COMPRESSIVE CRUSHING OF GRANITE WITH WEAR-RESISTANT MATERIALS

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ABSTRACT

Uniaxial crusher is a non-standard wear testing device designed and used at the Tampere Wear Center for evaluating the wear resistance of materials in compressive crushing. In this study, various wear resistant materials were tested and their wear surfaces characterized with scanning electron microscopy. In addition, the general suitability of the device for wear testing was evaluated.

Abrasive wear was the most common wear mechanism observed on the studied surfaces. Moreover, marks of surface fatigue were also seen. The material loss was mostly due to plastic deformation. Higher hardness was found to correlate with improved wear resistance, especially in cases where wear was purely abrasive.

Key words: Compressive crushing, abrasive wear, wear resistant materials

INTRODUCTION

Wear causes every year a huge number of service breakdowns, either directly or indirectly. This leads to heavy economical losses due to increased down times in production lines, not to mention the disasters happening when components break during operation.

Abrasive wear is the most common wear type. It is the predominant wear mechanism in chutes, rock crushers, hydraulic systems, and extruders. It has been evaluated that abrasive wear alone causes annually damages worth 1-4 % of gross national product in the industrialized countries [1]. Wear-resistant materials are widely used in cutting tools, metalforming tools, mining tools, and wear-resistant parts.

Material loss in abrasive wear is caused by hard particles or hard protrusions on the counter surface. The case of hard particles is called three-body abrasive wear and the case of hard protrusions on the counter surface two-body abrasive wear. In reality both mechanisms are occasionally present [2]. Abrasive wear mechanisms are typically divided into microploughing, microcutting and microfatigue [2,3].

In the process, where minerals are uniaxially crushed between two surfaces, high surface stresses arise, locally even up to 200 MPa. Compressive crushing processes consist of three phases; arrangement of particles, actual crushing, and grinding [4,5]. Under repeated loads, several micro indentations may cause subsurface cracking and eventually lead to surface fatigue [6].

Many standards have been created for the evaluation of abrasive wear resistance of various materials. They are useful for certain applications and for ranking of materials, but there is also a need for application specific wear tests. Ala-Kleme et al. [7] have studied the abrasive wear properties of wear resistant steel matrix composites in rubber wheel abrasion tests and compared the results with the ones received from laboratory cone crusher experiments. They concluded that the received results had no direct correlation to each other.

For the needs of case specific wear testing of crushing performance, several wear testing equipment have been constructed to simulate as close as possible the real wear environments, for example by Osara et al. [8] and Lindqvist et al. [9]. Tampere Wear Center, in turn, has developed a uniaxial crusher to simulate the wear conditions in compressive crushing of minerals. This study concentrates on the evaluation of the test method and its future development based on the received results.

EXPERIMENTAL PROCEDURE

The uniaxial crusher simulates compressive crushing of minerals. Gravel is crushed between two specimens with a constant force (23-86 kN) produced by pneumo-hydraulic power cylinder. A container feeds fresh gravel for each compression with the help of a feeding disc. A rotary actuator drops the crushed gravel out of the cup into a container below. Figure 1 shows the details of the crushing section of the device.

The counterpart for all specimens in the tests was tool steel. The walls of the cup are made from rubber to prevent the crushed gravel from sticking into the cup. While the gravel is crushed, the walls will expand, and after the crushing the stuck gravel will be released by recovery of the rubber.

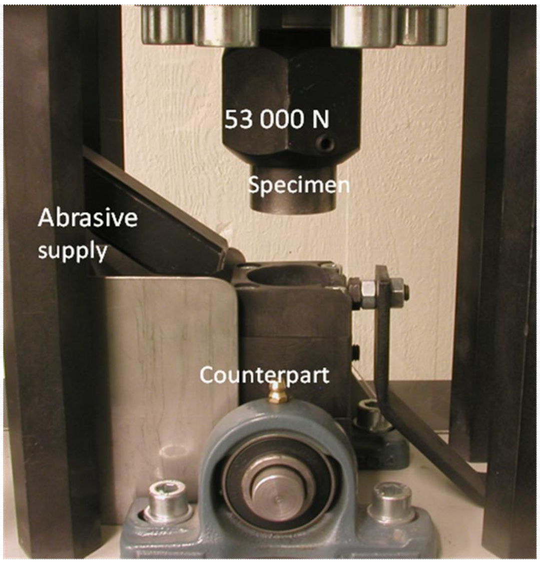

Figure 1. Crushing section of testing equipment.

Before testing, all specimens were ground and polished. The material hardness was measured with a Struers Duramin A-300 hardness testing device. The test cycle consisted of 1000 compressions. After every 100 compressions, the mass loss was determined by weighing.

The gravel used in this test was granite of size 4-6.3 mm from Sorila (Tampere, Finland) quarry. Compressive crushing was done with a constant force of 53 kN.

Eight materials were studied and their wear mechanisms determined. The specimens included wear resistant steels and WC-Co hard metals with several compositions. Structural steel was tested as a reference material. Table 1 lists all the specimens and their significant constituents. For steels, the most influential alloying element is carbon, and for hard metals cobalt.

Tested specimens were studied with Wyko NT1100 optical profilometer to determine the surface roughness. The method is based on the interference of light to measure the surface shape and roughness. Each dataset received from the profilometric measurements was filtered with a median filter to reduce noise and to remove unvalid data. Surface values were received as averages of five measurements.

The wear surfaces were characterized using a Zeiss ULTRAplus ultra high resolution field emission scanning electron microscope, UHR FEG-SEM.

Table 1. The compositions and properties of studied materials.

Specimen	Material	Hardness (HV10)	Composition
S355	Structural Steel	160	0.15 wt% C
Raex 400	Wear resistant Steel	424	0.25 wt% C
Raex 450	Wear resistant Steel	449	0.26 wt% C
Raex 500	Wear resistant Steel	531	0.30 wt% C
15Co-1	WC-Co	1162	15 wt% Co
15Co-2	WC-Co	1260	15wt% Co
20Co	WC-Co	1050	20wt% Co
26Co	WC-Co	870	26wt% Co
Counterpart	Tool Steel	690	

RESULTS

The results presented in the following are divided into two sections. The first section concentrates on wear resistant steels and the second one on WC-Co hardmetals.

Wear resistant steels

Figure 2 presents the results of crushing granite with wear resistant steels. Differences between the structural steel and the wear resistant steels are evident. The three wear resistant steels and the structural steel were classified according to their hardness. The hardest material (Raex 500) suffered least weight loss. Material removal rate at the beginning of the test was quite similar for all the specimens.

Initially, granite particles get easily stuck in the structural steel`s soft surface. Granite forms a protective layer on the surface and keeps the material removal rate low for the first 200 cycles. After 200 cycles, the material removal rate gets higher for S355 when the surface has reached a steady wear state.

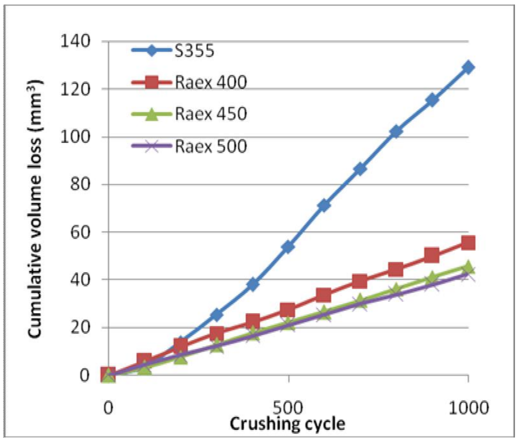

Figure 2. Cumulative volume loss for structural steel and three wear resistant steels in compressive crushing.

Wear rates for the individual samples of the wear resistant steels were more consistent than those for the structual steel sample, as indicated in Table 2.

Table 2. Wear rate statistics for the structual steel S355 and three wear resistant steel specimens.

Wear rates (mm^3/100 cycles)				
Specimen	min	max	median	average
S355	3.66	17.37	13.36	12.90
Raex 400	4.67	6.31	5.67	5.56
Raex 450	3.19	5.16	4.63	4.56
Raex 500	3.69	4.63	4.30	4.23

Figure 3 presents the optical profilometry inspection results for wear tested samples. An average of five measurements was used in the determination of the surface roughness, Ra. The more material was removed from the surface, the higher was the value for the surface roughness. Similarly to the volume losses, also the surface roughness values are proportional to the hardness of the sample surface. One of the commonly used definitions for hardness is, indeed, how well the surface can resist wear.

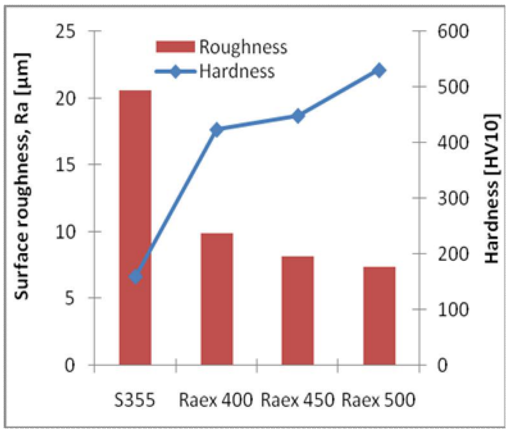

Figure 3. The surface roughness and hardness values for the wear resistant steels and S355.

WC-Co hardmetals

Four WC-Co hardmetal samples were tested with the uniaxial crusher. The testing procedure was the same for the WC-Co hard metals as for the steels. The results are presented in Figure 4. The volume loss was highest for 26Co, containing 26wt% cobalt, closely followed by 20Co with cobalt content of 20wt%.

For 15Co-1 and 15Co-2 specimens, the volume losses after the test cycle were similar for both materials. 15Co-1 had a more steady volume loss during the cycle than 15Co-2. The volume loss rate was clearly lower for the WC-Co specimens than for the steels, which made the measurements more challenging.

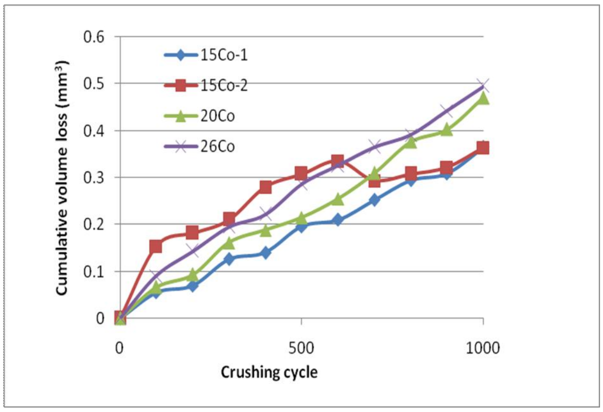

Figure 4. Cumulative volume loss for WC-Co hardmetals in compressive crushing.

Table 3 lists the wear rate statistics for the WC-Co specimens. Wear rates vary due to the combination of material removal and gravel stuck in the structure.

Table 3. Wear rate statistics for WC-Co samples.

	Wear rates (mm^3/100 cycles)			
Specimen	Min	max	Median	average
15Co-1	0.014	0.056	0.042	0.036
15Co-2	-0.042	0.154	0.028	0.036
20Co	0.027	0.067	0.047	0.047
26Co	0.026	0.091	0.052	0.049

Figure 5 shows the test results as a function of the cobalt content. All specimens have the same average carbide size (2.5 µm). 15Co-1 and 15Co-2 are quite similar in composition and show very similar volume losses, although they have a clear difference in hardness. Higher hardness and lower cobalt content gives lower volume loss among these specimens. Hardness is affected by the cobalt content as well as by the average carbide size, which in this case was the same for all specimens.

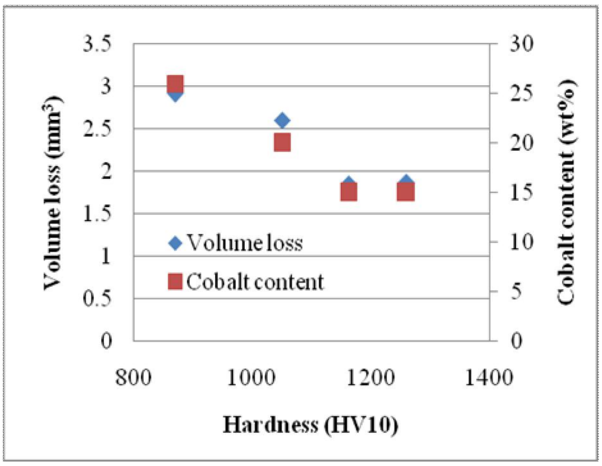

Figure 5. Volume loss of WC-Co specimens as a function of cobalt content and hardness.

Surface characterization

Characterization of the worn surfaces with optical profilometer showed similar results as discussed in the previous section; specimens arrange themselves according to their hardness. As for the steels, also for the WC-Co specimens an average of five measurements was used in the determination of the surface roughness, Ra.

Figure 6 shows the surface roughness and hardness values for the WC-Co specimens. The difference between 15wt% Co and 20wt% Co samples is quite significant. Between the two different 15wt% Co specimens, the one with a higher hardness had also higher Ra-values. Values for the 15Co-2 sample showed much higher deviations among the five datasets, being of the order of ±0.05µm. For 15Co-1, the deviation was only of the order of ±0.02µm.

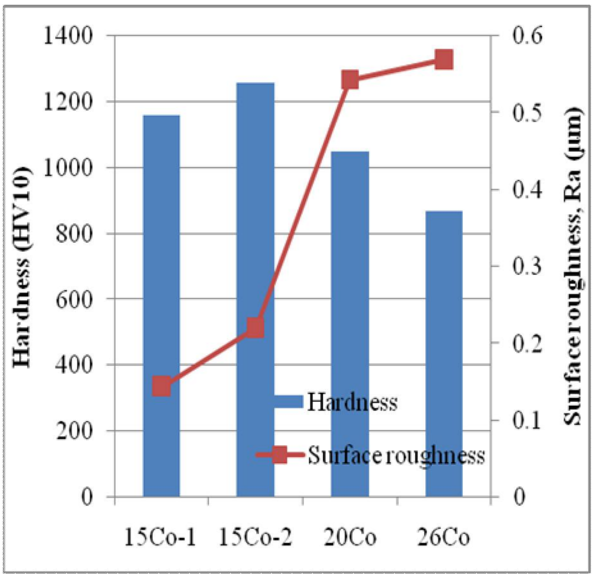

Figure 6. The surface roughness and hardness values for the WC-Co specimens.

On the surfaces several wear scars caused by the relative movement between the rock particles and the crushing surfaces were found. Typical for these scars is their shortness. The primary material removal mechanism in the structural steel and the wear resistant steels was plastic deformation, as can be seen in Figure 7. For S355 (Fig. 7A), the main mode of plastic deformation is microploughing and for Raex500 (Fig. 7B) microcutting. Material removal in WC-Co (Fig. 7C) is mainly caused by the binder phase extrusion and carbide cracking under the microindentations. The amount of adhered gravel is much higher in the structural steel (S355) and the wear resistant steels (Raex) than in the WC-Co hardmetals.

The crushing procedure causes indentations in the surface at microlevel. Occasionally these microindentations cause fatigue cracks in the surfaces, thus leading to surface fatigue. Indentations were a predominant phenomenon found in the wear surfaces by SEM. In specimen 15wt%Co-1, also marks of beginning surface fatigue due to repeated loading were seen. A surface crack is seen in Figure 8.

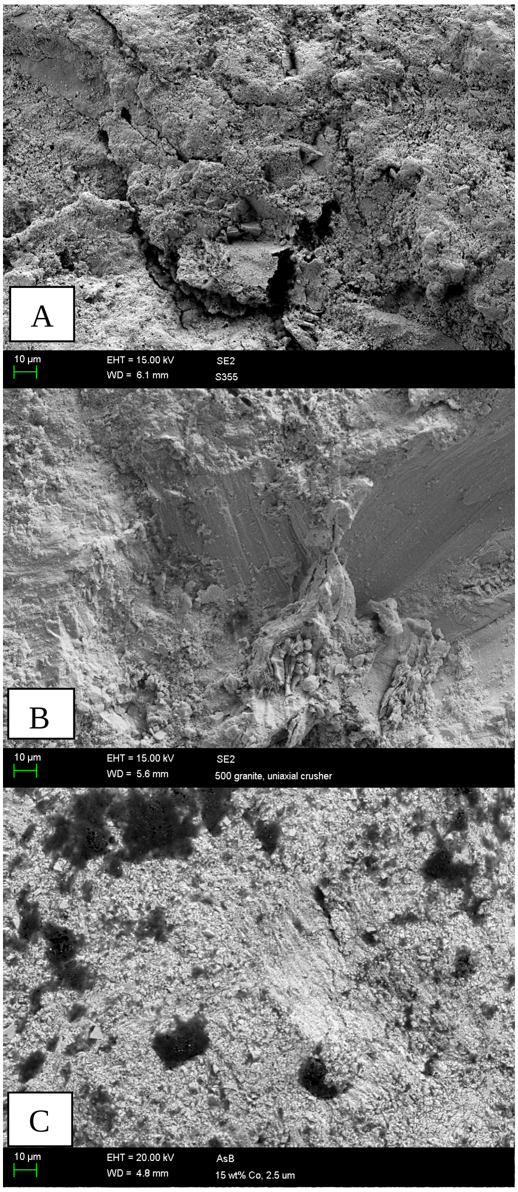

Figure 7. Wear surfaces of S355 (A), Raex500 (B), and 15wt%Co-1 (C).

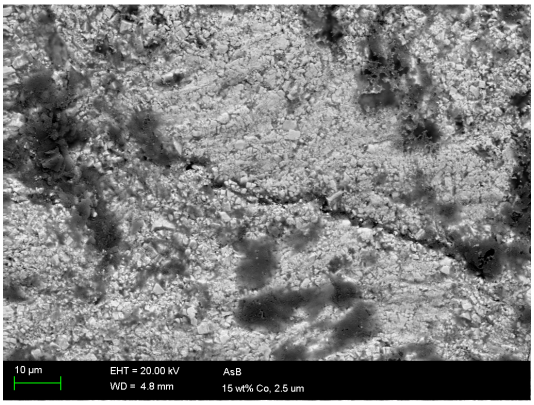

Figure 8. FEG-SEM image of a surface crack on the surface of specimen 15wt%Co-1.

DISCUSSION

The wear rates were more consistent for the steels than for the hardmetals. This is partly due to the greater overall material removal, which leads to more precise weighing of the specimens. With hardmetals, the material removal is much lower leading to an uncertainty in weighing because the abrasives get stuck in the surface. This behavior makes the WC-Co wear rates unstable, while the behavior of the wear resistant steels is more uniform. In the case of the structural steel, the wear rate was not as steady as with the wear resistant steels, because granite tends to stick in the soft surface of the structural steel.

According to Hutchings [2], when the spherical particle is 1.2 times or more harder than the crushing surface, the particle will indent the surface. As seen in the case of the structural steel, which has significantly lower hardness than granite, gravel penetrates the surface easily. In the surface characterization with SEM, abundant gravel embedded in the structure was found.

The hardness ratio of the wear resistant steel specimens is near the above mentioned 1.2 value. This explains the uniform wear rate of the wear resistant steels in these test conditions. Also the counterpart has higher hardness than the wear resistant steel specimens, and therefore counterpart will not suffer from significant wear. An increase in the carbon content gives higher hardness and higher abrasive wear resistance for the steels

WC-Co specimens performed in accordance of their hardness and cobalt content. They all had the same average carbide size. The material removal rate for all the specimens was low and the median and average values were quite close to each other.

The surface of WC-Co samples is much harder than the abrasive particles. This means that the particles will fail by plastic flow or brittle fracture before any significant plastic deformation taken place in the hardmetal. Due to the structure of WC-Co, most of the wear occurs in the low-hardness cobalt phase. In the carbide phase, the material loss can be seen as a detachment of crushed carbides.

The surface fatigue cracks in specimen 15wt%Co-1 are probably related to a single material fault in the specimen. No cracks were found in other WC-Co specimens, not even in the harder ones.

The influence of the lower hardness of the counterpart as well as the material removal rate from the counterpart would be useful information to make more conclusions of the WC-Co results. Terva et al. [10] have studied this subject with different rock-steel combinations using a crushing pin-on-disc device and found the effect of the counterpart material to be very significant.

CONCLUSIONS

The designed uniaxial crusher turned out to be an excellent testing equipment for evaluating and comparing materials in crushing conditions.

Over all, the uniaxial crusher ranks the materials according to their hardness, which is usually the dominant feature in abrasive wear resistance. The testing equipment needs more instrumentation to reveal also the real crushing forces and the maximum surface pressures affecting in specimens locally.

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