EFFECT OF ABRASIVE PROPERTIES ON THE HIGH-STRESS THREE-BODY ABRASION OF STEELS AND HARD METALS

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ABSTRACT

Especially in tunneling, the abrasiveness of rock is an important property, which can easily be determined by several methods developed for the purpose. With this in mind, it is rather surprising that the effects of different rock types on the wear mechanisms of engineering materials have not been too widely studied. In this paper, high stress three-body abrasive tests were conducted with four different abrasives with a relatively large (2-10 mm) particle size. As test materials, three different steels and three hard metals were used. The tests clearly showed that material type has an influence on how different abrasive and material properties affect the abrasive wear mechanisms and severity. For example with hard metals, the most important property of the abrasives is their crushability, as only small abrasive particles are able to properly attack the binder phase and cause high wear rates. On the other hand, it seems that the abrasiveness of rock is not the dominating property determining the severity of wear in the current test conditions for any of the tested materials. In fact, with steels no single abrasive property could be shown to clearly govern the abrasive wear processes. In any case, when using the determined abrasiveness values in wear estimations, the contact conditions in the method used for determining the abrasiveness values should be as similar as possible with the end application.

INTRODUCTION

Abrasive wear occurs widely in everyday life in both households and industry. The estimated annual cost of abrasive wear is 1-4 % of the GNP of the industrialized countries [1]. From the economical point of view, it has been estimated that in engineering abrasive wear is probably the most crucial type of wear [2].

A common way to study abrasive wear is to use the standard ASTM G65 dry sand rubber wheel test. However, the correlation of its conditions with real applications is not always clear. For example, when screening materials for mineral crushing applications, Ala-Kleme et al. [3] concluded that the correspondence of the rubber wheel results with the field test results was very poor.

Since the conditions play an essential role in the wear processes, application-tailored wear tests have been of increasing interest in the industry. In order to obtain results, which are closely related to the application, one should try to simulate the true conditions as well as possible. In abrasive wear testing, a good way of increasing the degree of reality is to use abrasives that are likely to be present in the intended application. Natural stones are therefore a good choice for abrasives when testing materials for earth moving and mining machinery.

Abrasive wear is a complex phenomenon and there are many variables to be taken into account, such as the wear environment, the type of motion, and the contact forces. Changing one variable can change the outcome of the tests substantially.

An essential variable in abrasive wear is the abrasive itself and its properties. The abrasive is in a big role largely determining the mechanisms with which the wear is happening. The effects of size [4–7] and shape of the abrasives [8–11] on wear have been discussed by several authors. The same abrasive properties may have different effects when conditions change, for example, from impacts to abrasion [12]. On the other hand, different wear mechanisms can be observed in systems where the conditions are similar and only the abrasive type is varied [12–14].

The abrasiveness of rock and soil and the methods of measuring it have been discussed widely in geology and tunneling [15–22]. Some methods used for determining the abrasiveness of rock are thin section analysis, Cerchar test, LCPC test, Schimazek index test, Sievers C-value test, Böhme grinding test [18], the brittleness value test, Sievers J-value test, and abrasion value and abrasion value cutter steel test [21]. The Cerchar abrasivity test is widely used for TBM tunneling and also for academic purposes [19,23]. On the other hand, it tests the properties of individual grains or blocks only [18] and is affected by the stress state of the rock [23]. The LCPC test is an abrasiveness test that enables the investigation of rock samples consisting of several grains with various sizes, and it has been reported to be one of the most used methods for determining the abrasiveness of rock materials in Europe [18].

There are only a limited number of papers, which take into consideration the properties of real rock materials in high stress abrasive wear conditions. Some researchers have investigated abrasive wear with larger size abrasives in impacting conditions [13,24–26]. On the other hand, in the abrasive wear tests, the particle size has often been restricted to less than a millimeter [4,5,12,26,27] even in the studies determining the size effect of abrasives or natural stones on wear.

The aims of this study are to compare different Finnish rock species and the wear type they produce in some typical mining and earth moving machinery materials under controlled compressive crushing conditions, and to find correlations between the rock properties and wear performance of selected steels and hard metals.

MATERIALS AND METHODS

Several different steel and WC-Co specimens were tested using the crushing pin-on-disc wear test procedure. Four different rock species were used as abrasives.

Metals and hard metals

The abrasive wear resistance of three steel and three hard metal grades were evaluated. Table 1 lists the steels along with their nominal mechanical properties and compositions. One of the steels was the commonly used structural steel grade S355 with a ferritic-pearlitic microstructure, and the two other steels were quenched wear resistant martensitic steels with different hardness, denoted as 400HB and 500HB according to their commercial hardness grade. Besides steels, three hard metal grades were also tested. Table 2 presents the hardness and nominal compositions of the hard metals. They all consisted of tungsten carbides (average carbide size 2.5 µm) with different amounts of cobalt as the binder phase.

Table 1. Nominal mechanical properties and compositions of the tested steels.

Material	S355	400HB	500HB
Hardness [HV]	172	423	505
Yield strength [N/mm^2]	355	1000	1250
Tensile strength [N/mm^2]	470-630	1250	1600
A5 [%]	20	10	8
Density [g/cm^3]	7.88	7.85	7.85
C [max%]	0.18	0.23	0.3
Si [max%]	0.5	0.8	0.8
Mn [max%]	1.6	1.7	1.7
P [max%]	0.025	0.025	0.025
S [max%]	0.02	0.015	0.015
Nb [max%]	0.05	-	-
Cr [max%]	-	1.5	1.5
Ni [max%]	-	1	1
Mo [max%]	-	0.5	0.5
B [max%]	-	0.005	0.005

Table 2. Hardness, density and nominal compositions of the tested hard metals.

Material	Hardness [HV]	Density [g/cm^3]	Composition [wt.-%]	
			WC	Co
WC-26Co	870	13.02	74	26
WC-20Co	1050	13.44	80	20
WC-15Co	1260	13.99	85	15

Abrasives

Table 3 lists the properties and nominal mineral contents of the used abrasives. As the abrasives are natural stones, their properties can vary locally and should be regarded only as approximates. The density, uniaxial compressive strength (UCS), and quartz content were obtained from the supplier of the rocks. The abrasiveness and crushability values were determined using the LCPC test, which is described in the French standard NF P18-579. The tests were conducted in the Metso Minerals Rock Laboratory in Tampere. The LCPC test gives the LCPC abrasion coefficient (LAC) and the LCPC breakability coefficient (LBC). In the test, a standardized steel block with hardness of 60-75 HRB is rotated in a 500 g batch of 4-6.3 mm rock in a container for 5 minutes [15]. The abrasiveness (LAC) is determined from the mass loss of the steel block and the crushability (LBC) from the rock sieving results using the following equations [19]:

$$LAC = \frac{m_0 - m}{M} \tag{1}$$

$$LBC = \frac{M_{1.6} \cdot 100}{M} \tag{2}$$

where m_0 and m are the steel block's mass before and after the test, respectively. M is the mass of the abrasive (500 g, i.e., 0.0005 t) and $M_{1.6}$ is the mass of the <1.6 mm fraction of the abrasives after the test.

The hardness values of the rocks were measured with Duramin A300 hardness tester. Several indentations were made, and the final average hardness was calculated by taking into account the relative fractions of the different phases and their hardness in the rock. The mineral compositions were determined with X-ray-diffraction.

Table 3. Properties and nominal mineral contents of the used abrasives.

Rock species	Tonalite	Granite	Gneiss	Quartzite
Abbreviation	T	GR	GN	Q
Quarry	Koskenkylä	Sorila, Tampere	Lakalaiva, Tampere	Nilsiä, Haluna
Density (kg/m³)	2660	2674	2747	2600
Uniaxial compressive strength (MPa)	308	194	64	90
Hardness (HV1)	960	800	700	1200
Quartz content (wt%)	40	25	24	98
Abrasiveness (g/t)	1460	1920	1430	1840
Crushability (%)	18	34	37	74
Nominal mineral contents (%)	quartz (40) plagioclase (40) biotite (17) amphibole (3)	plagioclase (45) quartz (25) orthoclase (13) biotite (10) amphibole (5)	plagioclase (36) biotite (25) quartz (24) orthoclase (7) amphibole (5) garnet(3)	quartz (98) sericite hematite

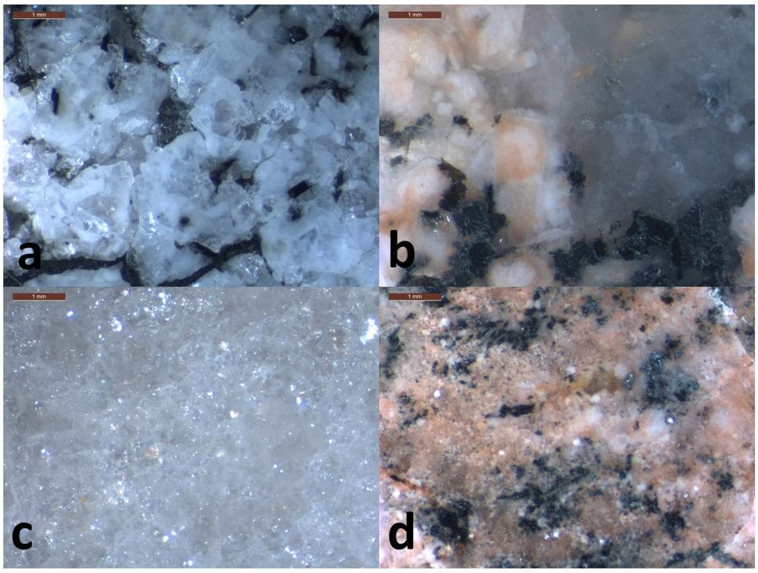

Figure 1. Images of the polished rock specimens used for wear testing a) gneiss, b) granite, c) quartzite and d) tonalite. Scale bar is 1 mm.

Figure 1 presents optical stereo microscope images of the polished surfaces of the abrasives. It can be observed that granite (1b) and gneiss (1a) have a similar and quite coarse grain structure. Tonalite (1d) consists of quite small size grains, and quartzite (1c) has the finest grain structure of the studied abrasives.

Figure 2 illustrates the appearance of the abrasive particles, revealing also the evident differences in their morphology. Gneiss (2a) has a quite heterogeneous structure including spherical, longitudinal and also flaky particles. Tonalite particles (2d), in turn, are quite round. Granite (2b) and quartzite particles (2c) have a quite similar morphology, consisting mainly of angular particles.

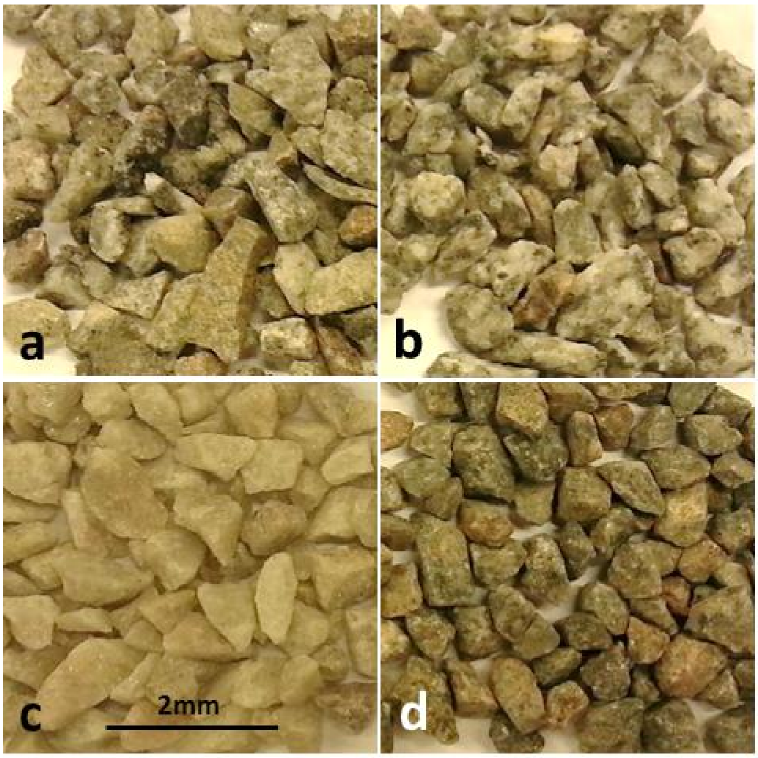

Figure 2. Images of the abrasive particles used for wear testing a) gneiss, b) granite, c) quartzite and d) tonalite.

Crushing pin-on-disc abrasive wear testing

The wear tests were conducted with a crushing pin-on-disc [14], which is a three-body high stress abrasive wear tester. It has a setup similar to the common pin-on-disc equipment, but it enables addition of 500 g of 2-10 mm abrasive between the pin and the disc. This helps to simulate heavy abrasive conditions better than, for example, the dry sand rubber wheel abrasion tester, where the size of the abrasive is 212-300 µm [28]. Figure 3 presents schematically the principle of the equipment.

Unlike in the common pin-on-disc setup, in the crushing pin-on-disc the pin and the disc are not in contact with each other during the test, and thus the wear is induced purely by the abrasives. In the test, the pin is pressed against the abrasive bed on the rotating disc with a force of 240 N for 5 seconds, followed by an idle time for the abrasive to replenish between the pin and the disc. The abrasive is maintained on the disc with a collar. The disc material was structural steel S355 (216 HV) for the steel samples and tool steel (690 HV) for the hard metal specimens.

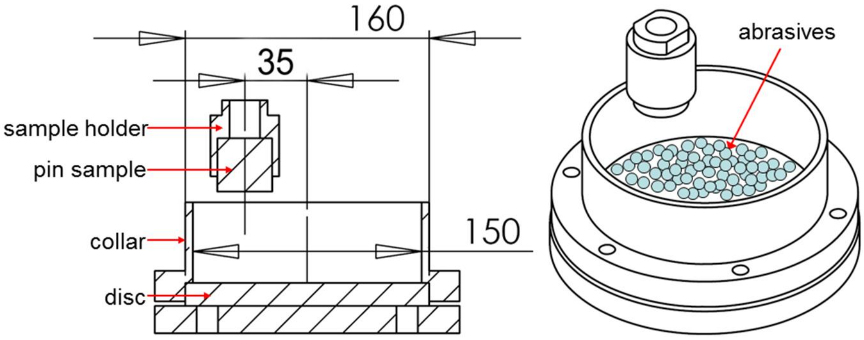

Figure 3. Schematic picture of the crushing pin-on-disc wear testing equipment.

Before the actual tests, the steel specimens were first subjected to a run-in period of 15 minutes, during which the steady-state wear was achieved. Also, in this way the effect of the embedded abrasive fragments on the mass loss was minimized. The total contact time when the pin was pressed against the abrasives was 20 minutes in each test. The wear was measured as mass loss, which was then converted to volume loss to enable better comparison of the wear in materials with different densities. Three repetitive tests were made on each specimen type.

After wear testing, the wear surfaces were characterized with Leica MZ 7.5 optical stereo microscope and Philips XL30 scanning electron microscope. Moreover, Wyko NT1100 optical profilometer was used to determine the wear surface profiles and to obtain numerical data of the roughness of the surface.

RESULTS

In this Chapter, the volume loss results are presented in relation to the properties of the abrasives. Also observations on the wear surfaces and the abrasive sieving results are presented and discussed.

Volume loss results

Higher hardness is generally known to enhance the abrasive wear resistance of materials, which was also clear in the current tests. Figure 4 presents the volume loss results from the tests with different abrasives in relation to the hardness of the test materials. Figure 4a shows that for the steels (hardness 172-505 HV) the trend is very clear, while for hard metals (Figure 4b) the correlation is less pronounced. The role of the abrasive type is clearest with hard metals tested with quartzite, the results being distinctly different from the results obtained for hard metals with the other abrasives. Also in steel specimens quartzite produces relatively more wear in the hardest alloy, but in the case of softer steels granite and gneiss clearly rise above it. This may result from the formation of an embedded quartzite powder layer on the softer materials, protecting the surface from being penetrated with larger size abrasives thus decreasing the wear rate [29].

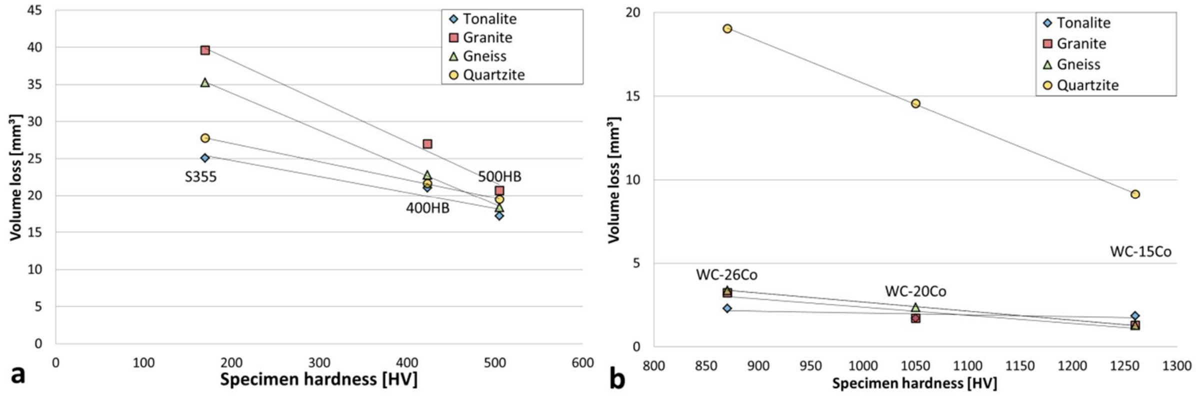

Figure 4. Volume loss of a) steel and b) hard metal specimens relative to their hardness.

Besides the volume loss of the pin, also the volume loss of the disc was monitored. For steels, the disc volume loss decreased as the pin hardness increased. This is probably because on harder materials the abrasive is more likely to pass the surface without embedding in it, and there is also less friction in the system.

Even though the pin and the disc are not in direct contact with each other during the test, the disc as the test counterpart has an effect on the moving of the abrasive in a three-body abrasion system [14,30,31]. The abrasive can move differently depending on whether the counterpart is softer or harder than the wearing part. For the tested steels, the pin/disc hardness ratio ranged from 0.8 to 2.3, while with the hard metals the ratio was 1.3-1.8. For both types of materials, the wear rate decreased as the ratio of the hardness of the pin and the disc increased, although no uniform dependence for both materials was found. It must also be kept in mind that in general the higher hardness of the specimen (pin) resulted in lower wear.

As there were distinct differences between the wear caused by different abrasives, the volume loss results were analyzed in view of the properties of the abrasives in order to find out, how they correlate with the wear test results and which properties have the largest effect. Figure 5 presents the wear results in relation to the crushability of the abrasives. It shows that there is a clear correlation between the wear of hard metals and the crushability of the abrasives, i.e., the amount of wear increases with increasing crushability. Moreover, the difference between the WC-Co grades is substantially larger when tested with quartzite compared to the other abrasives. For the steels, on the other hand, no such unambiguous trend can be observed. It is also worth noting that while the crushability seems to correlate with the wear rate of hard metals, for the uniaxial compressive strength (UCS) no such trend could be observed. This implies that while the uniaxial compressive strength is a measure of the overall rock strength, crushability is only a measure of the rock's ability to produce fine size particles during crushing.

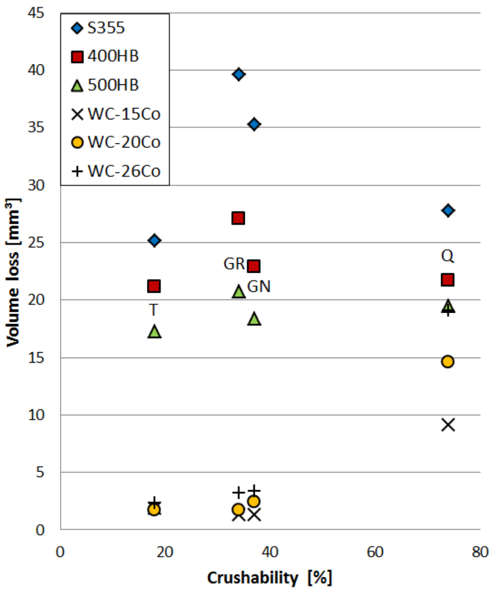

Figure 5. Volume loss of specimens in relation to the crushability of the abrasives.

Figure 6 presents the volume losses in relation to the abrasiveness of the abrasives. It is interesting to note that no clear linear correlation can be observed for either of the material groups. For example for steels, the abrasive with the highest abrasiveness value produces highest wear, but otherwise the results show only considerable scatter. This suggests that the contact conditions affect the abrasion process considerably and that the abrasiveness values determined with the LCPC test do not comply with the contact conditions prevalent in the crushing pin-on-disc test.

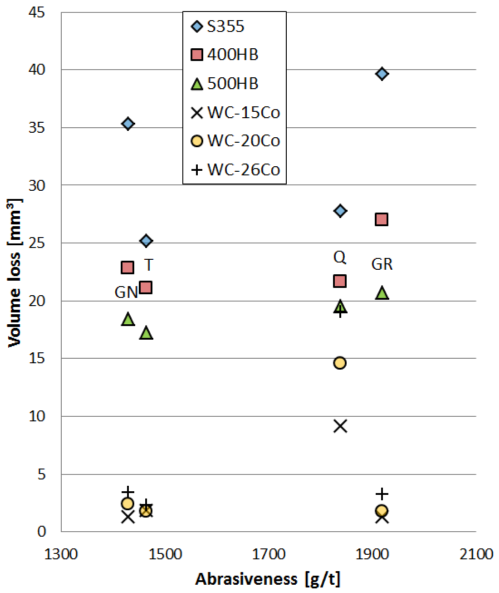

Figure 6. The volume loss of specimens in relation to the abrasiveness of the abrasives.

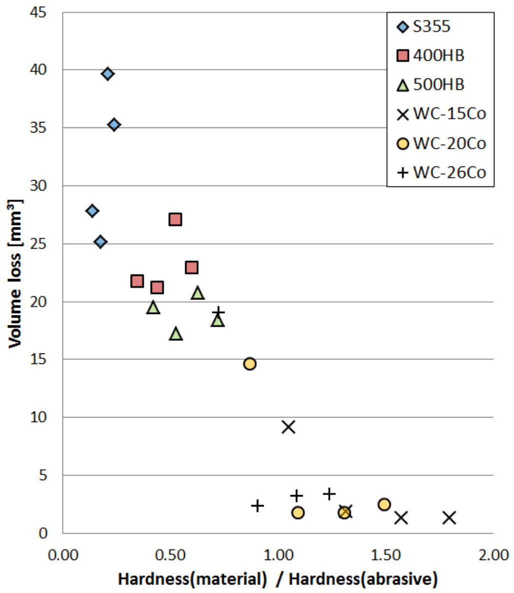

Figure 7. Volume loss dependence on the hardness ratio of the test material and the abrasive.

As hardness in any case plays a major role in the abrasive wear of materials and affects the choice of mechanisms by which it primarily happens, it is worthwhile to study also the effect of the hardness ratio of the test material and the abrasive on the wear process. It is generally taken that for a scratch to form the material hardness must be 80% or less of the abrasive hardness [32,33]. Figure 7 presents the volume loss as a function of the hardness ratio of the test materials and the abrasives. The trend is clear, showing that the higher is the hardness ratio, the lower is the wear rate. The value above which excess hardness does not anymore provide additional benefit seems to be around 0.9-1.1.

Abrasive sieving

Figure 8 presents the average sieving results of the abrasives after the tests with steels. The results are in good agreement with the crushability results presented in Table 3, where quartzite has a clearly higher and tonalite clearly lower crushability than granite and gneiss, which again are very close to each other. The LBC crushability values show the percentage of particles smaller than 1.6 mm after the LCPC test. A direct comparison between the crushability and the sieving results after the crushing pin-on-disc cannot be made due to different initial size distribution and test time. However, an approximate assumption can be made by comparing the crushability value with the percentage of particles smaller than 2 mm after the crushing pin-on-disc. These percentage values are presented in Figure 8 above the sieving results. The values are overall higher than the crushability results of the LCPC test, which is to be expected because of the crushing motion during the test, along with the longer test duration. However, the observations about the effect of crushability on wear remain similar when using either LCPC or application-specific crushability values.

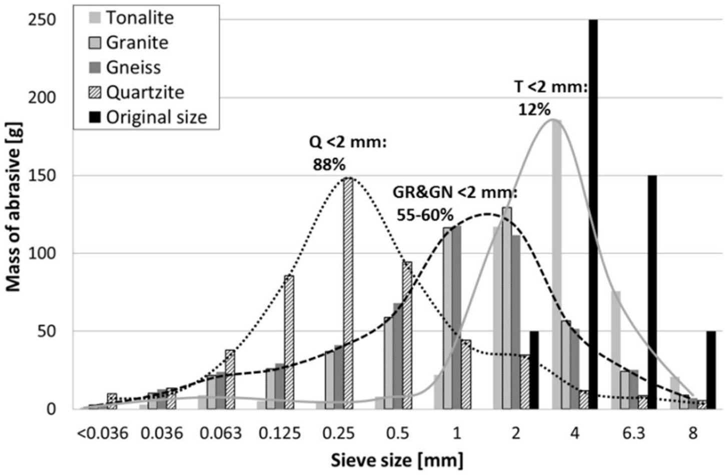

Figure 8. The average sieving results of the used abrasives after the tests with steels and the percentage of particles smaller than 2 mm. Also the original size distribution is shown.

Microscopy

The appearance of wear surfaces was investigated with a scanning electron microscope (SEM). Figure 9 presents the SEM images of 500HB specimens, where clear differences between the wear caused by different abrasive types can be observed. The specimen tested with granite (Figure 9b) contains wider and longer scratches compared to the specimen tested with gneiss (Figure 9a). Although granite and gneiss have approximately the same crushability and quartz content, their UCS are distinctly different, granite having values of about 194 MPa and gneiss about 64 MPa. As higher UCS transmits more effectively the crushing forces to the specimen, this leads to higher degree of deformation on the surface.

The specimen tested with quartzite (Figure 9c) shows the shortest and seemingly shallowest scratches. This is evidently associated with the high crushability value of quartzite, which means that quartzite breaks easily under high stress creating lots of small particles. This is also seen as the larger amount of very fine abrasive powder embedded on the surface, appearing as darker regions in the backscatter electron image.

Figure 9d shows the surface tested with tonalite, containing the highest amount of large scratches. The long scratches stem from the low crushability value of the mineral, enabling the particles to remain intact longer and thus to produce longer scratches.

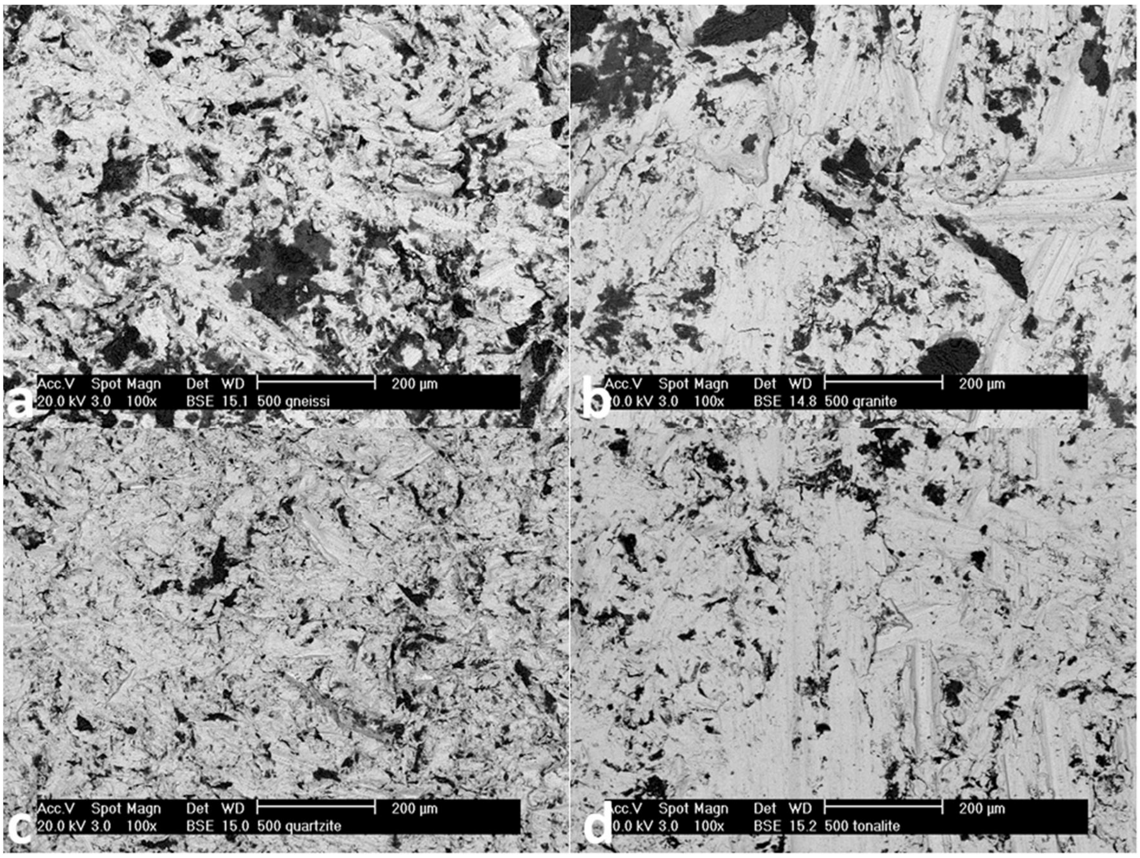

Figure 9. Backscatter scanning electron microscope image of 500HB steel tested with a) gneiss, b) granite, c) quartzite and d) tonalite. The metal is seen as light and the abrasives as dark areas.

Figure 10 shows the wear surfaces of the WC-Co specimens containing 26wt% of the soft binder phase, which is the reason for the relatively low hardness of the material. Although quartzite produced the highest wear rates in the hard metal specimens, the actual wear surface in Figure 10c has the least worn appearance. There are some scratches visible, but they are shorter and narrower than with the other abrasives. Gneiss (Figure 10a) has produced quite wide but shallow scratches, as could be expected due to the flakiness of the abrasive particles. Granite (Figure 10b), in turn, has produced much deeper scratches than gneiss, but otherwise the wear surfaces look quite similar. The scratches produced by tonalite (Figure 10d) are long but quite narrow, and the harshness of the wear surface is lowest of all abraded WC-Co samples. Tonalite has a quite high compressive strength, and therefore it is able to scratch the surface longer before any fracture of the rock appears. Due to the bluntness of the tonalite particles, they are not able to produce deep scratches.

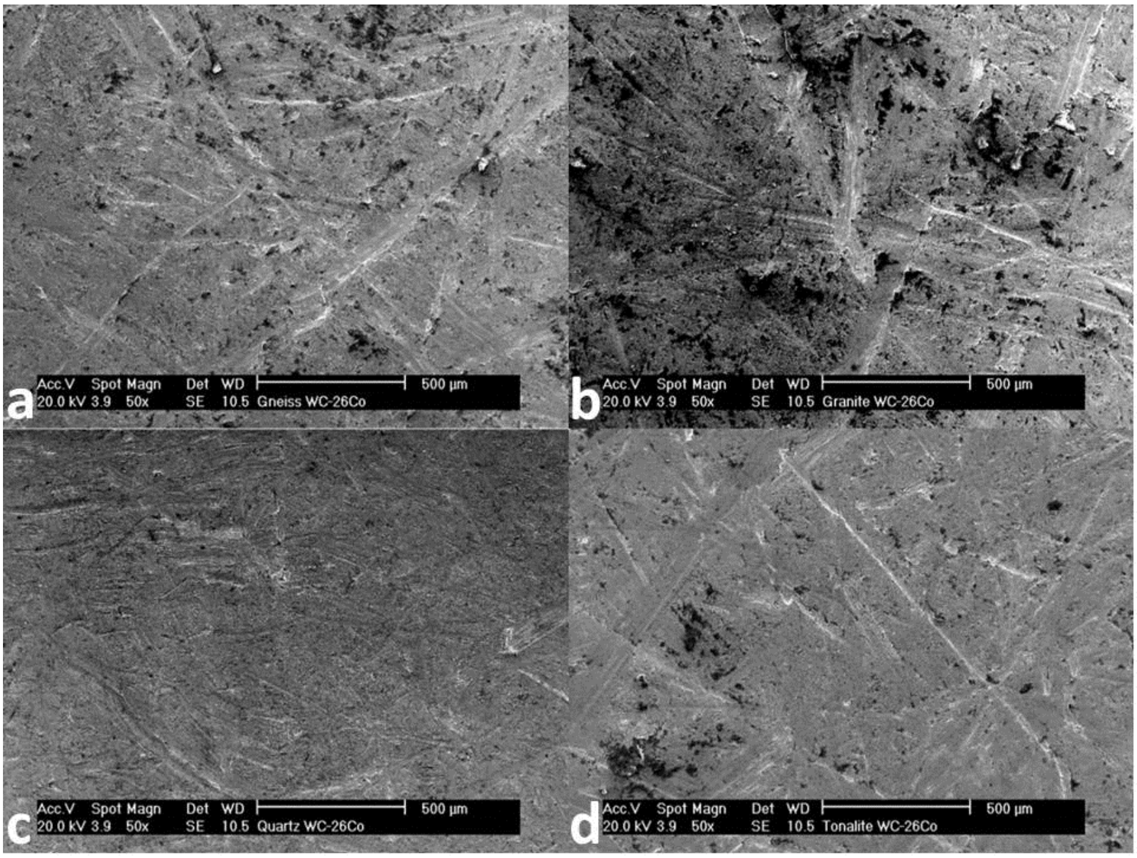

Figure 10. Scanning electron microscope images of WC-26Co hard metal tested with a) gneiss, b) granite, c) quartzite and d) tonalite.

Figure 11 gives a closer look at the wear surfaces of the WC-Co specimens. In all specimens, the carbides appear to be protruding from the surface, indicating that the binder matrix has worn more severely than the carbides. Also crushed carbides were found on every wear surface. The surfaces abraded with gneiss and granite look quite similar with more local binder phase removal than with quartzite, where the binder phase removal seems to be more general. With quartzite also the amount of crushed carbides appears to be higher, while tonalite seems to be producing the least amount of crushed particles. Re-embedment of crushed carbides was also observed on the wear surfaces.

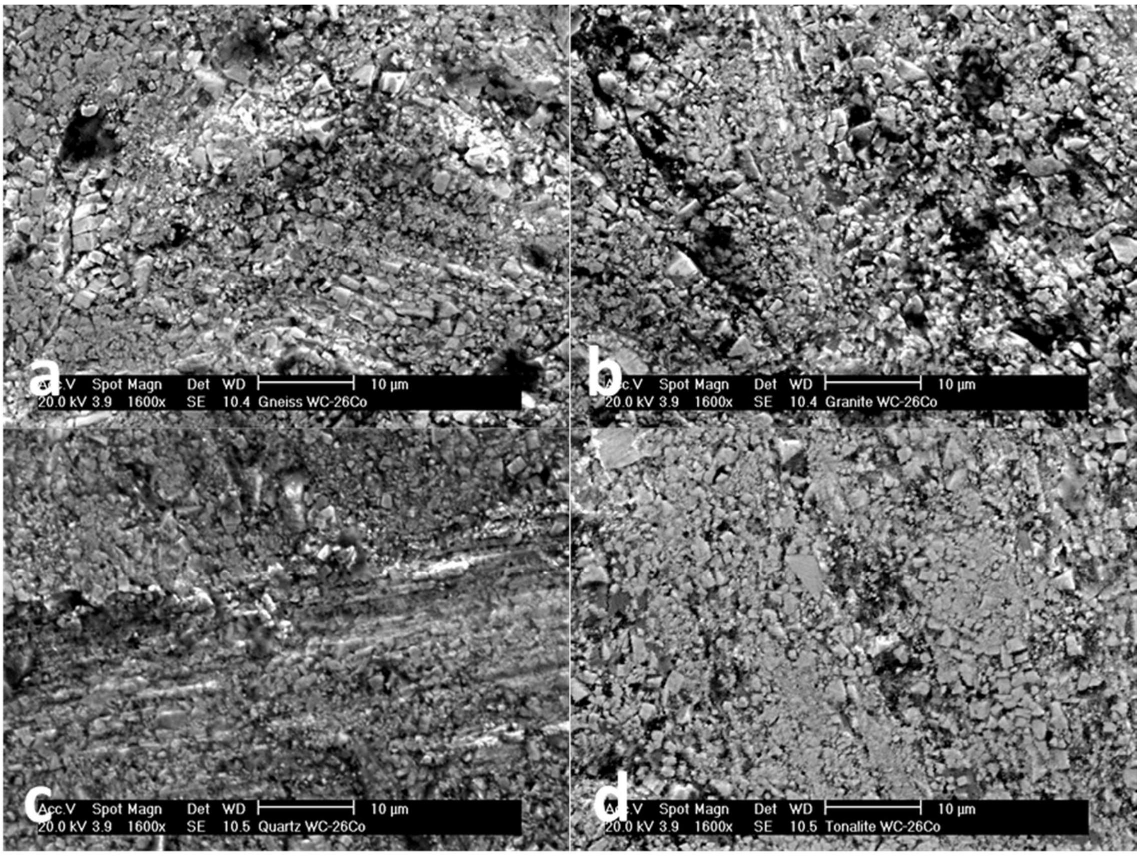

Figure 11. Higher magnification scanning electron microscope images of WC-26Co hard metal tested with a) gneiss, b) granite, c) quartzite and d) tonalite.

In addition to the SEM studies, also the surface roughness Ra values of the pin specimens were measured. As expected, the surface roughness was clearly smaller in the harder materials, but there were no distinct trends or differences observed between the different rock types.

The flat appearance of the steel surfaces observed with microscopy in specimens tested with quartzite could not be verified with optical profilometry. In fact, for the 500HB steel the surface roughness of quartzite worn specimens was to some extent higher than for the specimens tested with the other abrasives. This may be explained by the increased cutting caused by the presence of a large number of small and freshly ground sharp and very hard particles on the wear surface.

In the hard metals, quartzite produced clearly the roughest surfaces, as could be expected based on the volume loss results. On the whole, the Ra values of hard metals followed quite well the crushability values, the second roughest surface being produced by gneiss and tonalite leading to the smoothest surfaces.

DISCUSSION

In the current tests, quartzite produced wear in the studied materials in a clearly different manner than all the other tested abrasives. For steels, quartzite was relatively less abrasive than granite and gneiss. In hard metals, on the other hand, the wear produced by quartzite was 5-12 times higher than with any other abrasive. While the high bulk hardness enabled the hard metals to resist abrasive wear very well in general, the 500HB steel (505 HV) and the WC-26Co hard metal (870

HV) showed approximately the same mass loss when abraded with quartzite. Quartzite is clearly harder than the other used abrasives, and also its crushability is more than twice as high as that of any other of the investigated abrasives. The reason behind the observed differences in the wear test results regarding both the specimen materials and the used abrasives is likely due to the changes in the wear mechanism with changing material/abrasive combinations.

Hard metals consist of two phases: the carbides as the hard phase, and cobalt as the binder phase. In the current test materials, the binder content varied between 15 and 26 percent. Because the hardness of the cobalt matrix is relatively low (typically 140-210 HV), the bulk hardness of the hard metal decreases considerably with increasing binder phase content (see Table 2). Thus, if the hard abrasive particle is small enough to fit between the carbide particles, it can easily wear off the binder phase, leading to carbide pullout and breakage. This is why the high crushability of quartzite combined with high hardness is a more detrimental property to the hard metals than the high uniaxial compression strength or abrasiveness. As the abrasives are being crushed into smaller particles in a brittle manner, there are always fresh and hard angular particles available, which accelerates wear [9,11]. The same phenomenon has been reported also by Krahkmalev [34]. Another property highlighting the wear potential of quartzite is its higher hardness in contrast to the other abrasives used in this study.

All of the tested abrasives had a different combination of properties, which made it challenging to study the effect of just one property at a time. Quite interestingly, the high hardness, high UCS, and high quartz content made tonalite only a moderate abrasive. Terva et al. [14], who also conducted tests with granite and tonalite, suggested that the cause for the difference is in the breakage mechanisms of these two rocks: granite fracturing produces sharper contours that can penetrate the material deeper, thus causing more cutting damage.

On the steel wear surfaces, the differences in the wear behavior were clearly visible. The steels tested with quartzite and gneiss with lower UCS showed distinctly shorter scratches than the ones tested with abrasives with higher UCS. Petrica et al. [13] concluded that in a two-body contact the high-UCS abrasives produce cutting and ploughing, whereas the intermediate UCS abrasives produce more plastic deformation and abrasive grooves. This is in quite good agreement with the current findings, although the contact conditions in the tests were different.

In the high stress three-body abrasive conditions, crushability was found to be the key property of the abrasives in the wear of hard metals because of the wear mechanism based on the attack on the softer binder phase. In steels, a combination of moderate crushability and high enough abrasiveness produced the highest wear. In addition, for steels being relatively homogeneous in microstructure, the ability of the abrasives to transmit load without breaking and to maintain a reasonable portion of them sharp for easy penetration, are also important factors.

Abrasiveness of the rock is an important parameter when planning tunneling or excavations, but on the basis of the current results, attention must also be paid on the types of the materials used in the machinery and on the contact conditions existing on the site. The abrasiveness values are often determined using steels as the test material, like in the widely used Cerchar abrasiveness index or LCPC abrasiveness coefficient measurements. As observed in the current study, the wear behavior of steels and hard metals can be distinctly different when considering the wear mechanisms and the affecting abrasive properties, and therefore the abrasiveness values determined for steels do not necessarily apply to hard metals, which are used in many tools such as rock drilling buttons. Moreover, the crushability (LBC) values should also be taken into consideration, especially with hard metals.

Another issue is the contact conditions. The abrasiveness value only states that a certain rock type is abrasive in certain type of conditions, and although different abrasiveness values may have a correlation with each other [18,20], their applicability in the situation to be simulated must be carefully assessed. For example in the LCPC abrasiveness test, wear is occurring to a great extent by open two-body abrasion in the edge parts of the blocks, whereas in the current high stress three-body abrasion tests wear mostly occurs in the center part of the specimen as three-body abrasion under the applied external force.

The effects of abrasive properties in the abrasive wear behavior are quite complex to study. There is no single abrasive property that determines the wear rates for both material types tested in this work, i.e., ferritic-pearlitic and martensitic steels and hard metals. It is also possible that the abrasive properties have combined effects on wear, which should be studied in greater details.

CONCLUSIONS

In three body high-stress abrasive wear, the increased crushability of the abrasive increases the wear of hard metals, because it changes the effective wear mechanism: the small and hard particles increase the wear of the soft binder phase between the load-bearing hard phases. On the other hand, in steels with a relatively homogeneous microstructure, no clear correlation between the wear and the studied abrasive properties was found. Thus, the potential of an abrasive type to cause wear depends not only on the abrasive type but also on the wearing material. The different contact conditions explain the poor correlation between the wear test results obtained in this work and the LCPC abrasiveness values. As a consequence, it is essential that the contact conditions and the whole wear environment are properly taken into account when the effects of rock properties on the wear behavior are being determined. A better estimation of the wear behavior is obtained using test methods that simulate the true in-service conditions, such as high loads, large abrasive size, and the comminution behavior of the abrasive.

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