HIGH SPEED SLURRY-POT EROSION WEAR TESTING WITH LARGE ABRASIVE PARTICLES

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ABSTRACT

One of the testing methods used to simulate slurry erosion in laboratory conditions is the slurry-pot method. In this work, a novel high speed slurry-pot type erosion wear tester was constructed for testing of materials used in mining and other mineral handling applications. In the tester, the samples are attached to a vertical rotating shaft on four levels in a pin mill configuration. High speeds up to 20 m/s at the sample tip can be achieved also with large abrasive size up to 10 mm. In the tests, the equipment proved to be functional and durable even with the high loads created by the high speeds and large abrasive sizes. There are, however, variations in the slurry concentrations inside the pot during testing, leading to different wear rates at the different sample levels. Therefore, a sample rotation test method was developed. By rotating the samples evenly through all sample levels, the overall deviations between samples will be minimized. Furthermore, with the sample rotation method up to eight materials can be tested simultaneously. The slurry-pot is suitable for testing various materials, such as steels and rubbers.

Keywords: Wear testing; Slurry erosion; Slurry-pot; Mining, mineral processing; Steel; Rubber

INTRODUCTION

In industrial slurry pumping, the speeds can be up to 30 m/s and the size of the mineral particles, which work as abrasives in the system, can vary from micrometers to several centimeters [1]. Many of the previously developed or existing slurry-pot testers can achieve test sample speeds only up to 10 m/s. In addition, most of them are designed to work with small abrasive size, normally smaller than 1 mm in diameter. This means that both of these key parameters of slurry erosion wear testing have not been in the range typically encountered in real industrial applications, such as slurry-pumping and mining. According to Walker and Robbie [2], slurry pumps and pipes typically encounter particles of 0.1 mm to 10 mm in size, the speed of the slurry flow varying from 10 m/s to up to 25 m/s. Pumps used in mines or in dredging may also encounter much larger particles.

Several slurry-pot studies can be found in the literature [3-7], in most of them vertical sample positions attached to a disc or arms have been used. In these so-called whirling disc or whirling arm slurry-pots, samples are on the same level and normally in the upper half of the pot [3, 4]. Other possible sample positions in slurry-pot equipment are periphery [5] or horizontal positions [6, 7]. Horizontal samples can be on several levels starting from the bottom of the pot in the so-called pin mill arrangement. Besides the sample orientation and positioning, typical differences between the whirling arm/disc and the pin mill type equipment are slurry flow patterns, amount of samples, and velocity profiles on the sample surfaces. The design of the pin mill slurry-pot unit itself is based on industrial-size agitated mills [8], from which the laboratory size pin mill has been developed [6]. The pin mill configuration is the strongest and most durable for large particle and high speed slurry erosion testing.

During designing of the new tester, possible problems due to the non-uniform flow patterns and concentration variations inside the pot were considered. In vertical sample slurry-pots, a propeller at the base of the pot is normally used to pump the slurry in order to keep the concentration more constant at the level of the samples [4]. In the pin mill slurry-pot, however, the samples are on several levels, which renders the base propeller ineffective and other means are needed to solve the problem.

In the present work, a new high speed slurry erosion wear tester was designed and built for conducting both material ranking and material development experiments for industrial applications. Moreover, reproducible testing methods were developed. The target was to achieve high speeds with large abrasive sizes in order to simulate various industrial mineral and slurry handling conditions, such as slurry pumps and pipes, flotation cells, and dredging. The aim was also to obtain deeper understanding on the mechanisms of slurry erosion and related wear processes using abrasives of different types and sizes.

MATERIALS AND METHODS

The pin mill type slurry-pot unit consists of a pot and a rotating main shaft with wear test samples on four levels, as seen in Figure 1. Fins on the inner surface of the pot prevent abrasives from concentrating on the walls. The shaft is mounted on the lid and the motor is connected at the end of the shaft. Closing and opening of the pot is done by lifting the motor off the pot, which makes the samples easily accessible and changeable. Temperature of the slurry and the shaft bearing are monitored with thermoelements. The thermoelement for the slurry is located behind a fin. During testing, the pot can be water cooled with a copper cooling coil fitted around the pot, as seen in Figure 1.

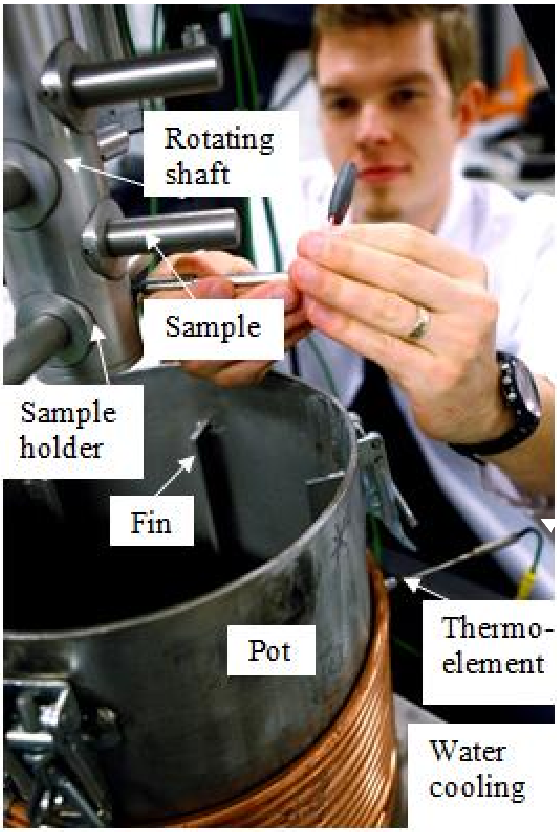

Figure 1. The pin mill type slurry-pot unit.

The sample holders, which are small bushings inside the shaft, can be changed for various sample sizes and shapes. For example sample profiles/shapes of round, square or plate can be used. In the current work, only round and square profiles were used. In addition for round sample profiles, the sample type in terms of sample length can be either full-length or half-length. Full-length samples go through the holder and the shaft, whereas the half-length samples are individually fixed to the sample holder. Thus the tests can be done with a maximum of four full-length samples or with eight half-length samples. Table 1 presents the main characteristics of the equipment.

Table 1. Main characteristics of the high speed pin mill slurry-pot.

Pot	
Diameter	273 mm
Height	300 mm
Main shaft	
Diameter	60 mm
Motor	
Power	7.5 kW
Samples	
Rotating radius	95 mm
Round profile	Ø 18.5 - 26 mm
Square profile	□ 15 x 15 mm
Plate sample	64 x 40 x 6 mm
Sample levels	from bottom of pot
4	145 mm
3	110 mm
2	75 mm
1	40 mm

The electric motor, which was selected to drive the slurry-pot, is able to deliver 2000 rpm with a full set of round samples and 1750 rpm with a full set of square samples. Thus, the maximum sample tip speed is 20 m/s or 17.5 m/s, respectively. All test runs were made at the maximum speeds.

The peripheral speed of the samples depends on the speed of rotation (rpm) of the main shaft and varies along the sample length. Figure 2 presents the values of the peripheral speeds along the sample length for the used speeds of rotation.

For the development of the equipment, test runs were made with round full-length AISI 316 stainless steel samples. The steel was selected due to its high corrosion resistance and rather low hardness of around 200 HV. Moreover, some half-length steel samples were used for checking the consistency of the tests. Figure 3 shows a tested steel sample with the fresh granite gravel that was used as an abrasive.

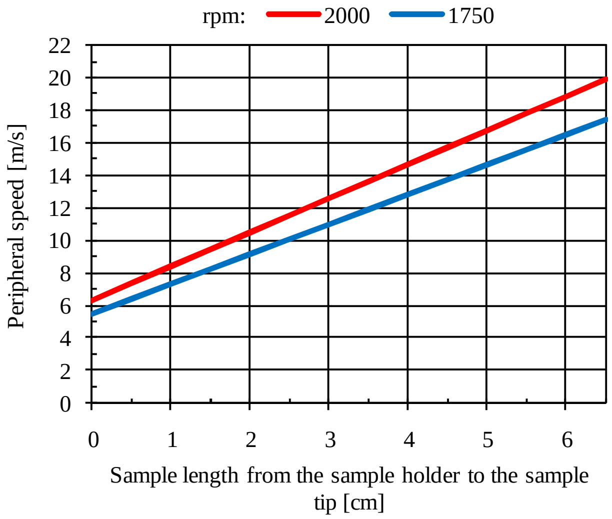

Figure 2. Sample peripheral speed distribution as a function of sample length for the used rotation speeds of the shaft.

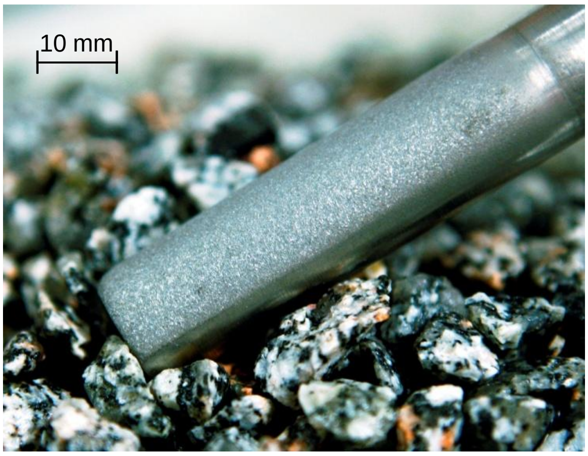

Figure 3. Round AISI 316 sample with granite gravel.

To verify the behavior of the equipment and the applicability of the test methods, also two wear resistant rubbers (A and B) with a square sample profile were used. Rubber A is a filled styrene-butadiene rubber compound (SBR) with a Shore A hardness of 60. Rubber B is a filled natural rubber compound (NR) with a Shore A hardness of 50. Rubber A is mainly intended for dry applications, whereas rubber B is designed especially for slurry conditions. Figure 4 presents a rubber sample after a wear test. For the present work, the sample angle was set to 45°. The same corner of the square profile was always pointing in the direction of the shaft rotation.

Figure 4. Rubber wear test sample with a square cross-section.

The abrasive in the tests was 8-10 mm granite gravel from Sorila quarry in Finland. The maximum abrasive size that can be used with a 95 mm rotating radius of the sample assembly is 10 mm, which is the space between the sample tip and the fins. If necessary the abrasive size could be increased by using shorter samples, but that would also change the slurry flow conditions.

The same slurry composition with 10 liters of water and 1 kg of granite was used in all tests. During the tests, the slurry was changed at set time intervals. In the tests, the maximum speed for high wear rates was the primary target.

RESULTS AND DISCUSSION

Two different test methods were used in order to study the behavior of the test equipment. In the tests with fixed sample positions, the samples were kept at the same sample level throughout the test. In the tests with sample rotation, all samples were rotated through all sample levels during the test cycle. Both methods were used for both steel and rubber samples.

Tests with fixed sample position

To determine how the slurry flow patterns and concentration differences affect the wear testing, six test runs with different durations were conducted with AISI 316 samples. Optimal test parameters, such as duration of the test and interval of the slurry changes, were also determined based on these runs. The slurry was always changed before a new run. As Figure 5 shows, the samples at the highest (L4) and the lowest (L1) levels gave the highest wear rates for all run durations. This is a clear indication of the non-uniform flow patterns and concentration variations of the slurry between different sample levels during the tests.

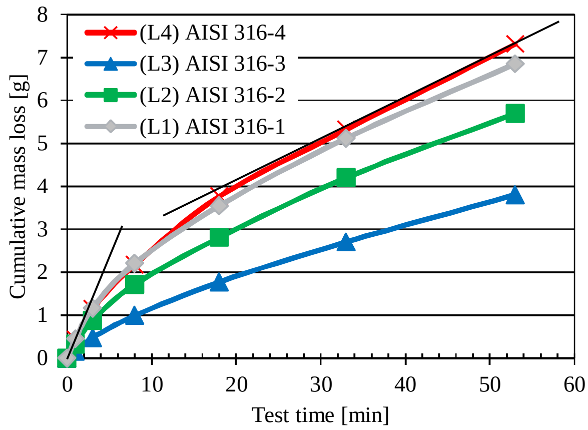

Figure 5. Cumulative mass loss results from the fixed sample position test runs. The slurry was changed before each run. Black trend lines indicate a change in the wear rate between short and long runs.

Figure 5 reveals a clear change in the slope of the graphs during the tests, as demonstrated by the two trend lines fitted to the data of sample AISI 316-4. The slopes decrease with increasing run time, indicating that the wear rate is decreasing because of the progressive comminution of the abrasive particles. As smaller particles have lower impact energy, they also cause less erosion wear in the sample [9]. In addition, the sharp edges of the granite rocks become rounded during the test, which also decreases the wear rate [10].

The comminution of the abrasives was analyzed by sieving the abrasive batch before and after the tests. Figure 6 shows the comminution effect for different run durations with steel samples. Already after one minute of testing at 2000 rpm, almost 50 % of the abrasive is less than 3 mm in size. After 20 minutes, 85 % of the abrasive is smaller than 1 mm.

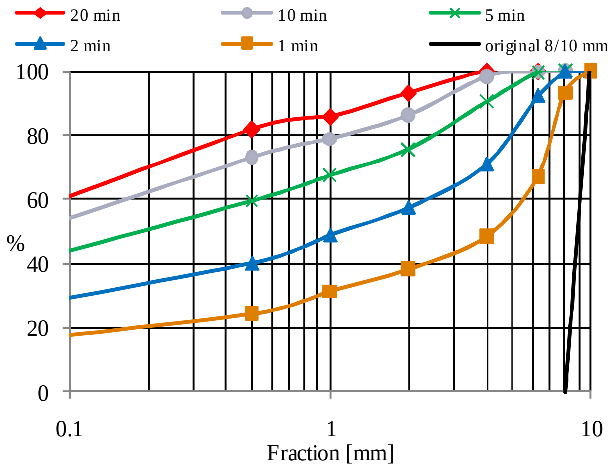

Figure 6. Abrasive size fractions after 1, 2, 5, 10 and 20 minutes of testing compared to the original abrasive size.

<u>Tests with sample rotation</u>

Because the tests with fixed sample position produced large variations in the results, an alternative test method was used. In the sample rotation method, each sample is tested at all levels (L1…L4) during the test. Based on the comminution and erosion rates seen in fixed sample position test results, a cycle time of five minutes was selected. The sample rotation test with four sample levels is composed of four runs, or multiples of them. After each run, the samples are weighed and the slurry is changed. Table 2 shows the sample rotation scheme used for the AISI 316 samples.

Table 2. In the tests with sample rotation, sample level is lowered by one after each run.

	Sample levels			
time [min]	AISI316-5	AISI316-6	AISI316-7	AISI316-8
0-5	L1	L2	L3	L4
5-10	L4	L1	L2	L3
10-15	L3	L4	L1	L2
15-20	L2	L3	L4	L1

Figure 7 presents the results of the tests with sample rotation for the AISI 316 samples: after a full rotation all tested samples show the same cumulative mass loss with a small deviation. The standard deviation of the cumulative mass loss was in this test set only ±0.35 %. The standard deviations of the fixed sample position tests shown in Figure 5 varied from ±40 % after one minute to ±26 % after 53 minutes. Because of the differences in the testing methods, i.e., run times and slurry change intervals, the deviation values are not directly comparable.

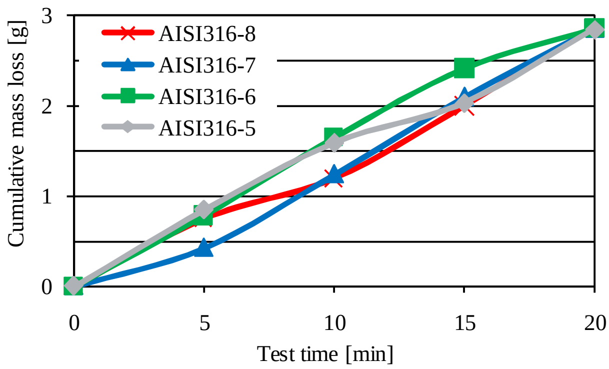

Figure 7. Cumulative mass loss results of a sample rotation test with AISI 316 samples. The sample levels and the slurry were changed after each five minute run.

The consistency of the small deviation was checked with an additional test using the same full-length samples and with two tests using new sets of half-length AISI 316 samples. With the used samples the deviation was now ±0.88 %, and with the new samples ±2.66 and ±2.73 %. The larger deviation with the new half-length samples may be explained with the increased number of individual samples, which can bring about more scatter in the experimental conditions met by individual samples. Still, the deviation less than 3 % can be regarded very small when the testing involves natural minerals.

<u>Comparison of wear resistant rubber materials</u>

Two wear resistant rubber materials were tested in order to evaluate the applicability of the described test methods for another material type and to compare the rubber materials' wear behavior with each other. The rubbers were first tested with the fixed sample position method, and the results turned out to be similarly level dependent as for AISI 316 shown in Figure 6. The results of the rubber tests are shown in Figure 8 at sample levels 2 and 4, which yielded the lowest and largest mass losses. The standard deviations in these tests were ±52…61 % for rubber A and ±20…49 % for rubber B.

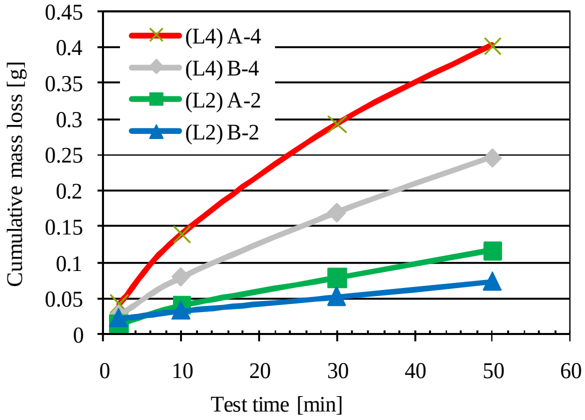

Figure 8. Results of the fixed sample position test for the rubbers (sample levels 2 and 4).

For the rubbers, the lowest wear rate occurred at level 2, while for the steel level 3 gave the lowest wear rate. This can be explained by the different test materials but also by the different sample profile, which leads to a different flow pattern during the test.

The results show that the wear losses for the rubbers were much smaller compared to the stainless steel. As a consequence, longer run duration with a 20 minute cycle time was selected for the tests of the rubber samples with sample rotation. Otherwise a similar rotation scheme as for steels was used (see Table 2).

Figure 9 presents the test results for the rubber materials with sample rotation. As with the steel samples, the same cumulative mass loss and small final deviation were achieved for all tested samples. The standard deviation of the cumulative mass loss was ±4.41 % for rubber A and ±3.43 % for rubber B. Thus, deviations were again much smaller than in the fixed sample position tests.

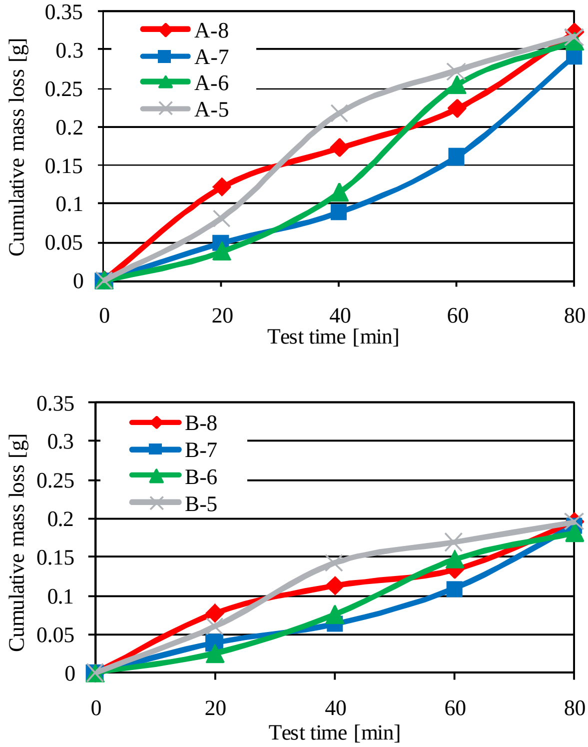

Figure 9. Cumulative mass loss results from the sample rotation test for rubber A (on the left) and for rubber B (on the right). The sample levels and the slurry were changed after each 20 minute run.

<u>Wear surfaces</u>

The wear surfaces, and for the steel samples also the cross-sections, were studied after the tests. The sample tips were rounded during the tests, as can be seen in Figures 3 and 4 for both the steel and the rubber samples. Figure 10 presents the wear surface of the AISI 316 sample, which is covered by a massive amount of particle collisions marks, tiny impact craters and short abrasive scars. The wear type can be classified as abrasive erosion, which means that abrasion is the dominating wear mechanism [11].

Figure 10. Wear surface of an AISI 316 sample.

Figure 11 presents a scanning electron microscope image of the wear surface cross-section. The cross-section is taken 3.5 cm behind the sample tip, where the tip rounding ends. Embedding of the abrasive particles, abrasive cutting of the surface, and peeling off of the deformed surface layers are all visible. Hard granite particles embed easily on the 200 HV steel surface, and sharp particles moving at high speeds produce abrasive microcutting.

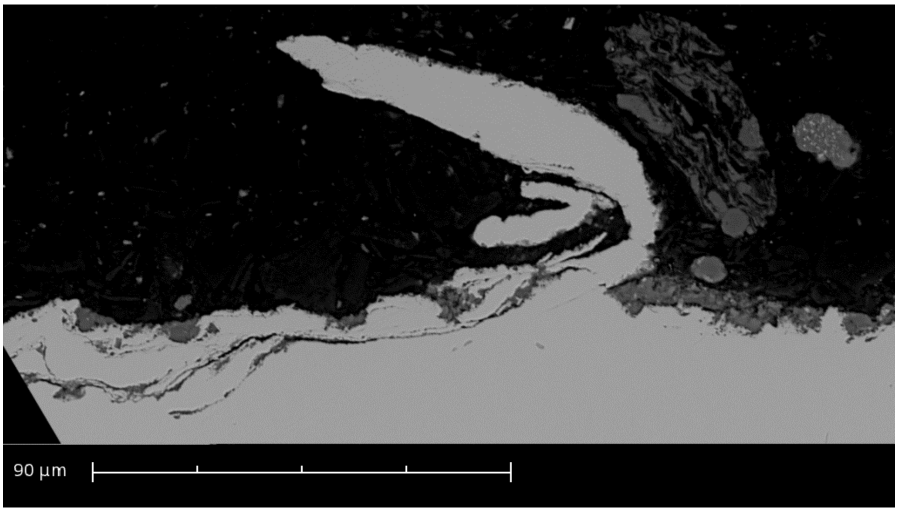

Figure 11. Wear surface cross-section of an AISI 316 sample.

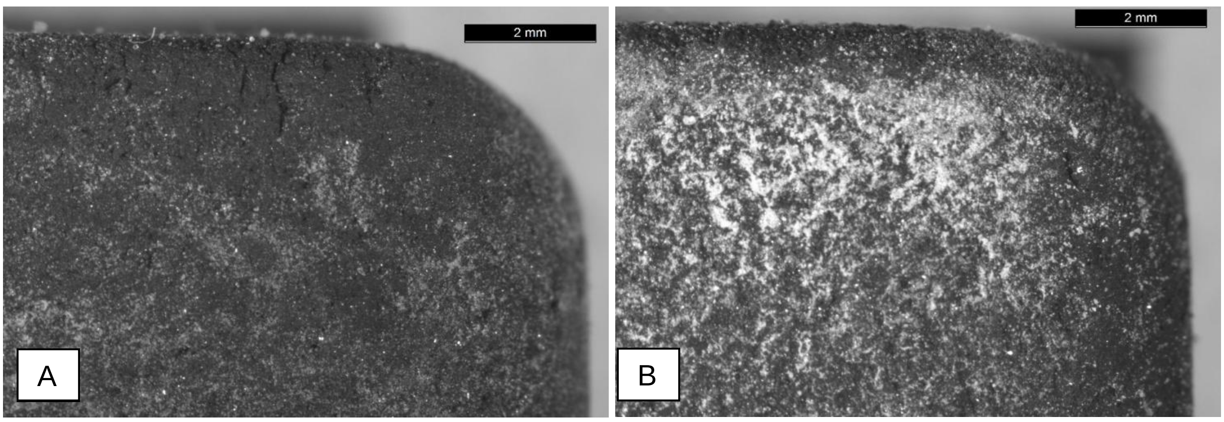

Figure 12. Wear surfaces from the leading edge of the tested rubbers. A) In rubber sample A, surface cracks on the edge are clearly visible and the tip is intensively rounded. B) In rubber sample B, no visible cracks on the edge can be observed and the rounding of the tip is much smaller.

The wear surfaces of the rubber samples were studied after the sample rotation tests with a stereo microscope. Figure 12 shows a comparison of the two rubbers, revealing some differences in their wear behavior. Both rubbers were worn smoothly without any lips peeling off. However, the surface cracks on the leading edge are clearly visible in rubber A, whereas the same edge in rubber B shows no or only minor cracks. Another observation is that the softer rubber B has a lot more fine abrasive particles embedded on its surface, which can later act as a protective layer towards the surface impacts. Furthermore, the tip of the rubber A sample is rounded more than the tip of the sample B.

DISCUSSION

With the fixed sample position test method, the non-uniform slurry flow patterns in the slurry-pot tester became clearly evident. The sample levels experience different wear environment and eventually different wear rates. This complicates the interpretation of the test results, in particular the comparison of the wear performance of different materials. It also limits the maximum number of materials that can be tested simultaneously, as only two samples can be placed on the same level in a test.

In the sample rotation test method, the samples are cycled through all sample levels at least once, which leads to only small deviations in the final mass losses. With this method, up to eight different materials can be tested at the same time.

In large particle size testing, the comminution of the abrasive may limit the available run duration. This can be solved by changing the abrasives regularly at set intervals, if constantly large particle size is required. The comminution rate depends on the abrasive type, particle size, shaft rotation speed and the sample material type. Also the sample shape and the number of samples affect the comminution process. Thus, the results of this study are strictly speaking only valid for 8/10 mm granite gravel with the given test parameters.

Wear surface characterization revealed multiple collision marks on both steel and rubber samples. The wear type, especially for the steel, can be classified as abrasive erosion, where the abrasion mechanisms are highly dominating due to relatively high kinetic energies produced by the high speeds and large particles. Microcutting in abrasive erosion usually happens at low impact angles, while high angles typically promote plastic deformation and/or surface fatigue [11]. In the pin mill type slurry-pot with round samples, basically all impact angles from 0° to 90° are possible on the round face of the sample. Wear of the deformed surface layers in the steels were caused by abrasive microploughing or low angle microcutting [12] rather than by surface fatigue, as there were also some embedded abrasive particles under the peeling layer.

The developed wear tester is capable of higher speeds with larger particles compared to other slurry-pot testers presented in the literature [3-7]. The small deviations in the sample mass losses of both the austenitic steel and the two rubber grades after complete sample rotation cycles proves that with the presented testing method it is possible to obtain reliable and repeatable results despite the different wear environment on the different sample levels.

CONCLUSIONS

- The target was to develop a laboratory slurry wear testing method simulating heavy duty conditions. The developed high speed pin mill type slurry-pot equipment is versatile and produces sample tip speeds up to 20 m/s with a large abrasive size up to 10 mm.

- The slurry needs to be changed regularly due to the high comminution rate of the abrasive particles. The comminution rate depends on the tested material.

- The abrasive size and shape affect the wear rate. In slurry erosion, large and sharp particles cause more wear than small and rounded particles. The large abrasives comminute markedly during the high speed testing.

- The samples can be tested using either the fixed sample position or the sample rotation method.

- The fixed ample position method produces high deviations in the results, and therefore it can be used for the abrasive characterization, testing samples in variable slurry concentrations at once, or testing a large numbers of samples of one or two different materials.

- In the sample rotation method, the deviations in the results are small and up to eight materials can be tested simultaneously.

- The equipment can be used to test many different types of materials, such as steels and rubbers, with several sample profiles in variable slurry conditions, including concentration, particle size, and abrasive type.

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