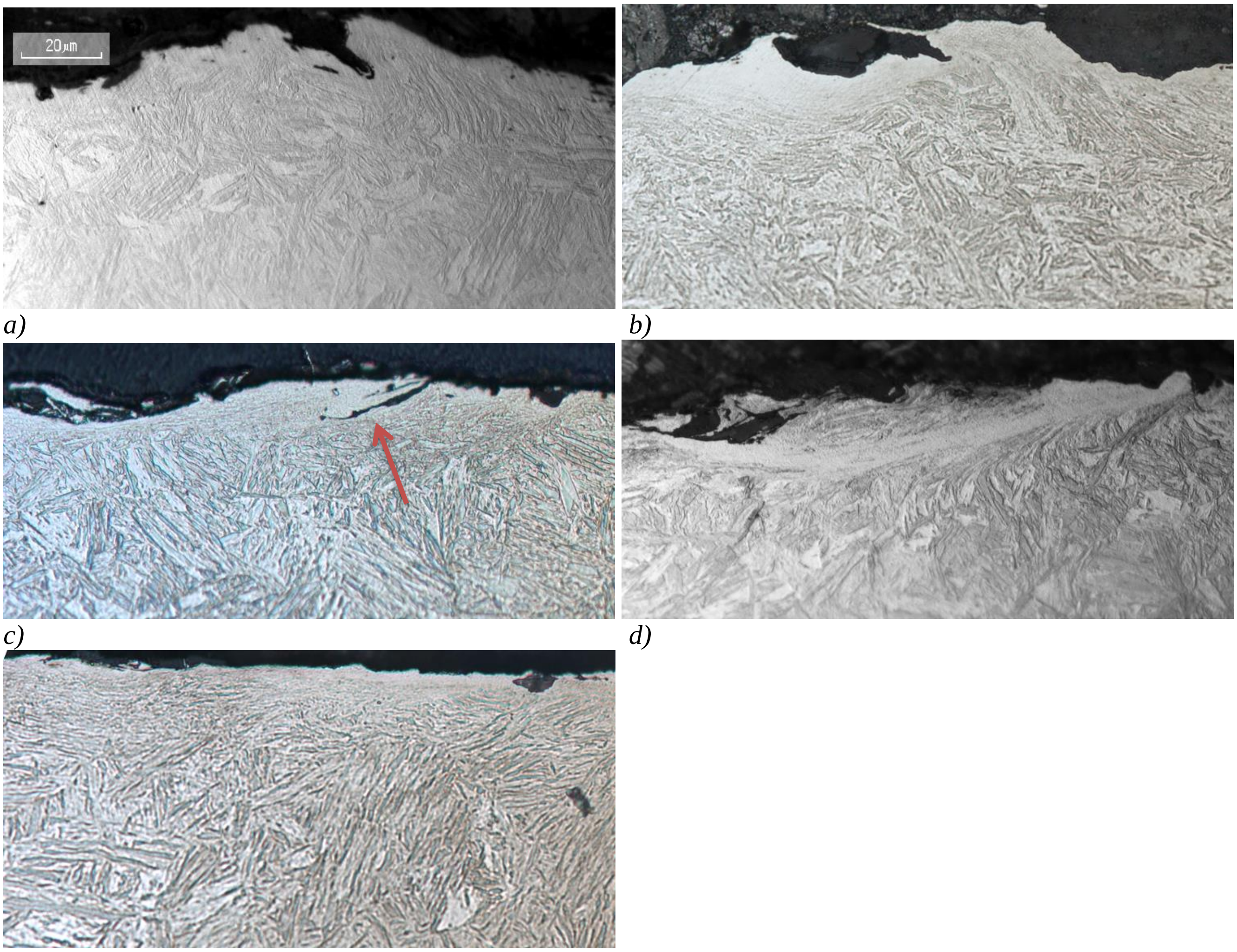


Figure 5. *Cumulative wear rates of the 500 HB steel in laboratory wear tests as a function of contact time.*

In the combined UC + CPoD tests, the mass loss in the crushing pin-on-disc test was 70% higher during the first 10 minutes compared to end of the test. This effect can be explained by the removal of the embedded rock layers and the white layers seen in the optical micrograph in Figure 6b. Figure 6c shows one of the several initial delamination points that were observed in the cross-sections of the combined UC + CPoD test samples. White layers were also formed in the tips of the dry-pot samples of both steels, but not on the crushing pin-on-disc surfaces. In the impeller-tumbler sample cross-sections, such as in Figure 6d, adiabatic shear bands similar to the case of single impacts were observed [13].



a) b) c) d) e)

Figure 6. *Optical micrographs of the wear surface cross-sections of the 500 HB grade steel samples tested with a) crushing pin-on-disc, b) uniaxial crusher, c) combined uniaxial crusher and crushing pin-on-disc, d) impeller-tumbler, and e) dry-pot. The arrow indicates delamination.*

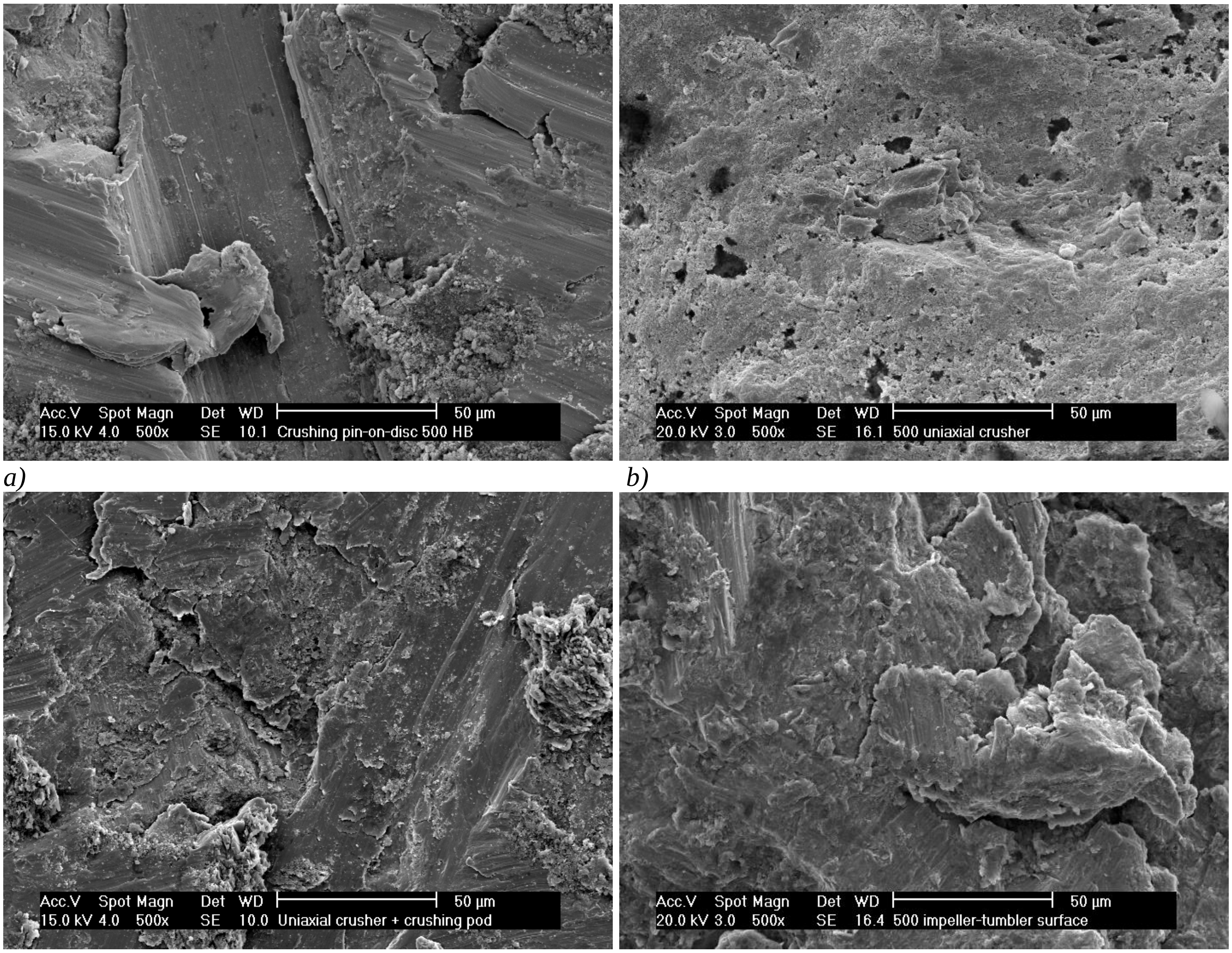
All wear surfaces were plastically deformed, work-hardened, and contained embedded rock. Figure 7, however, illustrates that also distinct differences exist between the wear surfaces produced by the different test methods. The crushing pin-on-disc wear surface resembles quite well the wear surfaces of the cutting edge. The surface is deformed with long scratches and contains occasional embedded crushed granite and marks of delamination. However, the direction of the scratches on the CPoD surfaces is random, because the pin can rotate freely during the test. Cutting was more prevalent in the 500 HB steel compared to the 400HB steel (Figure 8a).

In the uniaxial crusher, the gravel is always fresh with sharp edges. The used high compression forces deform the surface intensely and produce large dents and embed granite into the surface. When the surfaces were studied with a stereo microscope, they were found quite similar in appearance as the tip of the cutting edge. The wear scars were up to 70 µm deep, and the crushing of rock also caused occasional micro cutting of the wear surface.

One limitation of the crushing pin-on-disc method is that the applicable forces are quite low. The highest force that the system can produce is 500 N, but already then the rocks tend to ricochet under the pin sample. The uniaxial crusher can produce a significantly higher normal force of 53 kN, which deforms the surface of the steel samples much more, but the amount of cutting is very low. Combining of these two methods, however, is easy as the same samples fit to both systems. Thus, cyclic operation, high compressive forces, and sliding abrasive conditions were combined by testing the samples first with the uniaxial crusher followed by a crushing pin-on-disc test. Figure 7c shows an example of the increased propensity of the wear surface to delamination compared to the normal crushing pin-on-disc test.

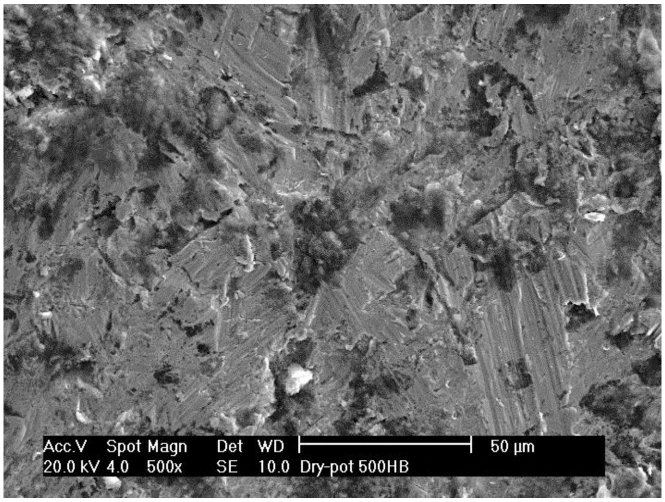
In the impact-abrasive conditions created by the impeller-tumbler, the wear surfaces were highly deformed, as seen for example in Figure 7d. In these tests the amount of sliding was much lower than in the crushing pin-on-disc tests or in the in-service conditions. The edges of the samples were rounded, because the gravel rotates freely in the tumbler and tends to cause chipping of the initially angular edges. Moreover, the wear rate in the tip area was visibly higher than in the areas closer to the sample holder, because the higher radial speed of the sample tip causes a gradient in the contact conditions. The cross-sections of the impeller-tumbler wear surfaces showed only very thin occasional white layers. The impact dents were up to 45 µm deep, but the variation in the depth of individual dents was high.

The dry-pot tests produced highly deformed wear surfaces with shorter scratches than the crushing pin-on-disc method (Figures 7e and 8b). The rocks are able to rotate freely in the test pot, and therefore both rolling and sliding abrasion are included similar to the in-service conditions. Of these studied wear surfaces, the one in Figure 7e resembles quite much the wear surface of the underside of the cutting edge shown in Figures 3c and 3d.



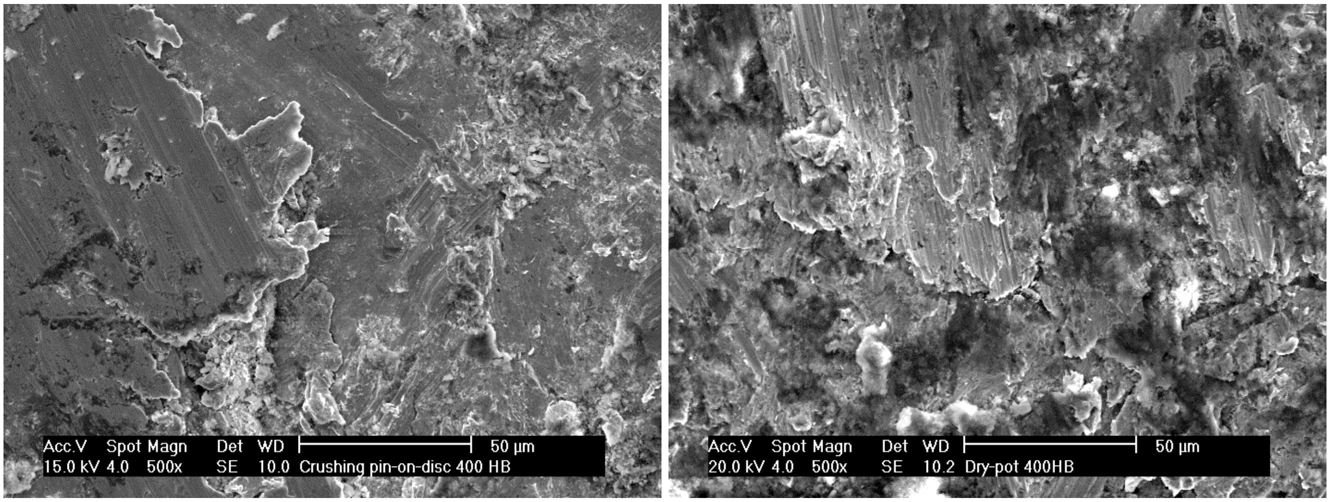
a) *b)*

c) *d)*



e)

Figure 7. *Scanning electron microscope images of the wear surfaces of the 500 HB grade steel samples tested with a) crushing pin-on-disc, b) uniaxial crusher, c) combined uniaxial crusher and crushing pin-on-disc, d) impeller-tumbler, and e) dry-pot.*



a) *b)*

Figure 8. *Scanning electron microscope images of the wear surfaces of the 400 HB grade steel samples tested with a) crushing pin-on-disc, and b) dry-pot.*

3.3. Comparison of the in-service sample with laboratory test samples

The underside of the cutting edge is in contact with gravel for a relatively short period of time during loading and unloading of the bucket. However, it is challenging to estimate the actual contact time of the cutting edge during operation, as it depends for example on the operator and the distances between the loader and the dumper. In order to obtain at least a rough estimate for the wear rate of the cutting edge for comparison with the laboratory test results, the total mass loss was spread over the average area of the cutting edge underside, because most of the material loss had concentrated there [9]. The contact time was selected as 21.5% of the total operation time, which is a typical loading time when the loader is close to the loading chute [14]. The shorter the real contact time, the higher is the wear rate. Figure 9, which displays the wear rates (mm/h) for all tests and conditions, shows that the estimated wear rate during the in-service operation is higher than in the laboratory tests. Of these tests, the dry-pot system produced the highest wear rates, which are also quite close to the estimated wear rate of the studied edge of the loading bucket.

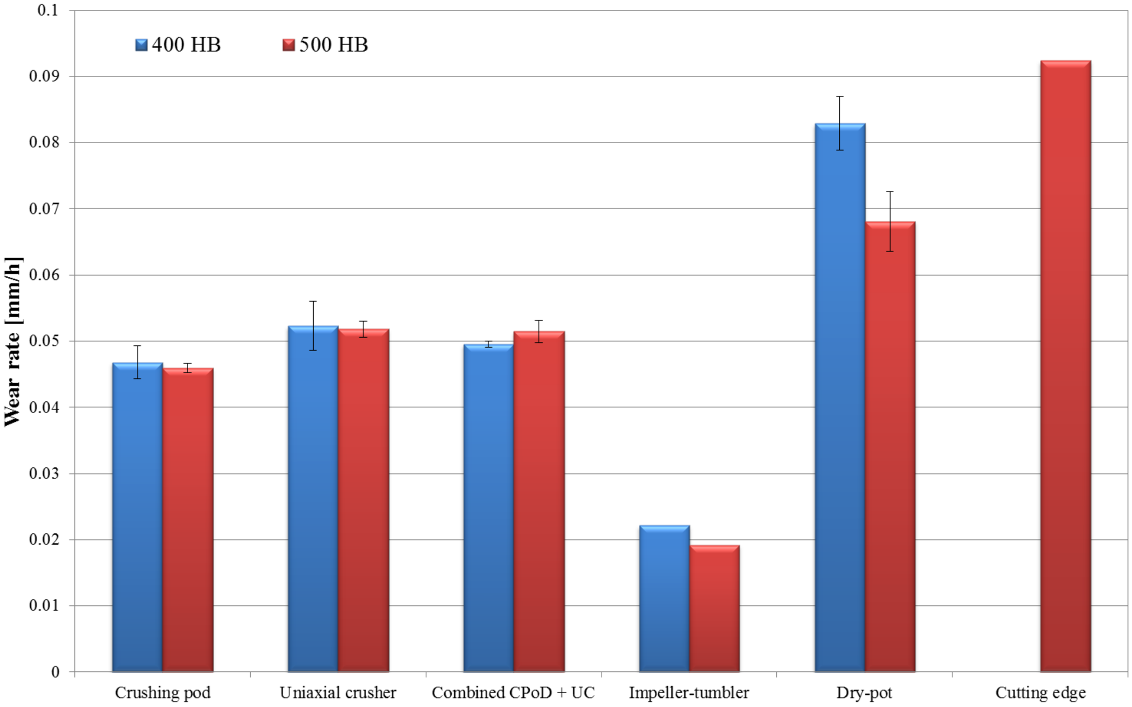


Figure 9. *Wear rates (mm/h) in the in-service operation of the cutting edge underside and in the laboratory tests with error bars presenting the standard deviation.*

4. DISCUSSION

The five different laboratory wear tests were selected with assumptions that the crushing pin-on-disc and dry-pot tests simulate the loading of a bucket, the uniaxial crusher portrays the heavy loads at the tip of the bucket, and the impeller-tumbler reproduces best the impacts during loading and unloading. These methods produce high stress abrasive or impact abrasive conditions with relatively large abrasive size. The used normal forces and the amount of sliding and rolling abrasion vary in each method, and thus they complement each other. However, it is quite challenging to assess the real relevance of these laboratory tests for the evaluation of the in-service performance of the cutting edges of mining loader buckets.

Work hardening of the steel occurred both in the field conditions and in the laboratory tests, but the amount of sliding abrasion and plastic deformation varied in each case. In the impeller-tumbler test impact wear dominates, and therefore it is not a very suitable method for simulating wear in this kind of application. The crushing pin-on-disc produced quite high relative wear rates and wear surfaces that were comparable to the cutting edge of the loader bucket. Based on the cross-sections, the wear surfaces in the crushing pin-on-disc tests resembled the top surface of the cutting edge, but the thick white layers found on the underside of the in-service sample were not detected. The forces that are used in the uniaxial crushing tests are closer to real applications, but the amount of cutting is clearly lower. Consequently, the hard white layers were thickest in the uniaxial crusher samples, which may momentarily improve the abrasion wear resistance of the steel against rocks. However, when a certain critical load is reached, the layers may start to delaminate [15]. This was the case especially when the UC and CPoD tests were combined. The white layers formed during the uniaxial crushing started to delaminate during the crushing pin-on-disc test. The wear rate of the 500 HB steel during the crushing pin-on-disc test cycle was slightly higher than that of the 400 HB steel. Hence, the harder white layers in the 500 HB steel laminated easier than the white layers in the 400 HB steel.

The white layers in the subsurface region of the in-service sample were much thicker than those observed in the laboratory tests. Xu et al. [6] concluded that the effect of white layers in the wear performance of digger teeth is negligible. They produced the white layers artificially before laboratory wear tests and noticed that they only slightly reduced the wear rates. However, the effects of surface hardening and the formation of tribological layers on the wear performance of steels should not be disregarded. The loading conditions have a marked effect on the material properties and also on the behavior of the surface in wear environments [16, 17].

The abrasive particle shape has a significant effect on the abrasive wear of steels. For example Stachowiak & Stachowiak [18] found that angular particles produced more cutting and sharp notches compared to round particles. Moreover, they stated that particle toughness and possible embedment in the steel affect the wear rates. In the mine, the loaded gravel is always sharp and the abrasive type and size vary markedly, from millimeter scale to meters. In this study, the selected abrasive was very close to real conditions. The hard granite gravel was always sharp in the uniaxial crushing, because the gravel was changed after every crushing cycle. In the crushing pin-on-disc method, the abrasive particles comminute but still stay quite sharp in the process. Blunting of the abrasives is highest with the impeller-tumbler and the dry-pot methods, where the freely moving abrasives tend to become rounded. For this reason, in these tests the abrasive was changed regularly.

In the mining conditions the rock always contains some amount of water, which may even be acidic. The water tends to lower the strength of the rock, but acidic conditions may increase the wear rates of the steel [19]. The rock material used in this study was granite, which is the most common rock type in the Finnish bedrock. The rock was dried at ambient room temperature to stabilize the test conditions. Consequently, possible tribocorrosion mechanisms were not included in this study, but with this kind of high wear rates it can be assumed that abrasion is too dominant for corrosion to have a marked effect on the results.

Dommarco et al. [2] stated that the relative wear rates of field tested bucket tips made from austempered ductile iron were at least four times higher than in the standard laboratory rubber-wheel tests. Moreover, they did not take into account the contact time during the bucket operation that still increases the difference. Thus, the wear conditions in that case were much more severe in the field compared with the laboratory tests, which was also visible in the comparison of the wear surfaces [2]. In the present study, the estimated wear rate (mm/h) in the operating conditions was 26 % higher than in the high stress dry-pot laboratory wear tests with large quarried granite particles. That is a quite reasonable result. All things considered, the test systems used in this study, especially the dry-pot, are much closer to the in-service application than the rubber-wheel test considering both the contact mechanisms and in the type and size of the abrasives.

It is always possible to improve non-standardized in-house built laboratory test equipment and associated test practices to better correspond to the in-service conditions. In this study, for example, adjustments with this aim were made by selecting granite as an abrasive, a long testing time for the impeller-tumbler tests, and the structural steel disc to be used as a counterpart in the crushing pin-on-disc tests. Moreover, the dry-pot testing enabled selecting the speed and angle of contact between the abrasives and specimens. The dry-pot system simulated quite well the loading of the bucket, where the steel blade slides into the pile of rock.

5. CONCLUSIONS

Several application oriented abrasive and impact-abrasive wear testing methods were used to simulate the wear behavior of the cutting edge of an underground mining loader bucket. Moreover, the relevance of laboratory testing in the evaluation of the in-service performance of cutting edges was assessed.

The work hardening behavior of the studied steels could be simulated with all testing methods used in this work. The hardened layers, however, appear to be thinner than in the in-service conditions due to the lower applied forces. The dry-pot wear testing method with an abrasive gravel bed produced similar wear rates and wear surfaces as the in-service operation. The abrasive type and size and the contact mechanisms were also quite similar when compared to the in-service conditions. In the crushing pin-on-disc tests the wear type was also similar but the forces much lower than in the in-service conditions. In the uniaxial crushing tests, the rock embedded in the sample in the similar manner as in the tip of the cutting edge due to the high compression forces. In the impeller-tumbler tests, the impact effect is dominant and wear concentrates on the tip and the edges of the sample. The results of this work indicate that proper simulation of the in-service conditions demands constant development of the test methods and careful evaluation of the obtained results.

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