# Erosive and abrasive wear performance of carbide free bainitic steels – comparison of field and laboratory experiments

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## Abstract

Carbide free bainitic (CFB) steels have been tested in two heat treated conditions and compared with currently used quenched and tempered (QT) steel in an industrial mining application subjected to erosive-abrasive wear. A conventional sliding abrasion and a new application oriented high-stress erosion wear tests were performed in laboratory. The results of the erosion and the field tests were compared. The microstructural changes were investigated by optical and scanning electron microscopy. The hardness and hardness profiles of the steels were measured. The results showed that in the laboratory tests, the abrasion and erosion wear rates of the CFB steels were 35 and 45 % lower respectively in comparison to the QT steel. In the field test, the weight losses of the CFB steels were about 80 % lower in comparison with the QT steel. The improved wear resistance of the CFB steel can be explained by its higher hardness and higher work hardening. The erosion wear test was able to simulate the work hardening effect and the wear mechanisms observed in the field test samples.

**Keywords:** Steel, Carbide free bainite; Erosive wear; Abrasive wear; Field test

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## 1. INTRODUCTION

The development of steels with ferritic-austenitic microstructures, often named carbide free bainite (CFB) produced by austempering of Si- and/or Al-rich steels, has led to an increased interest in investigating their wear resistance in different applications. Different laboratory tests have shown good wear resistance for the CFB steels when subjected to sliding wear [1-4] and rolling-sliding wear [5-6]. Initial erosion wear [7] as well as abrasion [8] wear tests of CFB steels have also shown promising results. The wear resistance of CFB steels is attributed to their fine ferritic laths surrounded by austenitic films. This result in high hardness and the lack of carbides gives the ability to transform the austenite to martensite by mechanical wear. In addition, the lath structure at the surface is refined by the wear and the surface hardness is increased [3-4]. Due to excellent wear resistance of steels with CFB microstructure, they have shown to be suitable to be used in applications as rails [7, 9], and cutter-knifes [10].

This background was the motivation for the testing of the CFB steels in real industrial mineral handling applications, in which the components are subjected to severe erosive and abrasive wear. In addition, the need of developing a more application oriented wear test method for testing of these steels was recognized. The goal of the new test method was to simulate the real wear conditions and wear surface deformations in a mineral handling application better than the usual conventional testers, such as rubber wheel or abrasive paper test.

Based on previous excellent rolling-sliding laboratory results of a CFB steel [11] and the information presented in the literature, the aim of this work was to compare the wear resistance of a CFB steel with the quenched and tempered (QT) steel used in industrial equipment for sorting of iron ore. The bars used in this application are subjected to a combination of high-stress abrasion and erosion wear, which gives the possibility to study whether the CFB steels are suitable materials for the bars. Furthermore these steels were also subjected to both a conventional sliding abrasion wear test and a new application oriented high-stress erosion wear test in laboratory. The latter was designed to simulate dry erosion and abrasion wear in mining applications.

## 2. MATERIALS, TESTS AND ANALYZES

The materials tested were a QT steel and a high Si-alloyed CFB steel austenitized at 950 °C and austempered at two different temperatures; 270 and 300 °C. The QT steel used was in as received QT-condition. Table 1 presents the material properties for the steels. The hardness and Charpy-V impact energy values were measured from the laboratory tested materials. Ten hardness measurements with 1 kg load and three impact tests were performed on each steel. Other mechanical properties of CFB270 were measured in a previous work [12]. Tensile test has not been performed on CFB300 samples.

*Table 1. Test materials and their properties.*

| **Material** | **QT** | **CFB270** | **CFB300** |
|---|---|---|---|
| Hardness [$HV_1$] | 310 ± 10 | 601 ± 14 | 506 ± 17 |
| KV [J] | 97 ± 4 | 16 ± 2 | 19 ± 2 |
| $R_{p0.2}$[N/mm$^2$] | 800 | 1650 | |
| $R_m$ [N/mm$^2$] | 900 | 2050 | |
| $A_5$ [%] | 10 $_{min}$ | 16 | |
| C [%] | 0.38 $_{max}$ | 1.0 | |
| Si [%] | 0.35 $_{max}$ | 2.5 | |
| Mn [%] | 0.80 $_{max}$ | 0.75 | |
| Cr [%] | 1.60 $_{max}$ | 1.0 | |
| Ni [%] | 1.60 $_{max}$ | | |
| Mo [%] | 0.30 $_{max}$ | | |

Sample preparation for characterizations was performed by grinding in several steps followed by stepwise polishing finished by silica suspension "Mastermet". Nital (3%) solution was used as etchant. Optical microscopy (OM) and scanning electron microscopy (SEM) were used to characterize the microstructure and X-ray analyses by PANalytical EMPYREAN XRD equipment was used to reveal the phases in the steels. The software HighScore Plus was used to analyze the XRD-data. The surface roughness was measured by Wyko NT1100. Charpy-V tests were performed on test samples and also on samples machined from heat treated bars. The wear surfaces and their cross-sections were characterized by SEM in order to determine the wear mechanisms and level of deformations.

## 2.1 Abrasion wear tests

Abrasion wear tests were performed at Lulea University of Technology using a modified ABR-8251 abrasive wear tester, presented in Figure 1 [13]. The tester uses a flat reciprocating sample, sliding on top of abrasive paper (width 6 mm) wrapped around the surface of a wheel. The paper moves a certain distance after each reciprocating movement of the sample and new paper is mated for the next stroke. The initial surface roughness of the samples was approximately 15 μm. The abrasive paper used consisted of a mixture of 60% $Al_2O_3$ and 40% $ZrO_2$ particles with a grain size of approximately 270 μm and a measured hardness of 1750 $HV_{0.3}$. The sliding distance used was 180 m and the load was 16N.

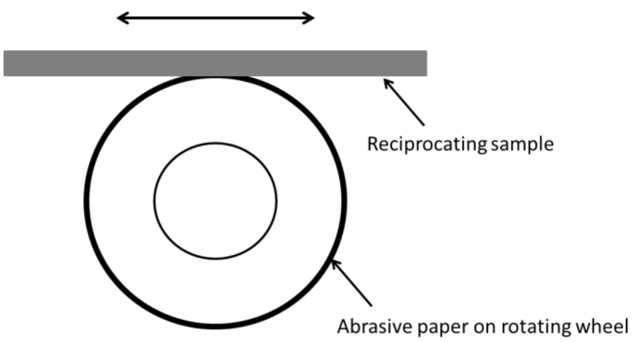


*Figure 1: Test configuration for abrasion wear tests.*

The mass of the samples was measured before and after the test. The specific wear rate was calculated after each test as follows:

$$SWR = \frac{\Delta V}{p * s} \qquad \text{(Eq 1)}$$

$$\Delta V = \frac{\Delta m}{\rho_S} \qquad \text{(Eq 2)}$$

The volume loss of the sample, ΔV is in [mm³], p the load in [N] and s the sliding distance in [m], Δm is the measured mass loss in [g] and $\rho_S$=7,9 g/cm³ the density of steel. Hardness and surface roughness of the samples were measured before and after the tests.

## 2.2 Erosion wear tests

The erosion tests were conducted with a high speed slurry-pot type erosion tester [14] in Tampere Wear Center operated at Tampere University of Technology. For this study, new application oriented test method was developed, called high-speed slurry-pot with dry abrasive bed (dry-pot). In the dry-pot method the pot tester is used without a liquid carrier medium and the test samples are totally submerged under a bed of dry abrasive particles.

In this study, the tester was used with dry 8-10 mm granite gravel. Figure 2 presents the test configuration, showing the round Ø 25 mm samples and the granite abrasives. During the tests the samples were located at the two lowest levels and sample rotation [14] was utilized, i.e. all samples were tested on the both sample levels in each test. This ensures that the wear condition was similar for all the samples. For each steel three samples were tested. The total test time was 30 minutes and after 15 minutes the samples were weighted and repositioned to new levels. Also the 8.2 kg gravel batch was changed after 15 minutes. The rotational speed was 1000 rpm which corresponds to the speed of 10 m/s at the end of the sample tip. Also one hour test was done to check if longer time would have any effect on the wear process, but for CFB materials the wear rate stayed the same, and for QT steel it did increase by a small amount.

*Figure 2: Dry-pot test configuration for the erosion wear tests. Before the test samples are submerged in to the abrasive bed.*

The granite used was originating from Sorila quarry (Tampere, Finland). Hardness of the granite was around 800 HV and the solid density 2.65 t/m$^3$. The nominal mineral composition included plagioclase (45 %), quartz (25 %), orthoclase (13 %), biotite (10 %) and amphibole (5 %).

## 2.3 Field tests

Field tests were performed at LKAB plant in Malmberget with reference bars (QT) and bars with two different austempering treatments (CFB 270 and CFB 300). The length of the bars was 700 mm and diameter 30 mm. The bars were tested in two sorting machines (Mogensen Sizer SEL2026-D2), with two sections each, equipped with 2 x 15 bars.

The iron ore pieces, consisting of magnetite and gangue, were moved by sliding and shaking from the upper level set of bars to the lower level and then to grids with different mesh sizes. The arrangement with an upper and a lower set of bars is presented in Fig. 3. In each machine 30 QT and 30 CFB bars were mounted and subjected to the wear; CFB 270 steel bars were mounted in one machine and CFB 300 in the other. The bars were located in two sections of each machine; the QT bars on top in the first and CFB bars on top in the second section. The test lasted for 28 days and about 125 000 tons of material passed each section. The hardness and the mass of each bar were measured before and after the test and the specific volume loss (SVL) during the field test was calculated according to:

$$SVL = \frac{\Delta V}{m_{section}} \qquad \text{(Eq 3)}$$

The calculated volume loss ΔV and the amount of iron ore which passed the section during the test, $m_{section}$ was used to calculate the SVL [$mm^3$/kg].

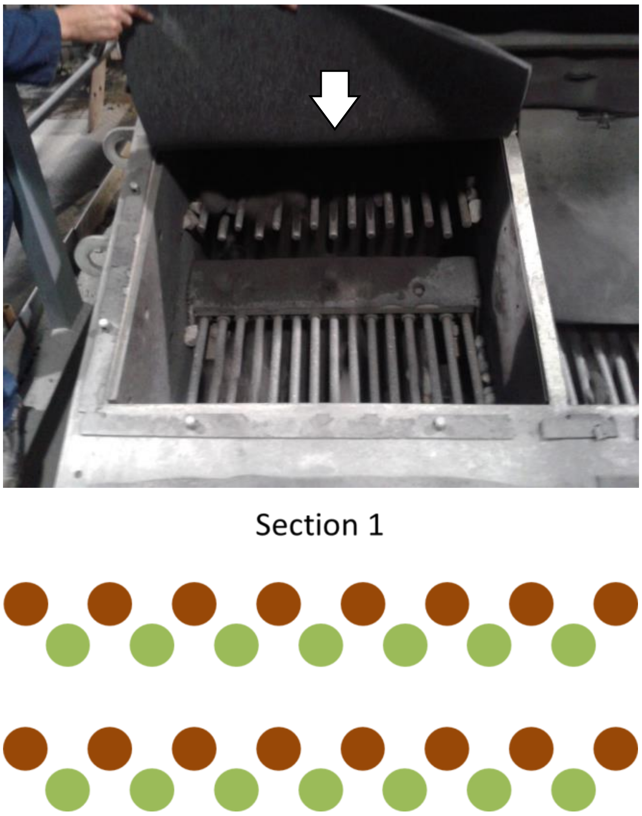


*Figure 3: The field test arrangement of bars in one of the sections used for the tests. Upper Fig. with half of a Mogensen sorting machine, showing upper and lower levels with 15 bars each. Lower Fig. shows principal sketch of upper and lower level set arrangement of bars. Different colors designates different test materials.*

## 3. RESULTS

The CFB microstructure contains fine ferritic-austenitic laths and in addition also small white grains of blocky austenite and/or martensite (MA). This can be seen in Fig. 4 in which the microstructure of CFB300 is shown. The microstructure was similar in both CFB steels.

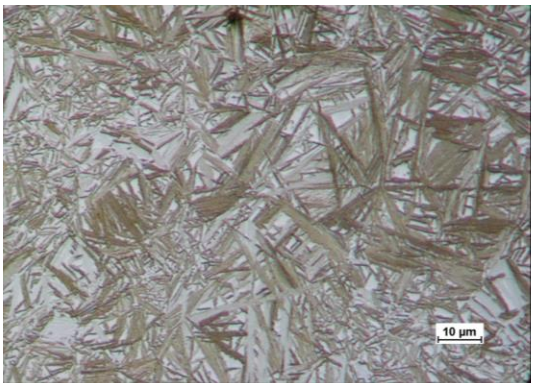


*Figure 4: Microstructure of Nital etched CFB300.*

Hardness values of the white MA constituent were lower than for the alloy in average; hence the MA constituent mainly consists of austenite. The amount of MA constituent was estimated to 5.1 ± 1.9 % for CFB270 and to 10.7 ± 1.3 % for CFB300 samples.

## 3.1 Abrasion wear tests

The samples were weighted and both surface hardness and roughness was measured before and after the tests, Table 2 presents the results. Measurements after abrasion wear tests show that the hardness did not increase during the test. This can be explained by the low perpendicular load applied and abrasive cutting of the outermost surface layer. The volume loss for samples was calculated from the mass loss for having abrasion wear test result in SWR, shown in the table. The initial Ra value of the samples was about 15 μm and the abrasive wear test resulted in a decrease of this value due to the grinding.

*Table 2. Surface hardness of samples before and after abrasion wear tests together with specific wear rate and Ra values after the tests.*

| | $HV_{0.2}$ before | $HV_{0.2}$ after | SWR [$mm^3$/Nm] x$10^{-3}$ | $R_a$ [μm] |
|---|---|---|---|---|
| QT | 304 ± 9 | 303 ± 13 | 11.5 ± 1.1 | 8.5 |
| CFB270 | 588 ± 11 | 585 ± 9 | 9.1 ± 0.7 | 8.2 |
| CFB300 | 503 ± 25 | 490 ± 30 | 10.6 ± 0.3 | 6.9 |

The wear test results showed that the SWR was considerably lower for the CFB steels but that the $R_a$ values were about the same for all tests. SEM analysis of the worn surfaces revealed three different wear mechanisms (Fig. 5). Whereas QT steel showed more of ductile flaking in comparison with the both CFB steels, the much harder CFB steels showed more microploughing and microcutting as a result of the abrasive wear test. No difference between the CFB270 and CFB300 wear surfaces was detected.

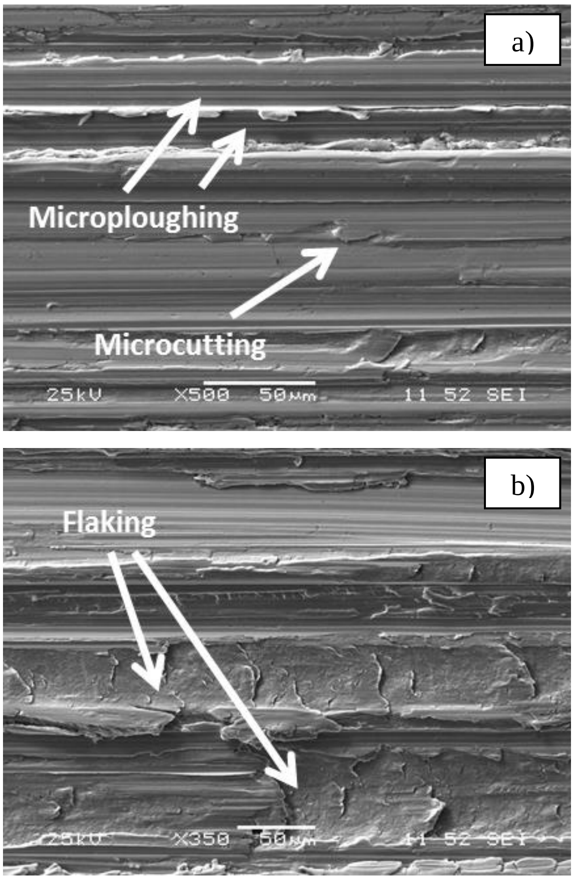


*Figure 5: SEM image after abrasion wear test of a) CFB270 showing microcutting, and microploughing, b) QT showing flaking.*

### 3.2 Erosion wear tests

Erosion wear test results with standard deviations are presented in Table 3 with surface hardness measurements. The highest volume losses were generated by QT samples. CFB sample with lower austempering temperature and highest hardness resulted in lowest volume loss. The surface hardness increased with about 140 HV for the CFB samples and but only about 60 HV for the QT samples.

*Table 3. Surface hardness of samples before and after erosion tests with volume loss results.*

| | $HV_{0.2}$ before | $HV_{0.2}$ after | Volume loss [$mm^3$] |
|---|---|---|---|
| QT | 311 ± 4 | 371 ± 20 | 288.4 ± 12.0 |
| CFB270 | 618 ± 17 | 790 ± 29 | 150.0 ± 3.4 |
| CFB300 | 547 ± 10 | 653 ± 58 | 173.2 ± 4.0 |

During the test the granite abrasive particles were comminuted. By sieving the used abrasives, it was noticed that the originally 8-10 mm size range was reduced to 0.1-10 mm, with majority of the particles being between 1-8 mm.

Figure 6 presents SEM image from the wear surface of the erosion tested CFB270 sample. Image was taken with the backscatter detector (BSE), thus the regions appearing dark are embedded gravel and lighter regions are steel. The image is acquired 3 mm from the sample tip along the centerline, i.e. the leading side of the sample during the test.

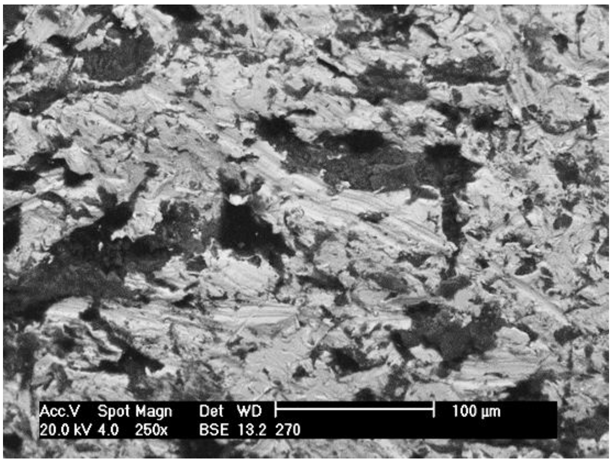


*Figure 6: Scanning electron image of erosion tested CFB270 sample, showing embedded abrasives and short scratches on the erosion surface.*

All materials showed similar wear surfaces in general with heavily worn areas due to the multiple impacts with high velocity. The main difference between the QT and the CFB samples after the dry-pot test were the length of the scratches. The wear surface of the CFB showed short scratches whereas the QT wear surface were highly deformed with dents. Also it was clear that the amount of embedded abrasives was highest in the QT samples. The two CFB qualities showed much lower, but still notable abrasive embedment in the surfaces.

The measurement of the phase composition at the surfaces by XRD after the erosion tests showed that the amount of austenite had decreased for the austempered materials as a result of the erosion as seen in Fig. 7. In addition to austenite, also the ferrite/martensite amounts were measured. This value includes only ferrite before the wear test, but a mixture of ferrite and martensite for the worn samples.

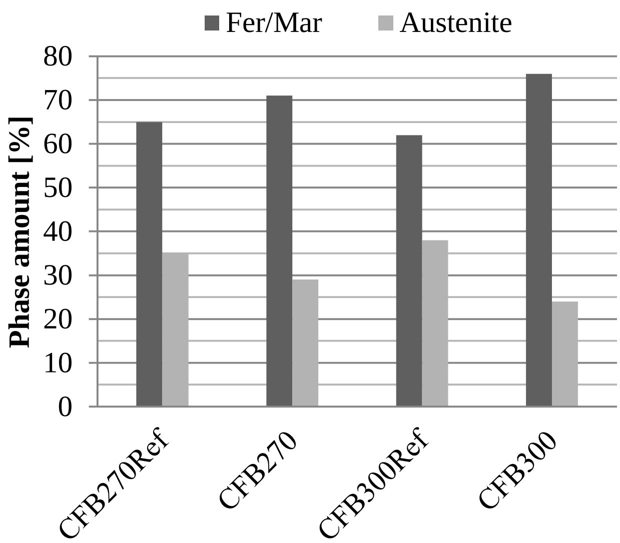


*Figure 7. Retained austenite and ferrite/martensite amounts before (Ref-values) and after erosion tests.*

### 3.3 Field tests

The surface hardness of the field tested bars, was measured before and after the tests and the average specific volume losses were calculated after the field tests. Table 4 presents the results. The SVL of the bars with CFB structure is 4-6 times lower in comparison to that of the conventional QT bars. The results also show standard deviations with a large scatter, from 8 to 43 %. The wear of bars was more unevenly distributed in section 1 in both machines, than in the other sections. Especially the difference between the sections in machine 2 was twice as large in comparison with that of machine 1. This could explain the large deviation of QT samples in machine 2. The most likely explanation for this is that majority of the feed, or most of the largest ore pieces on machine 2 did, for some external reason, pass through section 1. The size of the individual ore pieces varied a lot, as the official data given showed that the weight of the pieces was up to 5 kg. From that it can be estimated that the particle size range was between 0 and 150 mm. The hardness measurements show that the hardness increased with about 190 HV for the CFB structures as a result of the wear, while the hardness of the QT structure only increased with about 40 HV.

*Table 4. Average specific volume losses of field tested bars. Each value is an average measure of 30 bars.*

| | $HV_{0.2}$ before | $HV_{0.2}$ after field test | SVL Machine 1 [$mm^3$/1000kg] | SVL Machine 2 [$mm^3$/1000kg] |
|---|---|---|---|---|
| QT | 317 ± 4 | 358 ± 20 | 0.222 ± 0.018 | 0.288 ± 0.124 |
| CFB270 | 593 ± 13 | 777 ± 46 | | 0.050 ± 0.015 |
| CFB300 | 495 ± 22 | 692 ± 53 | 0.047 ± 0.014 | |

The CFB270 has slightly higher SVL in comparison with CFB300 even though it is harder, but when compared to QT, CFB270 was 83 % better, while CFB300 was 79 % better than QT. Also the results between the sections 1 and 2 were checked individually to confirm that the external deviation in machine 2 did not have caused any error in the interpretation of the results.

Figure 8 presents SEM BSE image from the wear surface of CFB 270 sample tested in the field. The image is acquired from the centreline of the sample, i.e. the top side of the steel bars in the sorting machine. In the field test the large, up to 5 kg, ore pieces caused larger scratches than what was observed in the dry-pot tests. Also the deformed areas were larger in size and showed clearer surface topography. Otherwise the wear mechanisms for CFB steels were the same, consisting of heavy deformations due to high energy impacts and abrasive scratching. The QT instead showed heavily cut surface and areas with very high deformations.

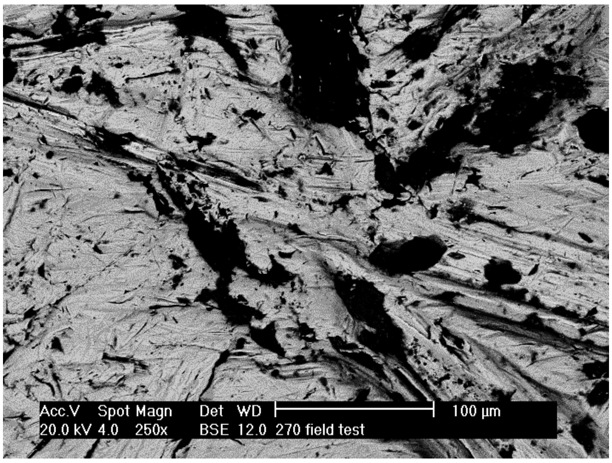


*Figure 8. Scanning electron image of field tested CFB270 sample, showing embedded abrasives (dark) and longer scratches on the wear surface.*

## 3.4 Wear surface cross-sections

As the wear surfaces showed similar wear mechanisms in the dry-pot and field tests, the cross-sections from the tested samples were also characterized with SEM and by hardness measurements. Hardness profiles were measured from the cross-sections with a micro-hardness tester with a load of 50 g. Fig. 9 shows that the hardness profiles for both CFB-materials were quite similar after the tests. In the figure surface hardness values are from Tables 3 and 4, thus measured with 200 g load.

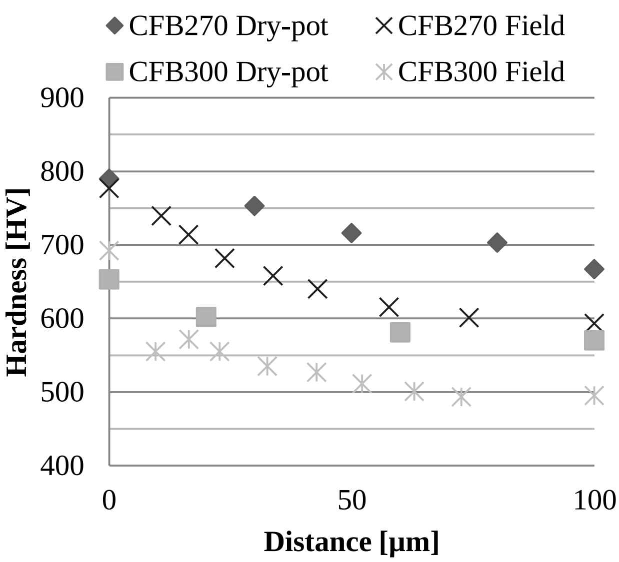


*Figure 9. Hardness profiles after field tests and dry-pot tests of the two CFB materials, CFB300 and CFB270.*

Fig. 10 shows the cross sections of the field tested and the erosion tested surface of the CFB 300 sample. The arrow is indicating the estimated impact direction of the abrasives towards the sample surface. The direct impacts towards the surface produced similar large dents in the both surfaces. Penetration and deformation depths of the abrasives were about twice as deep in the field tested specimens, probably caused by the larger particle size.

Fig. 11 shows the cross sections of the field tested and the erosion tested QT samples. Now the arrow is indicating slightly oblique impact angle for the particles, as the figures are taken from the side part of the round bars. It can be observed that the lateral impact towards the surface produced similar main features into the both surfaces with entrapment of the abrasives and the formations of plastically deformed lips.

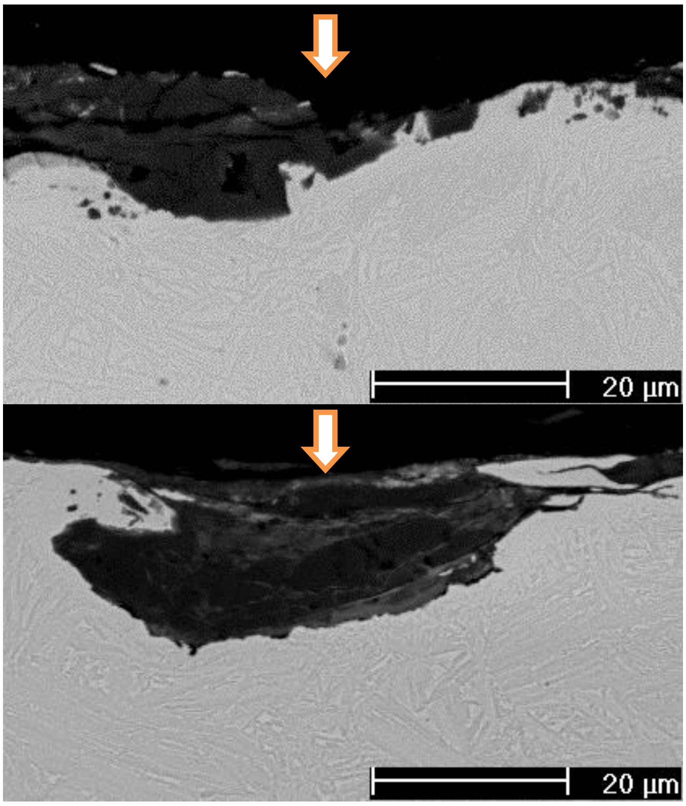

*Figure 10. The cross-section of the erosion tested (above) and the field tested (below) CFB300 specimen. The arrow indicates the direction of the impact.*

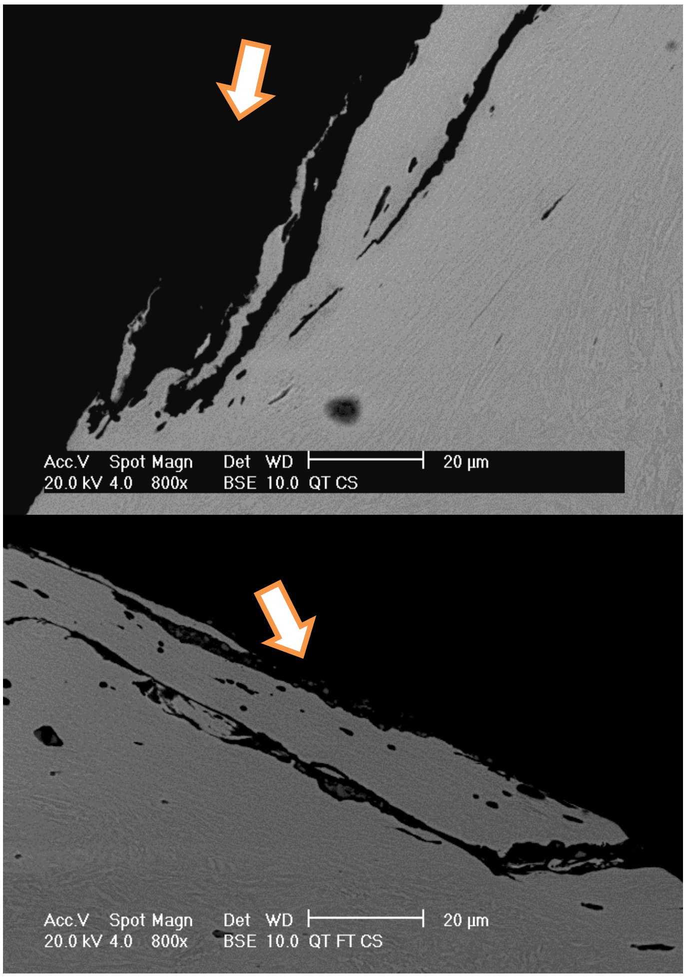


*Figure 11. The cross-section of the erosion tested (above) and the field tested (below) QT specimen. The arrow indicates the direction of the impact.*

## 4. DISCUSSION

The CFB-steels were compared against the QT-steel in an application subjected to a combination of erosive and abrasive wear. In addition of field tests, also laboratory scale studies were performed with abrasion tester and dry-pot erosion tester. Fig. 12 presents comparison of all wear tests. The results are scaled to the result of QT reference material in each test. The summary of the results shows that the dry-pot test method is closer to the real industrial application as the conventional abrasive paper wear test. Also the deviations in the dry-pot results are much smaller than in the abrasion test.

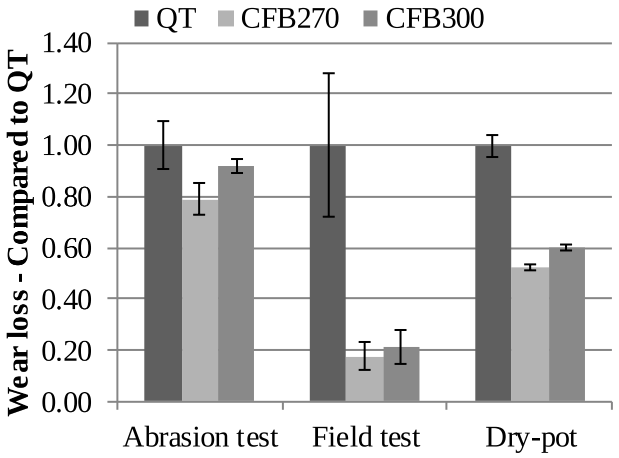


*Figure 12. Summary of the wear test results.*

Laboratory scale abrasion studies scaled the materials in similar order as in the field tests, but the wear surfaces were dissimilar. The predominant wear mode in abrasion tester was 2-body abrasion. The work hardening effect was not observed while the wear involved only sliding of the surface against sand paper. This low-stress wear test method results in ploughing tracks on the samples surface but the load on the surface is not high enough to result in any work hardening effect or notable surface deformations.

The dry-pot condition was more severe with high speed combined with larger abrasive size than in the abrasion test. The wear resistance of the samples increased with increasing surface-hardness, but not linearly. High number of impacts with large size abrasives work hardened the surface and increase in the surface hardness was observed after the dry-pot tests, as was presented in Fig. 10. Furthermore, the surface and cross-section studies of the wear tested samples showed that the dry-pot method did produce very similar wear mechanisms and material response, i.e. work hardening, surface deformations and tribolayer formation, in comparison with those obtained in the field test.

In the field test, the difference in volume losses between the QT samples and CFB samples was higher than in the dry-pot test. The field tested surfaces contained longer cutting marks which exposed more fresh steel surfaces towards the impacts. In the dry-pot tested samples, the level of embedment was observed to be higher in the wear surfaces. Cutting was also observed but not as extensively as in the field tested samples. Nevertheless, it should be noticed that the field tested surfaces were studied after service of 28 days, whereas the dry-pot tested wear surfaces after a relatively short test period. Also the abrasives were different types in the dry-pot and the field tests, and the particle size was much larger in the field test. Nevertheless, the test materials showed similar abrasive erosion wear surfaces in both tests.

When the cross-sections of the dry-pot samples were characterized, two different features were found. Towards the direction of rotation the cross section had more craters produced by impacts whereas in the sides the cutting marks were dominant. Similar features were also found on the cross-sectioned field tested samples and both types of samples had embedded stones. In the field tested samples these layers were more distinct mechanically mixed layers of steel and stone. Such composite surface layers have been observed also in earlier studies where the testing with natural stones has been made [15, 16].

The effect of the embedded abrasives needs also to be considered. This changes the properties of the wear surfaces. At the very beginning the pure steel surface changes into the combination of the steel and stone. The softer the surface the more stone can be mechanically mixed into the surface and affect the further wear behavior. In some cases it might benefit the surface by improving the wear resistance but it has also been suggested that the softer surfaces with mixed stone might increase the wear rate by spalling the whole layer [15].

In the field tests, the stone used as abrasive was iron ore with wide size distribution of particles, largest pieces being up to 150 mm in size, whereas in the dry-pot the used abrasive was granite gravel with original size of 8-10 mm. As the dry-pot method is batch operated, the size of the particles is very effectively reduced by crushing during the test, producing constantly new sharp edges for cutting. After 15 minutes of test the abrasive batch was renewed. However, the scatter of the field test results was much larger than in the dry-pot tests, thus showing the difficulty in producing reproducible field tests.

## 5. CONCLUSIONS

The abrasion and erosion resistance of carbide free bainitic steel with two different austempering treatments were studied in the field test, in laboratory abrasion test and in application oriented laboratory erosion test. A commercial quenched and tempered steel, that is the standard material in the field test application, was used as a reference material. CFB steels had the lowest wear rates in every test type. The difference was highest in the field tests and in the dry-pot tests where the sample surfaces were work hardened. The hardness profiles of these samples were similar for the dry-pot tests and the field tests performed. In abrasion tested samples no increase of surface hardness was observed. These results imply that CFB steels are a good candidate for applications subjected to wear in which high-stress erosion and abrasion are prevalent.

The mechanisms resulting in an increase of the surface hardness and wear resistance of the CFB steel structures achieved in erosion wear test and in the field test are deformation hardening in combination with transformation of austenite to martensite at the surface. The dry-pot test developed and used in this work has shown ability to simulate the real wear in application very accurately. The results and the characterization indicated that the dry-pot method produced similar conditions for wear tests as the field test. Although the laboratory abrasion tests ranked the materials in same order it failed to simulate surface deformations completely and the main wear mechanisms were different than in the industrial application, also the deviations of the results the highest. The essence of the similar wear conditions in material selection tests is therefore highlighted.

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