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Abrasion wear performance of quenched wear resistant steels

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1. Introduction

The wear resistance of commercial quenched wear resistant steels is commonly categorized by their Brinell hardness. The hardness grades are considered almost as standards, although the wear resistant steels are standardized only in China. Nevertheless, these steels are not as similar in wear resistance as they generally are thought to be.

Abrasive wear properties of commercial 400 HB grade quenched wear resistant steels were tested to obtain a better understanding of the consistency of their wear performance. In total 15 different trade names from manufacturers all over the world were included in the study. The testing method simulated heavy abrasive wear in rock crushing and mineral processing, which are typical applications for the quenched wear resistant steels.

In this paper, properties such as hardness, hardness profiles, microstructures and chemical compositions of commercial 400 HB grade quenched wear steels were studied and reasons for the differences in their wear performance further discussed.

2. Materials and methods

Fifteen 400 HB grade quenched wear resistant steels were tested with the crushing pin-on-disk high stress abrasion wear tester [1] at the Tampere Wear Center. Figure 1 illustrates the device, in which the gravel is cyclically pressed between a rotating disk and a sample pin. Table 2 presents the size distribution of the granite gravel that was used as an abrasive.

The test method is based on the pin-on-disk principle but without a direct pin-to-disk contact. The pin with a 36 mm diameter crushes the abrasive against the rotating disk. Each test in this study included a 15 minute pretest to reach steady-state wear, while the actual test duration was 30 minutes. The disk rotation speed was 20 rpm, and the pin was cyclically pressed down for 5 seconds and then lifted up for 2.5 seconds. In the current tests, 1.1 bar pin pressure was used, which gives a 235 N nominal crushing force. The disk material was S355 structural steel with hardness of 200 HV. Three samples of each test material were tested. The wear rates were determined by weighing the samples five times during the tests.

Five of the fifteen wear tested steels were selected for a closer examination. The selection was based on the overall performance and initial surface hardness of the materials. Thus, steels with the lowest and highest mass losses and hardness values were selected.

The tested steels had a nominally similar alloying and

the same microstructure and hardness, i.e., they were all martensitic boron steels from the low-alloyed carbon steel group. Sheet thickness was 10 mm for steels A, B, C and E, and 12 mm for steel D. Table 2 presents the chemical compositions of the selected steels analyzed by optical emission spectrometer at Metso Minerals.

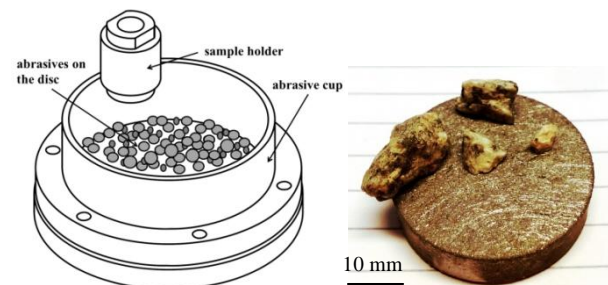


Figure 1 Crushing pin-on-disk wear test device and a wear test sample with granite abrasives.

Table 1 Size distribution of the granite gravel used in the tests.

Abrasive size [mm]	Mass fraction [g]
8 / 10	50
6.3 / 8	150
4 / 6.3	250
2 / 4	50
Total	500

Table 2 Chemical compositions of the studied steels.

Steel	A	B	C	D	E
Chemical composition (wt%)					
C	0.16	0.15	0.15	0.18	0.14
Si	0.4	0.28	0.22	0.2	0.38
Mn	1.38	0.96	1.35	1.38	1.41
P	0.015	0.012	0.007	0.015	0.014
S	0.002	0.003	0.002	0.003	0.001
Cu	0.01	0.02	0.05	0.06	0.03
Cr	0.14	0.37	0.41	0.18	0.46
Ni	0.04	0.07	0.09	0.06	0.04
Mo	0.15	0.1	0.01	0.19	0
Al	0.034	0.031	0.1	0.04	0.025
N	0.005	0.006	0.005	0.009	0.007
V	0.01	0.01	0.004	0.01	0.01
B	0.003	0.001	0.002	0.001	0.002

Before the wear tests, one millimeter was machined off from the sample surfaces to get rid of the decarburization layer and thus to reach a stable hardness depth. The surface hardness was measured from six

points over the test surface. The standard deviations of the measured values were small, 5–10 HV only. Moreover, the hardness profiles of the cross-sections were measured from the untested and tested samples. The microstructures of the steels, the wear surfaces and the wear surface cross-sections were characterized by optical and scanning electron microscopy. Nital was used for etching.

3. Results

Between the nominally similar 400 HB steels some substantial wear performance differences were observed. For example, the variation in the initial surface hardness values was more than 25 %, and in wear tests the differences in the mass losses were as high as 53 %. On the other hand, the mass loss of the hardest steel was not the lowest, and the steel with the lowest hardness did not have the worst abrasive wear performance.

Figure 2 presents the wear test results and the surface hardness values as averages of three tested samples. The results clearly indicate that surface hardness differences do not explain the variations in the mass losses.

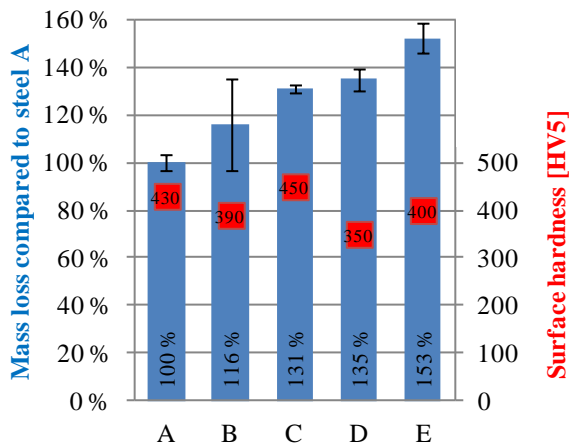


Figure 2 Wear test results with standard deviation and initial surface hardness values. Average mass loss for steel A was 0.142 g.

3.1. Wear surfaces

After the wear tests the wear surfaces were studied with optical and scanning electron microscopy. Figure 3 presents the wear surfaces of steels A and E. In general, the steels with higher wear rates contained more scratches, which also were longer and deeper. The only exception was steel D, which did not have any deep cutting marks and was also less scratched than steel C. All steels had plenty of embedded granite on the surface.

For steel B, which showed the biggest scatter in the mass loss, all three wear surfaces were a little bit different in terms of surface scratching. In the most worn sample, long scratches were found all around the surface, while in the least worn sample only about a quarter of the wear surface contained such clearly visible scratches.

3.2. Hardness profiles

The hardness profiles of the steels were measured

from untested samples. Figure 4 presents the profiles. General trends of the hardness profiles, from surface to the depth of one millimeter, were steadily positive for steels A and B.

Moreover, it was observed that the hardness profile of steel D was fluctuating from 350 to 460 HV. This indicates problems in the quality and the manufacturing process, either the rolling or heat treatment, of this steel.

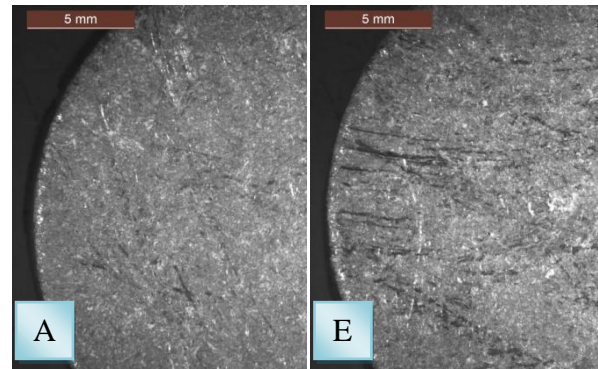


Figure 3 Stereo microscope images of two wear surfaces.

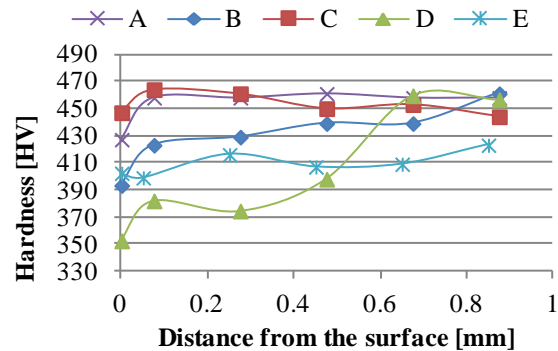


Figure 4 Hardness profiles from the untested samples.

3.3. Microstructures

The microstructures were analyzed from the cross sections of the untested samples. The characterization showed that all steels had a tempered martensite microstructure. Figure 5 presents optical micrographs of the steels. All tested steels contained large amounts of tempered martensite, the lath structure of which was well visible in the optical microscope. Unetched white grains seen in the micrographs are untempered white martensite, which is a hard and brittle phase.

Steels B, D and E had the largest parent austenite grain size, and steel A had the most homogenous microstructure. The steels with highest hardness values, A and C, had the shortest martensite laths, which also appeared rather thick. Steel C contained larger white martensite grains compared to steel A, which together with steel B had the finest white martensite grains.

3.4. Wear surface cross-sections

The surface deformations, changes in the microstructures, and microhardness values were determined from the wear surface cross-sections. For all steels, the surface layers were heavily deformed and the martensite laths were mechanically fibered. The thickness of the visibly deformed layer varied from some micrometers to about 60 μm .

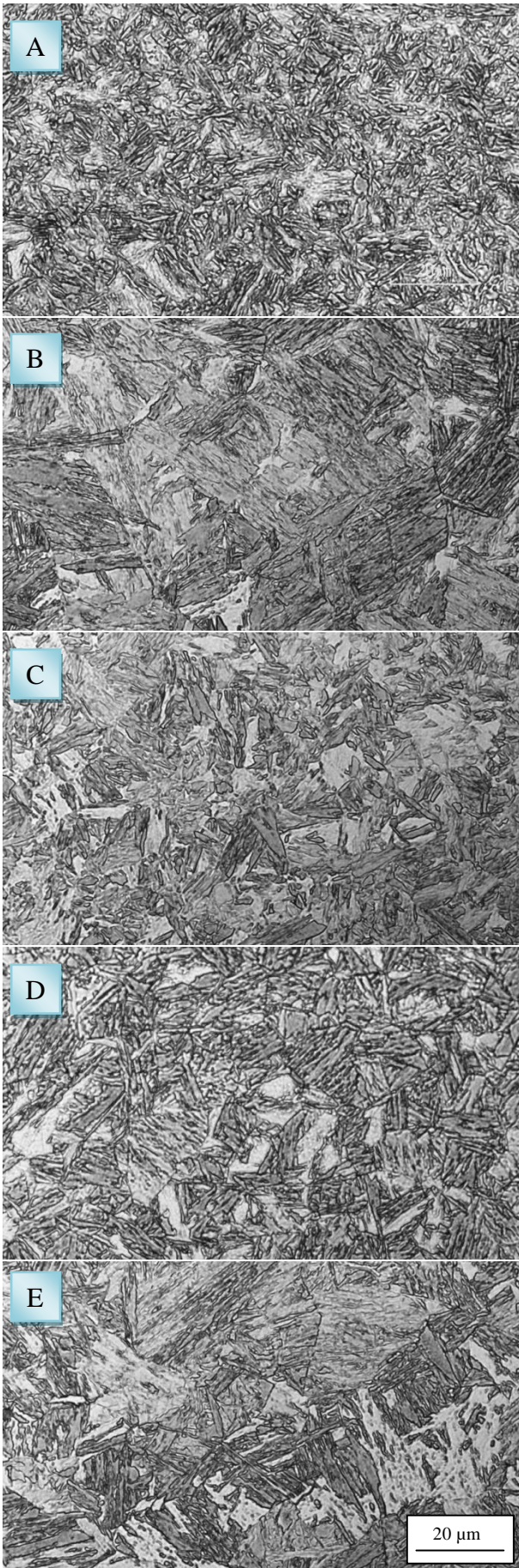


Figure 5 *Optical micrographs of the studied steels.*

The clearest difference in the deformation behavior of the studied steels was in their ability to deform plastically and in the average thickness of the deformed layer. Steels A and B were more evenly deformed than the others, and their deformed microstructures were also still mostly distinguishable. The other steels contained more very thin layers with very fine microstructures and high hardness. The hardest layer in steel B was 605 HV0.05, as for steel C it was 820 HV0.05.

Figure 6 shows the difference between steel B, which showed the highest amount of plastic flow, and steel C, which had the highest hardness and plenty of evident rather brittle chip formation. Almost in all plastically deformed areas on the surface of steel C, cracked or partially detached surface layers were observed.

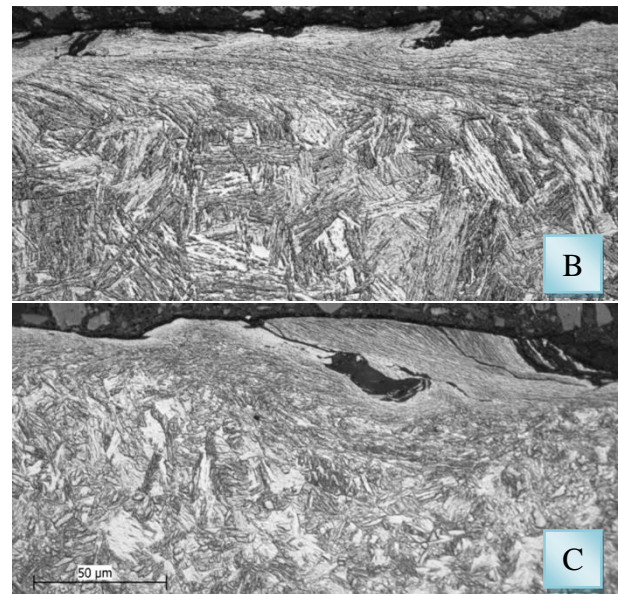


Figure 6 *Optical micrographs of the wear surface cross-sections of steels B and C.*

4. Discussion

There were significant differences in the heavy abrasion wear performance of the studied 400 HB grade quenched wear resistant steels. The wear rate of steel A, which had 430 HV surface hardness, was 31 % lower than that of 450 HV steel C, and even 53% lower than that of 400 HV steel E. Consequently, if one wear resistant steel is changed to a nominally similar steel, the risk of unexpected failure of the wear part is evident.

4.1. Chemical composition and microstructure

The wear performance of steels usually depends on the concentration of their main alloying elements, carbon, molybdenum and boron. These elements all are important for the quenched wear resistant steels, as they either raise the hardness, like carbon, or more importantly enhance the hardenability of the steel, like molybdenum and boron [2]. Moreover, the combined concentration of nickel and molybdenum also affects the wear performance. Steel D had the highest carbon and molybdenum content of the studied steels, but the strongly fluctuating hardness profile points to some manufacturing problems. Therefore steel D will be

omitted in the further discussion.

Steel A had the highest of boron and combined nickel-molybdenum contents and the lowest wear rate. Nickel-molybdenum as a combination has a larger effect on the hardenability of the steel than either one of the elements alone. Boron has the biggest effect on the hardenability as a single alloying element, even in small quantities. Boron also helps to remove nitrogen and therefore increases toughness. [2]

Steel E with the worst wear performance did not contain any molybdenum and obviously therefore exhibited the poorest hardenability of the studied steels. The large amount of white martensite in its microstructure and the negative hardness gradient also support this conclusion.

Steels A and C had similar hardness, but the grain size of steel C was larger and it also contained more of the brittle white martensite. The reason for this can be the aluminum content, as steel C contained substantially more aluminum than the other studied grades. Aluminum and also nickel have been reported to increase the stacking fault energy of austenite and thereby to hinder the martensite formation [3]. For martensitic wear resistant steels the amount of white martensite over tempered martensite is crucial, because white untempered martensite is very brittle.

Furthermore, there were some differences in the total amounts of the alloying elements. Generally all alloying elements either decrease the M_s -temperature or restrain the decomposition of austenite, both resulting in the retardation of martensite formation [2]. Steel B, which had the finest white martensite grains, had clearly the smallest amount of alloying elements, in total 2.01 wt%, while steel E had the highest amount of 2.52 wt%. Steels B and E had almost the same bulk hardness, but the difference in their wear performance was notable, obviously due to the large difference in their alloying.

Thus, for wear resistant steels, a sufficient amount of carbon and boron with high combined nickel-molybdenum level to provide acceptable hardenability is needed. Moreover, proper manufacturing methods and accurate quenching processes provide a homogenous martensitic microstructure with low amounts of fine grained white martensite, like in steels A and B.

4.2. Surface deformation and work hardening

The deformation depth visible in optical microscopy was small, at highest only about 60 μm , but the hardness gradient extending deeper into the material also seemed to affect the abrasive wear caused by the granite particles up to 10 mm in size. Misra and Finnie [4] reported for soft steels that particles larger than the thickness of the hardened layer can penetrate it and thereby decrease or completely eliminate the effect of work hardening. However, when the subsurface layers are hard and preferably have a positive hardness gradient, it will require more energy for large particles to penetrate the surface.

Hardell et al. [6] reported that different quenching methods for the same boron steel resulted in very different hardness values but still comparable wear

performance in unidirectional abrasive wear. They concluded that this was due to the work hardening of the surface layer. In the current work, the initially second softest steel work hardened most and was ranked second in the wear performance.

It appears that in heavy abrasive wear the surface needs the ability to withstand multidirectional and repeated deformations. Moreover, support from the hard layers beneath the surface is needed to prevent abrasives from penetrating and causing deep scratches. The initial surface hardness is not so decisive when the abrasive wear causes marked work hardening of the surface. This was especially evident when steels B and C were compared with each other. Particularly in rock crushing and other mineral processing applications, work hardenability of the steel has a significant effect on its abrasion wear resistance.

5. Conclusions

Nominally similar 400 HB grade quenched wear resistant steels do not perform equally under heavy abrasion wear, and hardness alone is not an accurate predictor of the steel's wear performance. Alloying and manufacturing of the steel and thus its microstructure and hardness profile have a significant effect particularly on the work hardening behavior of the steel during abrasion, leading to different wear performances under such conditions.

Acknowledgements

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