

# **Erosive-abrasive wear behavior of carbide free bainitic and boron steels compared in simulated field conditions**

*E. Vuorinen<sup>1\*</sup>, V. Heino<sup>2</sup>, N. Ojala<sup>2\*</sup>, O. Haiko<sup>3</sup> and A. Hedayati<sup>1</sup>*

<sup>1</sup>Luleå University of Technology, Department of Engineering Sciences and Mathematics, 97187 Luleå, Sweden

<sup>2</sup>Tampere University of Technology, Department of Materials Science, Tampere Wear Center, P.O.Box 589, 33101 Tampere, Finland

<sup>3</sup>University of Oulu, Faculty of Technology, Materials Engineering and Production Technology, P.O.Box 4200, 90014 Oulu, Finland

## **Abstract**

The wear resistance of carbide free bainitic (CFB) microstructures have recently shown to be excellent in sliding, sliding-rolling and erosive-abrasive wear. Boron steels are often an economically favorable alternative for similar applications. In this study, the erosive-abrasive wear performance of the CFB and boron steels with different heat treatments was studied in mining related conditions. The aim was to compare these steels and to study the microstructural features affecting wear rates. The mining related condition was simulated with an application oriented wear test method utilizing dry abrasive bed of 8-10 mm granite particles. Different wear mechanisms were found; in boron steels, micro-cutting and micro-ploughing were dominating mechanisms, while in the CFB steels, also impact craters with thin platelets were observed. Moreover, the CFB steels had better wear performance, which can be explained by the different microstructure. The CFB steels had fine ferritic-austenitic microstructure, whereas in boron steels microstructure was martensitic. The level of retained austenite was quite high in the CFB steels and that was one of the factors improving the wear performance of these steels. The hardness gradients with orientation of the deformation zone on the wear surfaces were one of the main affecting factors as well. Smoother work hardened hardness profiles were considered beneficial in these erosive-abrasive wear conditions.

## **Keywords**

Steel, carbide free bainitic, erosive wear, abrasive wear, microstructure, field test

\* E-mail: [esa.vuorinen@ltu.se](mailto:esa.vuorinen@ltu.se), Phone: +46 920 493449, Fax: +46 920-491084

\* E-mail: [niko.ojala@tut.fi](mailto:niko.ojala@tut.fi), Phone: +358 50 317 4516

## 1. INTRODUCTION

The wear resistance of carbide free bainitic (CFB) steels is based on their very fine-grained microstructure consisting of bainitic ferrite mixed with retained austenite produced by austempering. More traditional boron steels have fine-grained martensitic microstructures subjected to different degrees of tempering. The structure of CFB steels combines high initial surface hardness with good work hardening capability. The isothermal transformation during austempering at low temperature range (200-300 °C) creates two-phase structure of bainitic ferrite and austenite enriched with carbon. The addition of silicon is utilized to prevent the formation of carbide precipitates, and the high carbon content lowers the temperature for bainite reaction and stabilizes the retained austenite [1]. Despite the carbide-free structure of the bainitic ferrite laths surrounded by films of retained austenite, high hardness and strength levels can be achieved due to the very thin platelets of the bainitic ferrite, reaching to the nanoscale [2,3]. The room temperature stable austenite transforms into martensite by mechanical wear, which together with refined surface structure leads to notable work hardening [4–6]. This mechanism has also shown to contribute to the excellent wear resistance of CFB steels in sliding [4,5,7,8], sliding-rolling [9–13] and erosive-abrasive wear [14–16].

Boron steels often offer an economical alternative for many applications subjected to wear due to relatively cheap costs and the easiness by which the quenched and tempered boron steels can be processed. Boron steels are low alloyed steels with carbon contents between 0.15 and 0.35 wt%, with additions of B (<0.0005%). Boron is added to improve the hardenability of steels, and often more expensive alloying elements can be replaced by boron for equivalent hardenability. Thus, good strength, hardness and also adequate toughness and weldability properties can be achieved with relatively low carbon content [17]. Quenched boron steels are usually tempered for better ductility and toughness. They are used in different agriculture (harrow discs, knives), railway and mining applications (shovels, spades) for example. Abrasion resistance [18–20] and rolling sliding resistance [21,22] of boron steels have been investigated by laboratory tests but also in the field [20]. Based on this background it is of great interest to compare the recently reported excellent wear resistance of CFB steels [4,5,7-16] with the wear resistance of conventional boron steels subjected to different forms of wear.

In this study the erosive-abrasive wear resistance of CFB and boron steels with different heat treatments were compared and the effect of microstructure on wear was investigated. An application oriented dry-pot laboratory test method with 8-10 mm granite gravel was used to produce erosive-abrasive wear environment that simulates the wear mechanisms and the wear surface deformations observed in mining equipment used in handling of iron ore [14]. In addition, the results were compared with the results from the previous work where the wear performance was evaluated also in a field conditions.

## 2. MATERIALS AND METHODS

Two steels, both with two different heat treatments, were tested in this study; a conventional boron steel and a high carbon steel. The boron steel was tested with two different heat treatment condition: austenitized at 900 °C and then quenched in water (BQ), and the other following the quenching tempered for two hours at 200 °C (BQT). Low-temperature tempering was applied to achieve increased toughness without significant loss of hardness. The other steel was also tested with two heat treatments for acquiring carbide free bainitic (CFB) microstructures: Austenitization was performed at 950 °C and followed by austempering at 270 or 300 °C (CFB270 and CFB300 respectively) in salt bath. In discussion part, the current results will be also compared to an industrial reference steel, i.e. a conventional low hardness quenched and tempered (QT) steel [14]. Table

1 presents the chemical compositions of the steels with their surface hardness and Charpy-V impact toughness values. The chemical compositions of these steels were determined by optical emission spectroscopy (OES). Microstructure for the boron steels was tempered lath martensite and the CFB steels showed microstructure consisting of ferritic laths surrounded by retained austenite.

**Table 1:** Test materials and their properties.

Material	BQ	BQT	CFB270	CFB300	QT
Hardness [HV <sub>1</sub> ]	522 ± 7	514 ± 5	601 ± 8	548 ± 11	310 ± 10
KV [J]	39 ± 4	54 ± 2	16 ± 2	19 ± 2	97 ± 4
C [%]	0.26		1.0		0.35
Si [%]	0.24		2.5		0.31
Mn [%]	1.12		0.75		0.72
Cr [%]	0.42		1.0		1.35
Ni [%]	0.14		0.12		1.36
Mo [%]	0.030		0.01		0.18
Cu [%]	0.22		0.17		
Ti [%]	0.047		0.008		
B [%]	0.005 (max)				

The erosive-abrasive wear tests were conducted in Tampere Wear Center at Tampere University of Technology. A high speed slurry-pot erosion wear tester [23] was used with dry abrasive bed (dry-pot) for these application oriented wear tests. In the previous study this device was shown to simulate industrial mining process by producing same wear mechanisms and similar deformations [14]. The tester comprises of a rotating main shaft where the samples are attached in horizontal positions. The current tests were done similarly as in the previous study, i.e. having samples in two lowermost sample levels submerged into the abrasive bed, as presented in Fig. 1. Before a test is started the samples will be totally submerged under the bed of abrasives, i.e. samples are not visible.



**Figure 1:** High speed slurry-pot on the left as 3D illustration and on the right the same device with dry-pot test method showing a test sample inside the abrasive bed before completing the abrasive filling.

Samples were round bars with diameter of 25 mm and length of 94 mm of which 60 mm was subjected to wear. Same side of the bar was always faced towards the impacts. Rotational speed of 1000 rpm was used which corresponds to the sample tip speed of 10 m/s. Six samples of each QT and CFB steels were tested during the two studies, and two samples of the both boron steels were tested in the present study. The tests were done with the sample rotation test method [23], which means that the sample levels were changed during each test so that every sample was tested in each sample position. Sample rotation method ensures that the test conditions are similar for all samples during a complete test. The tests were composed of four 15 minute cycles, giving total test time of 1 hour. After each cycle the abrasive batch was changed, and the samples were weighted and repositioned to new levels. Each cycle had an 8.2 kg batch of the granite gravel. The abrasive used for the test was 8-10 mm Sorila granite gravel. It has quite high compressive strength, ~200 MPa, and

hardness of ~800 HV. The main mineral phases in Sorila granite in the order of decreasing volume are; plagioclase, quartz, orthoclase, biotite and amphibole.

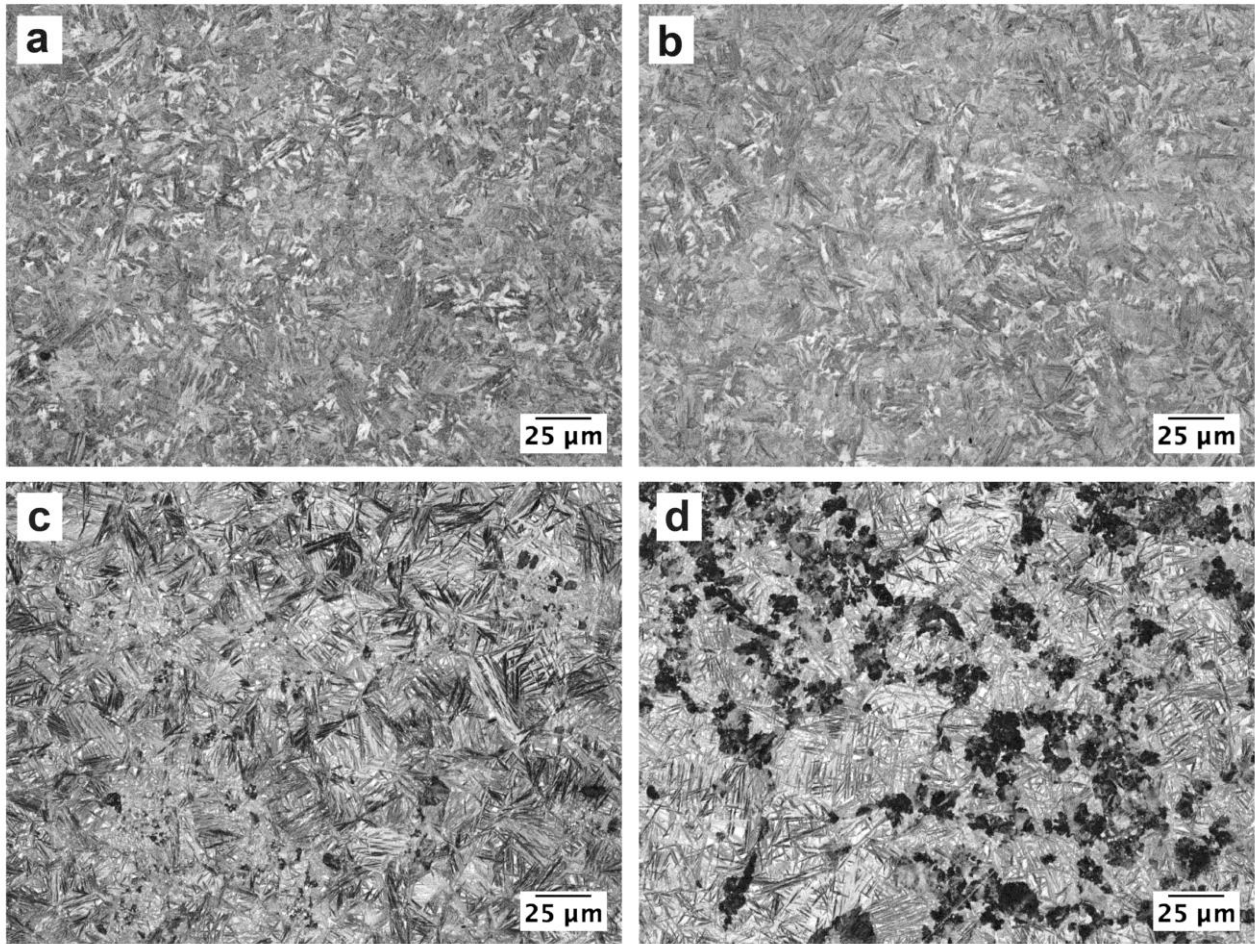
Sample preparation for characterizations was performed by grinding and polishing. Nital solution was used as etchant in cross-sectional studies. Laser microscopy (Keyence VK-X200 laser scanning confocal microscope) and scanning electron microscopy (SEM, Philips XL 30 and FESEM, Zeiss Sigma) were used to determine the wear mechanisms (wear surfaces), compare deformation depths (cross-section) and to characterize the microstructures. X-ray analyses was performed by Siemens PANalytical EMPYREAN diffractometer with monochromatic  $\text{CuK}\alpha$  radiation with 40 kV and 45 mA, and HighScore Plus software was used to analyze the XRD-data. The samples were cut to suitable length (10 mm) and thickness (6 mm) from the tested bars at a distance of 5 to 15 mm from the tip of the bar and the XRD measurements were performed on the worn surfaces. The surface roughness values were measured by optical 3D-profilometer ( Alicona InfiniteFocus G5) based on the ISO 4287 standard. After the wear tests hardness profiles were measured by microhardness tester using 50 g load.

### **3. RESULTS**

The presentation of results is divided into four sections. The microstructures of the materials presented in the first part is followed by presentation of the wear test results and in the third section the wear surfaces are analyzed and in the final section the wear behavior is characterized.

#### **3.1 Microstructure analysis**

The boron steels exhibited nominal lath martensite microstructure, as presented in laser microscope images in Fig. 2. No distinct differences could be recognized between the two variants of the boron steel in the nital etched laser images. The average prior austenite grain size for boron steels was 12  $\mu\text{m}$  and the grain structure was fairly equiaxed. Whereas, the CFB steels showed some differences between the variants. The needle-shaped ferritic laths were found in both, but the amount of dark, pearlite-like microconstituent, was higher in CFB300. Laser micrographs and FESEM images both present the bulk microstructure of the steels.

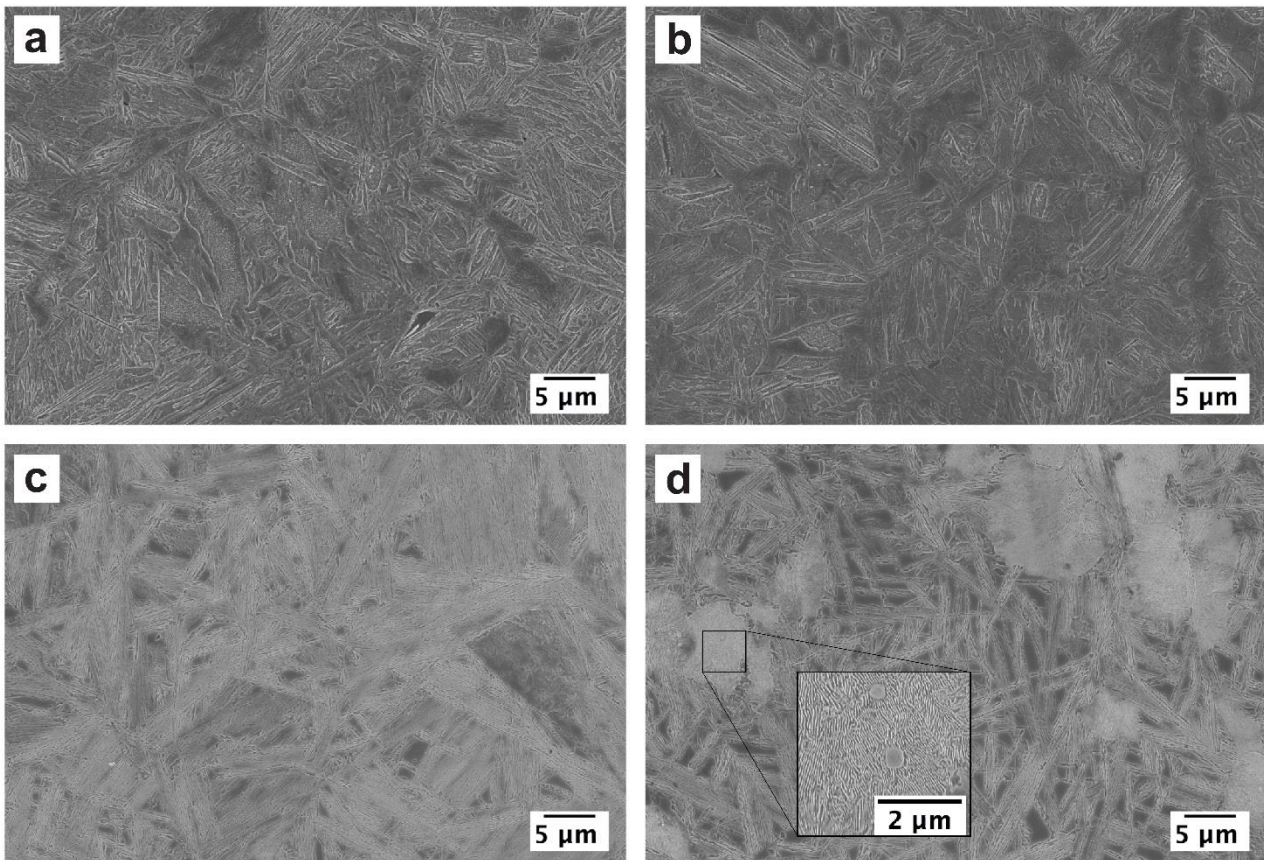


**Figure 2:** Laser micrographs of the tested steels: (a) BQ, (b) BQT, (c) CFB270 and (d) CFB300.

The microstructures were also examined with the FESEM for more details. Fig. 3a-b presents fine martensitic lath structure of the boron steels, but no substantial differences were found. Carbides have started to form in both steels and the microstructure was tempered martensite for both steels, which indicated that the quenched specimen has been exposed to auto-tempering. The moderate alloying of the boron steels resulted in relatively high martensite transformation start ( $M_s$ ) temperature, and auto-tempering occurred during quenching.

The CFB microstructures consisted of the bainitic-ferritic laths and retained austenite. The bulk microstructure in Figure 3c and 3d showed the microstructure and closer inspection revealed the fine lath size. The high surface hardness of the CFB steels also indicated that the fine platelet structure has been obtained. Small amount of martensite was also present. Again, with the CFB steels, the major difference was the amount of pearlite-like microconstituent, as presented in Fig. 3c-d. CFB300 had more very fine lamellar pearlite-like areas that appeared white in the SEM images. Significantly higher carbon content was measured for the precipitates shown in the magnified image in Figure 3d in comparison to the surrounding matrix. This suggests to the formation of unwanted carbides or to very high carbon retained austenite island. Few possibilities for the abnormal microstructural constituents were suggested. Some local changes in the chemical compositions might have occurred leading to lower carbon content. Then eutectoid composition could have been reached and islands of pearlite-like areas have been formed. Another possibility is that deviations during cooling have resulted in the formation of some type of hypereutectoid microstructure consisting of pearlitic structure. The latter presumption is supported by the fact that the presence of lamellar structure was more evident in the bulk and became more dominant approximately 5 mm below the surface. Hence, the cooling rate could have been notably slower in the middle of specimens leading to the pearlite-like microstructure. Nevertheless, the desired

microstructure of bainitic-ferritic laths and retained austenite was obtained near the surface with the aimed high hardness.

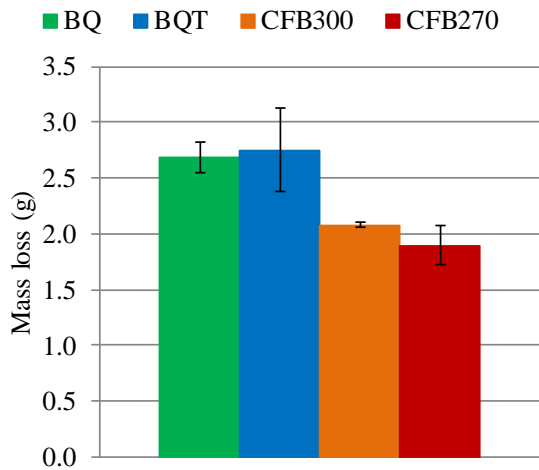


**Figure 3:** FESEM images of microstructures of the tested steels: (a) BQ, (b) BQT, (c) CFB270 and (d) CFB300 with a higher magnification image from the cloudy island structure.

### 3.2 Erosive-abrasive wear tests

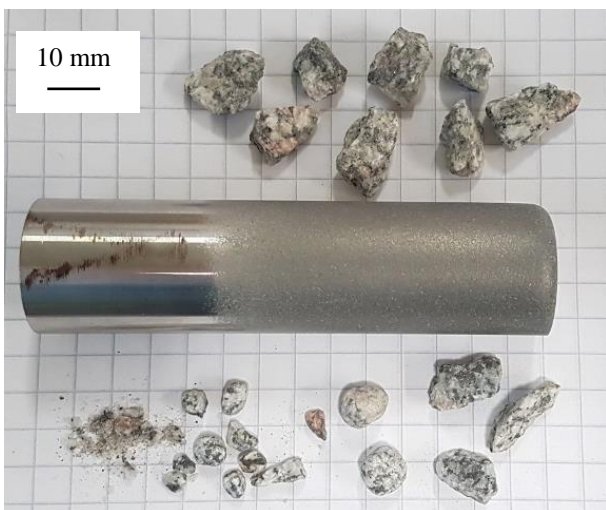
The results after 60 minute tests with dry-pot with 8-10 mm granite gravel as abrasive are presented in Fig. 4. Results showed that the boron steel had higher wear rates than the CFB steels. Also, the deviations of the boron steels were in average higher than CFB steels. The deviation of the BQT, 13.8 %, was rather high, but for the others the deviation was in normal levels for large particle wear tests with a natural abrasive (1-9 %). After the first 30 minutes of the tests the ordering of the materials were exactly the same, but the difference between the boron and the CFB steels was smaller, 24 % versus 37 % in average, thus the steady-state wear was reached during the first 30 minutes. The mutual differences were the same at both 30 and 60 minutes – about 3 % between the boron steels, and about 9 % between the CFB steels.





**Figure 4:** Dry-pot test results after 60 minutes. Average values of three CFB and two boron steel samples are presented.

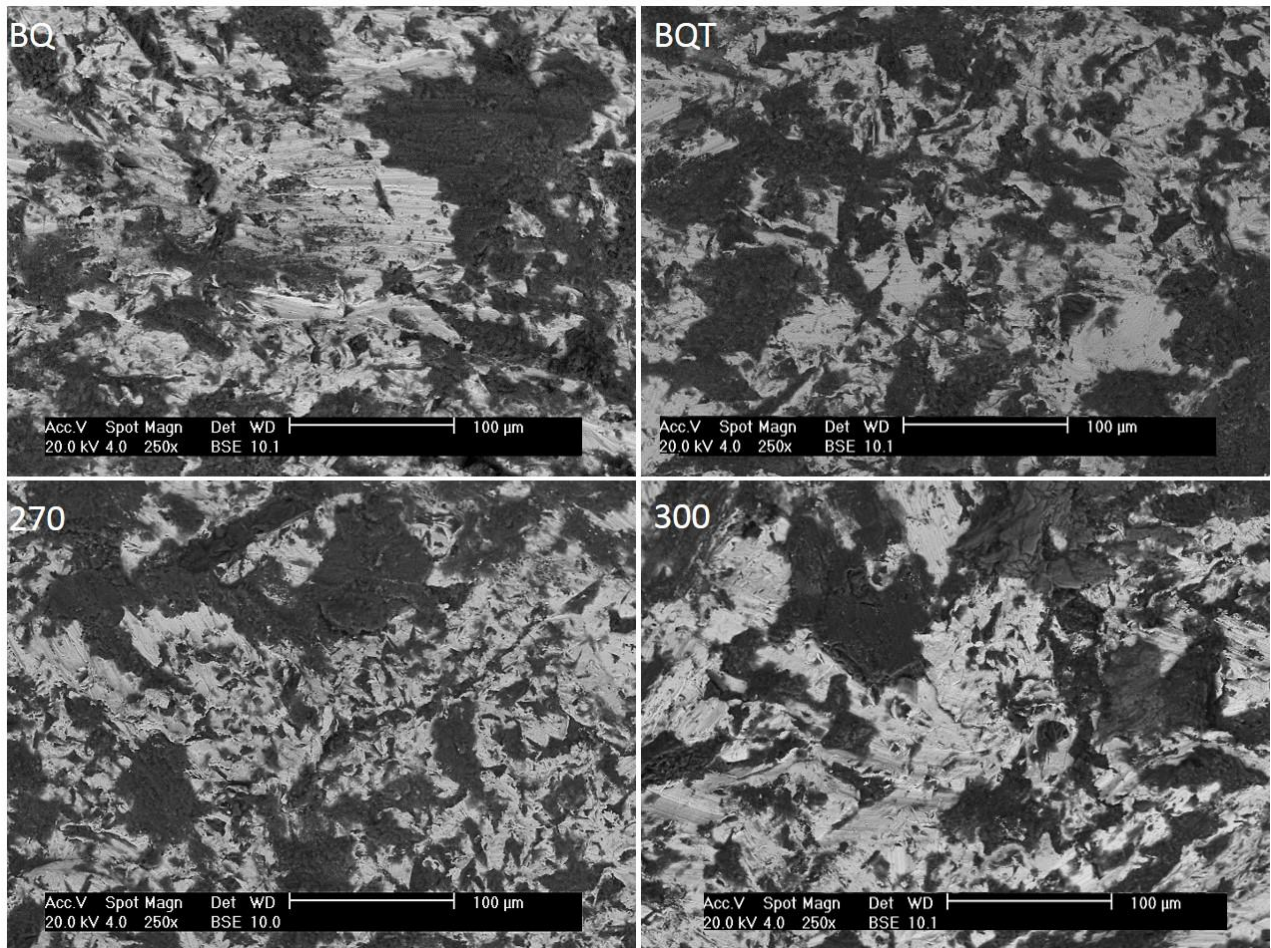
The abrasives were comminuted during the tests. Originally 8-10 mm particles were reduced to 0.1-10 mm, with 13 % of 8-10 mm, 40 % of 4-8 mm and 36 % of 0.125-1 mm size fractions. Unused and used abrasives are shown in Fig. 5. During the comminution, the granite particles were fractured and new sharp abrasive surfaces were created.



**Figure 5:** Tested CFB300 steel sample with unused (above) and used abrasives (below). The area exposed to wear is also visible on the sample surface.

### 3.3 Wear surfaces

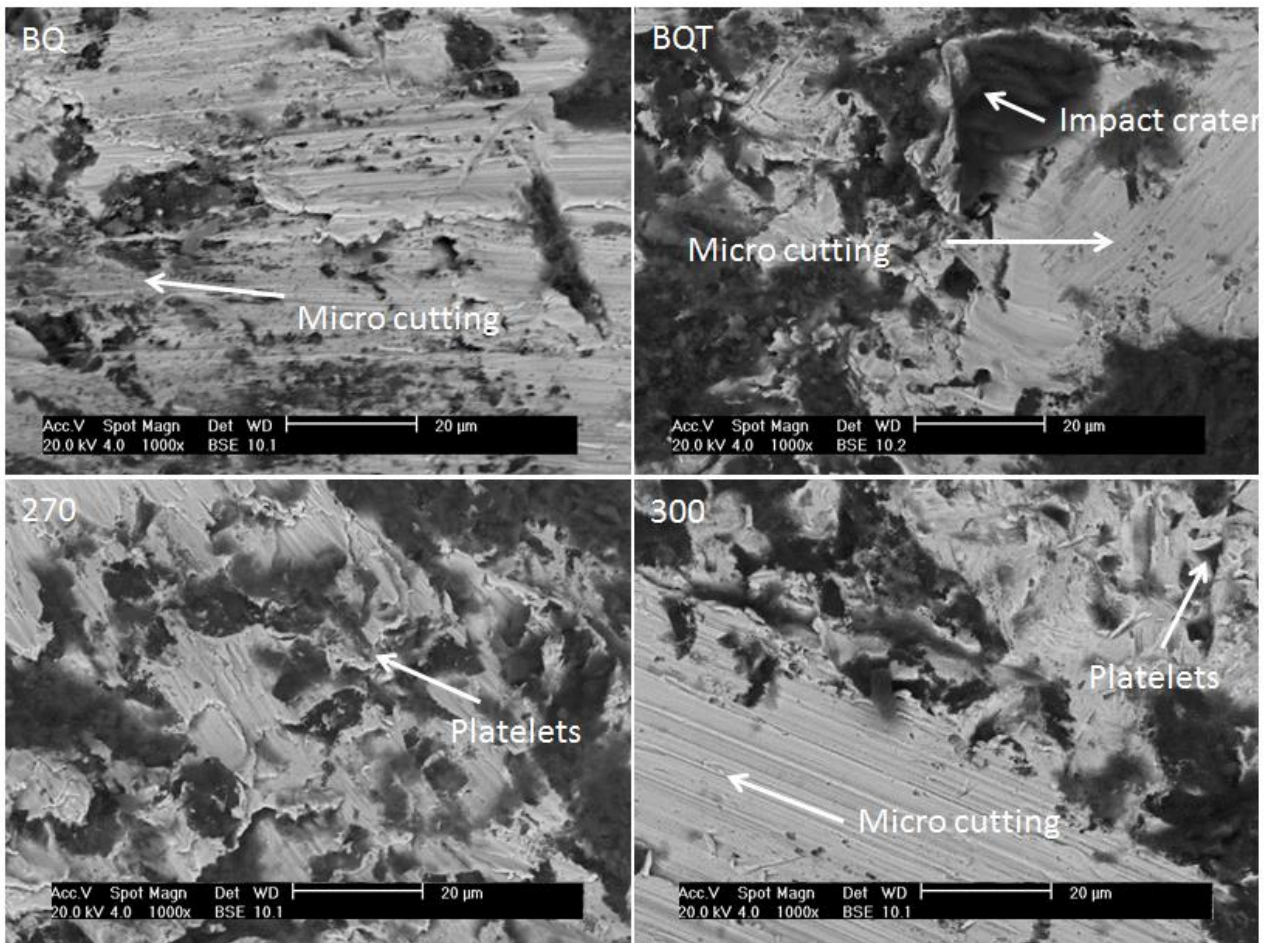
After the wear tests, it was observed that the level of abrasive residues on the wear surface was highest for the steels with higher hardness (CFB-steels). The overall presence of the wear surfaces showed that the level of cutting was higher for boron steels and the level of abrasive residues on the wear surface was lower. Fig. 6 presents SEM images of the wear surfaces after the erosion wear tests to provide information about the wear mechanisms. Images were taken with BSE detector that shows elemental contrast between light and dense materials, i.e., steel is seen as light areas whereas rock material appears darker. All images were taken from the impact side and 2 mm from the sample tip.



**Figure 6:** SEM images of wear surfaces 2 mm from the sample tip.

Fig. 7 presents scanning electron microscope images of the wear surfaces at higher magnification. The wear marks on the boron steels was generally deeper which was also confirmed by the surface roughness values. The surface roughness values were Ra; 2.02, 2.08, 2.20 and 2.11  $\mu\text{m}$ , and Rq; 2.65, 2.63, 2.89 and 2.72  $\mu\text{m}$ , respectively for the CFB270, CFB300, BQ and BQT. All steels showed extensive abrasive embedment, generally the abrasives were more likely to attach to the impact craters and to the end of the scratches produced by cutting. The boron steel wear surfaces were dominated by microcutting and microploughing with some impact craters. In addition to minor level of microcutting and microploughing, shallow impact craters were dominant features on the wear surfaces of CFB steels. Due to the repeated impacts, these impact craters looked more like thin platelets.

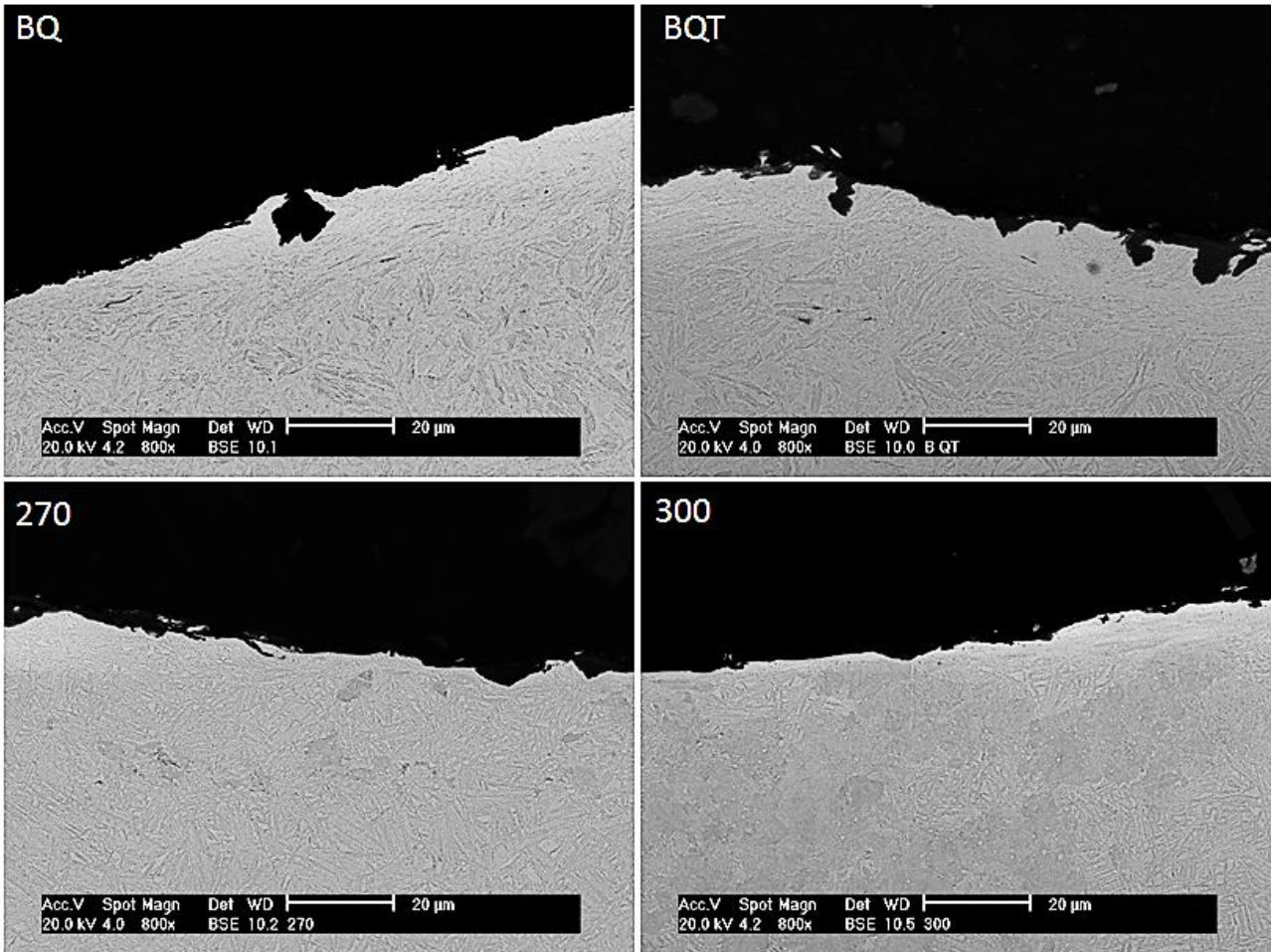




**Figure 7:** SEM images of wear surfaces 2 mm from the sample tip.

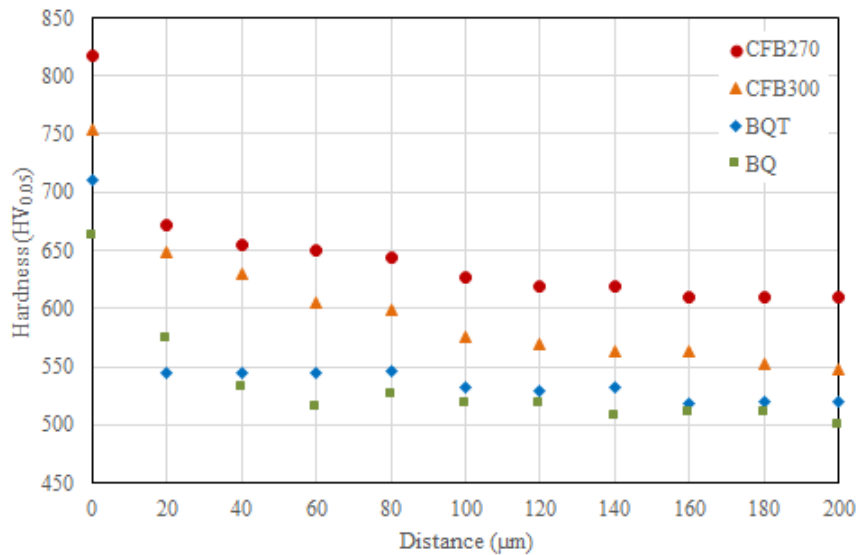
### 3.4 Characterization of wear behavior

Cross-sectional studies from the tested specimens revealed differences on the level of deformation. The observed deformation depth was between 10 to 20  $\mu\text{m}$  in the cross-section of the BQT steel and the embedded abrasive particles were found to reach the depth of 20  $\mu\text{m}$ . In general, the BQ steel had the most deformed surface layer of the steels tested, i.e. the grain size was finest. The depth of this layer was around 5  $\mu\text{m}$ . The average deformation depth of the both CFB steels was at similar level (0 - 5  $\mu\text{m}$ ). The deformation layer of CFB300 was finer than that of the CFB270. Occasionally higher deformation depths, 10 - 20  $\mu\text{m}$ , were found on the CFB300 below the embedded abrasives. None of the deformation layers showed any clear orientations, but the boron steels had the sharpest interface under the surface layers. Figure 8 presents SEM BSE images of the longitudinal cross-sections taken from the samples centerline. The material removal at the surfaces of the CFB steels was limited to very thin surface layer with low profile impact craters in comparison with impact craters of the boron steels, which were deeper and usually filled by embedded abrasives. Note that the cross-sections of steels BQ and CFB300 were at the other side of the sample centerline than the BQT and CFB270 that resulted in difference in the mirrored appearance of the cross-sections in Fig. 8.



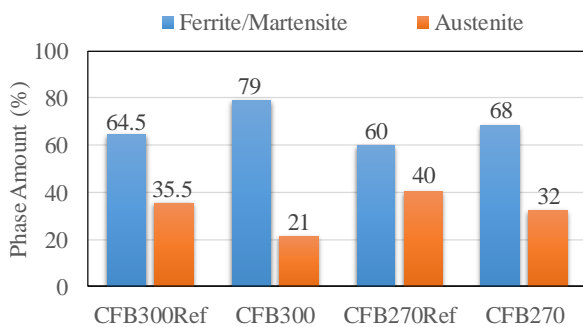
**Figure 8:** SEM images of the cross sections, 2 mm from the sample tip.

Before the wear tests, the bulk hardness values of the materials were 601, 548, 522 and 514 HV1 for the CFB270, CFB300, BQ, and BQT materials, respectively. The hardness profiles for the first 200  $\mu\text{m}$  beneath the worn surfaces are presented in Fig. 9. The surface hardness values after the tests were 820, 750, 730 and 660 HV0.05 respectively for the four materials. The hardness gradient for the first 80  $\mu\text{m}$  under the surface were larger for the BQ and BQT steels than for the CFB steels. The BQ and BQT steels showed increased hardness values only close to the surface, 20  $\mu\text{m}$  from the wear surface the hardness values were rather close to the bulk hardness. The hardness profiles of the CFB steels showed that the hardness was gradually decreased to the bulk level at around 100  $\mu\text{m}$  from the surface as seen in Fig. 9. This supported the findings about the near surface deformation from the cross-sections.



**Figure 9:** Microhardness profiles for the CFB-steels and the boron steels from the worn surface towards bulk. Surface hardness value is an average of ten indentations, as the other values are an average of five indentations.

According to XRD analyses of the phases present, the main phase in water quenched (BQ) and quenched and tempered (BQT) steels was martensite, but a small amount (0.3 - 0.7%) of iron carbide was also detected in these steels. The XRD patterns of the both CFB steels consisted originally of ferrite and austenite and after the erosion tests some of the austenite was transformed into martensite. The amount of austenite was nearly the same, 35 and 40 %, in the CFB steels prior to the wear testing. After wear testing, the austenite content decreased to 21 % for CF300 and to 32 % for CFB270. This was caused by the austenite-to-martensite transformation induced by the impact-erosive loading. Fig. 10 summarizes the XRD data regarding the stress induced phase transformation in the CFB steels. Ref-values refer to the phase content before the tests.



**Figure 10:** Austenite and ferrite/martensite amounts before (Ref-values) and after erosion tests.

#### 4. DISCUSSION

The boron and CFB steels with their different microstructures consisting of martensite and carbide free bainite, respectively, were studied in this work. Both had very fine-grained lath microstructures. The initial hardness of the CFB300 steel was almost the same as for the BQ and BQT steels while the CFB 270 had higher initial hardness. The main difference in the microstructures was that the martensitic lath structures of the boron steels contained also carbide precipitates, while the laths in the CFB structure contained bainitic ferrite and austenite. The desired microstructure was obtained in the surface of the CFB samples, even though abnormalities consisting of pearlitic-like lamellar structure and precipitates were found in the bulk closer to the center of the specimens.

The hardening in the surface layer was higher in the CFB steels caused mainly by the austenite-to-martensite transformation confirmed by the XRD measurements. This transformation is enabled by the deformation energy [24,25] and the volume of martensite is larger than austenite which causes compressive stresses in the surface region of the material. A second possible cause of the higher hardness increase in the surface layer is the higher strain hardening ability of the phases in the microstructure. The carbide free bainitic microstructures include ductile ferrite-austenite in comparison with the lath martensite microstructure containing carbides in the boron steels. The inevitable cutting/wearing of the outermost surface layers should be easier for the martensite/carbide structures in comparison with the much more ductile ferrite/austenite structure. In addition, this difference in structure could be a contributing reason to why the wear resistance of the CFB steels is higher in comparison to the boron steels. Both, CFB and boron steels, have high surface hardness after wear, but the ability to withstand high-stress erosive-abrasive wear without cracking appears to be more significant for the CFB steels. As mentioned, this could be explained by the greater strain hardening capability of the carbide free bainitic structure and the stress-strain induced austenite to martensite transformation. For the given surface hardness, the more ductile microstructure seems to perform better in erosive-abrasive wear conditions.

The smoother hardness profile from the surface towards the bulk was one important factor that increases the wear resistance of the CFB steels in comparison with that of boron steels. The higher hardness just under the worn surface with smooth hardness profile towards the bulk, gives better support to the deformation layer and decreases the embedment depth of the particles hitting the surface [26]. Also it has been proposed that in abrasion strong work hardening with lack of smooth hardness gradient or orientation of the deformed layer may lead to decreased wear resistance by loss of ductility on the surface of the steel [26–28]. This can be the reason why the CFB300 steel had better erosion wear resistance in comparison with the BQ and BQT materials with almost the same initial bulk hardness.

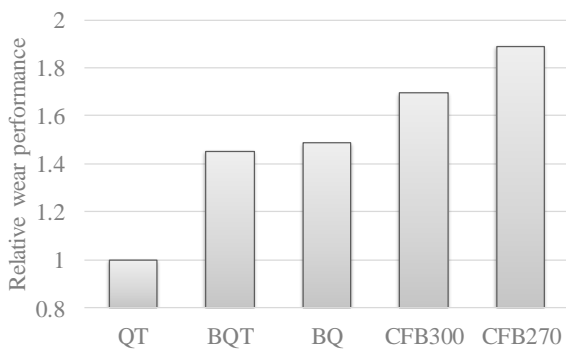
The dominant wear mechanisms were different for both of the tested steel types. CFB steels had more evidence of the extrusion of material at the exit end of impact craters, which produced thin platelets after multiple impacts. The amount of this wear mechanisms was higher in the harder CFB steel (CFB270) due to the lower ability to deform under the impact loading. In the boron steels, the main wear mechanisms were microcutting and microploughing. The embedment of the abrasives occurred deeper in the boron steels and the deformation depth was larger than in the CFB steels. However, the deformation layer of the BQ steel was at the same level with the CFB steels due to the constant material removal produced by the occurred wear mechanisms (microcutting and microploughing). The abrasives used in this study were granite particles that have quite high compressive strength and the hardness of 800 HV, which is similar with the obtained surface hardness of CFB steels. The constant impacts of the granite particles towards the sample surfaces and to each other ensured that new sharp edges were constantly produced and the material removal rate and the deformation were high during the tests.

The CFB steels have shown good wear performance in both laboratory and field tests [14]. The high surface hardness has proven to increase the wear resistance. However, the more traditional QT, BQ and BQT steels had significantly higher impact toughness when compared to the tested CFB steels and could provide better resistance against wear by high impact loads. It is evident that in the tested environment of abrasive-erosive conditions the impact toughness alone is not significant feature for the wear resistance. Surface hardness, fracture toughness and prevention of crack propagation together with impact toughness have been reported to generate the properties required for good abrasive wear resistance [29]. Atkins [30] concludes that both hardness and toughness are vital for the prevention of material removal. Though, in some cases increased resistance to sliding wear has been attributed to increased Charpy-V toughness [31]. Nevertheless, Charpy-V impact toughness is a measure of the materials resistance to fracture in the presence of a notch. There is not necessarily a correlation with the Charpy-V toughness and the plane strain fracture toughness,  $K_{IC}$ , even though both measurements are utilized to determine the fracture properties of a material. The wear of steels is more

complicated and cannot be clearly predicted by simple means of fracture tests. The results of this study point out that even with poor Charpy-V notch test results, a harder steel might still show excellent abrasive-erosive wear performance without showing any brittle behavior.

The surface of steels is subjected to plastic deformation during wear and cracks may be initiated. As mentioned, the prevention of these cracks to propagate under the worn surface is essential. It prevents the work hardened surface layer from cracking and peeling off. This ability to prevent material from detaching should be emphasized in discussion of wear resistance of steels, but it is rather difficult to measure due to the work hardening and different properties of various microstructures. The austenite-to-martensite transformation induced by high stresses creates hardness gradients to the surface, but the transition layer to bulk can be either smooth or sharp [26].

Fig. 11 presents a comparison of the current study with the previously achieved field test results [14] in which the CFB steels were compared against the QT reference steel in a mining application. The hardness of the QT steel, the material currently used in the field application, was 310 HV and the surface hardness increase caused by 30 min long tests in the dry-pot erosion test was about 60 HV. The increase of the hardness values for the CFB270 and CFB300 steels were 172 and 106 HV respectively in the 30 min long tests. The surface hardness increase for the BQ and BQT steels in the current study was close to the CFB steels – measured after 60 minutes of testing. In the previous work, the comparison in the field showed that the CFB steels had 4 - 6 times lower wear rate in comparison with the QT steel. The comparison between the equivalent 30 minutes dry-pot tests presented in Fig. 11, shows that the boron steels are about 30 % inferior to CFB270, but 50 % better than the QT reference from the mining application.



**Figure 11:** Relative wear performance of the steels compared against field test results acquired in previous study [14]. Performance of the QT set as one and others scaled accordingly.

## 5. CONCLUSIONS

The results of the current work with novel carbide free bainitic steels (CFB270, CFB300) and traditional boron steels (BQ, BQT) and the comparison with previously performed laboratory and field tests on quenched and tempered steel (QT) and CFB270 and CFB300 was conducted to find out the wear performance of the steels. The carbide free bainitic steels show nearly 30 % improved wear performance in comparison with the boron steels. The two boron steels had similar wear resistance, and no clear differences could be measured between the quenched (BQ) and quenched and tempered (BQT) variants. The previous study with a softer, conventional QT steel and CFB steels proved that carbide free bainitic steels can withstand the harsh demands of mining environment. Despite low Charpy-V impact toughness results, the CFB steels did not fail by brittle fracture during wear testing. In the current study, the boron steels showed roughly 50 % better performance compared to the reference QT steel in the earlier field test.



CFB steels exhibited fine ferritic-austenitic microstructure and boron steels had martensitic microstructure with carbides formed during quenching (auto-tempering of BQ) or tempering process (BQT). Also pearlite-like microconstituent was discovered in the CFB steels, but not close to the surfaces. The better wear performance of the CFB steels in comparison with the boron steels can be explained by the different microstructure and its phases. The large amount of retained austenite could be one of the major factors in improving the wear resistance. Austenite transforms into hard martensite when subjected to heavy erosion-abrasion or impacts. However, there is a risk of formation of brittle deformation layer. In the tested CFB steels, the transformation of austenite into martensite apparently did not create such layer. This was confirmed by microhardness measurements of the worn samples. The CFB steels showed smoother hardness profile than the boron steels. Thus, the hardness gradients together with orientation of the deformation zones on the wear surfaces dictated the wear performance of the steels.

Different wear mechanisms were observed in the steels. Microcutting and microploughing were more dominating in the boron steel samples, whereas the CFB steels had more shallow craters with thin platelets formed by repeated impacts. Extrusion of material could be seen at the exit end of the impact craters with CFB steels. The dry-pot test method used in these tests has shown to produce steady-state wear already after 30 min testing time. The test simulates erosive-abrasive wear well and can be used to evaluate the performance of different steels in the actual mining applications.

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