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Edge and particle embedment effects in low- and high-stress slurry erosion wear of steels and elastomers

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ABSTRACT

Slurry transportation via pumping is an increasingly viable alternative for the conventional fine particle pumping, but there are also many applications involving larger particles. However, most of the published studies on slurry erosion have been conducted with fine particle sizes. In this work, also large particle slurry erosion of commercial wear resistant materials is studied. A high speed slurry-pot wear tester was used with edge protected samples to simulate the wear conditions in industrial slurry applications where edge wear is minimal. Two wear resistant steels together with natural rubber and polyurethane lining materials were tested, and the results were compared with the results of the same materials tested without sample edge protection. The tests were performed using 15 m/s speed, two sample angles, and slurry concentrations with particle size ranging from large 8/10 mm granite to fine 0.1/0.6 mm quartz. In all conditions, the steel samples showed stable wear behavior, whereas the elastomers gave notably inconsistent results in different test conditions. In general, steels exhibited better wear performance with large particles and elastomers with fine particles, and the wear losses were 40–95% lower when edge wear was inhibited. With increasing abrasive size, the edge wear becomes more dominant and the particle embedment decreases.

1. Introduction

Slurry pumping is a sustainable option for transporting solids in large mining related operations. The slurry pipeline technology is relatively young with about 10,000 km of active pipeline around the world. For the first time, minerals were transported via a pipeline in the 1960's, whereas long distance pipelines, i.e., longer than about 900 km, emerged only in the 1990's. [1] At the same time, slurry transport has replaced conveyors in mines [2]. In general, slurry is defined as a mixture of liquid and solid particles that can be transported by pumping [3]. Particle size and also the speed of the slurry can vary quite widely from application to application [4–6]. The particle size can be from fine micron size particles to large particles of tens of millimeters in size [3]. In the published studies, larger particle sizes have not been extensively used. Mostly the particles used in slurry wear experiments have been under one millimeter in size [7–9]. Large particle sizes have only been used by Jankovic [10] (up to 5 mm particles) and Ojala et al. [5,6,11] (same 8–10 mm particles as in this study). In soil abrasion tests with a pot tester, Jakobsen [12] have used up to 10 mm particles with high 75–100% concentration of solids.

The industrial slurry applications related to mining can be divided into two categories, small and large particle applications [6]. In the small particle applications, normally particles smaller than 1 mm in size are handled with slurry concentrations typically between 50 and 70 wt% and slurry flow speeds varying in the range of 10–25 m/s [4]. In the large particle applications, the particle size can be up to 50 mm with concentrations typically lower than with small particles at around 10–20 wt%, and with speeds up to 30 m/s [13]. In addition, especially with large particles as for example in dredging, the concentration and particle size may fluctuate quite much during the operation. As an application oriented wear tester, the high speed slurry-pot has highly turbulent wear conditions inside the pot, which correlates quite well with many practical applications. The test method generates a wide distribution of particle impact angles but still provides a good working environment and reproducible test results [5].

Only a few of the slurry erosion related publications deal with quenched steels [14–16] or elastomers [17]. Madsen [18], who tested both quenched steels and elastomers compared several steels and a couple of elastomers using both laboratory-prepared slurries and slurries acquired from the field. In the tests, he used a laboratory tester with edge protected samples. He concluded that with the 2 wt% 0.2/0.3 mm laboratory sand slurry the elastomers had an advantage over the tested

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metals, but with the field slurries with abrasive size up to 1.7 mm, white cast iron and wear resistant steels were better or on par with the elastomers. Also Xie et al. [19] compared steels and elastomers using fine particles with three different low-stress slurry wear test devices. In the tests with two of these devices, the samples were edge protected. Xie et al. concluded that during slurry transportation the impact angles of the particles are random, i.e., the flow is turbulent. In their fine particle low-stress slurry tests, elastomers had supreme wear resistance over the steels.

In the studies published on slurry wear [14–16,18–26], five different wear tester types have been used: a Coriolis erosion tester, slurry-jets, a pilot pipe circuit, slurry-pots, and slurry sliding abrasion tester. All of these systems have been, or could have been, equipped with edge protected samples, but none of the studies addressed the effect of edge wear or its influence on the wear process.

Edge wear and its effect on overall wear losses have been studied before in dry conditions. Terva et al. [27] studied edge wear in high-stress abrasion with different-sized granite and quartz abrasives using structural and tool steels. They concluded that the edge effect may vary between 1 and 50%, depending on the abrasive size and type and the tested material. With granite the edge effect was bigger than with quartz. The largest abrasive size used, i.e., 8/10 mm, caused the highest edge wear for both materials. Ratia et al. [28] studied the role of edge-concentrated wear in high-stress impact-abrasion with large granite abrasives at two different sample angles using two structural steels and a 400HB wear resistant steel. They concluded that the edge effect varied between 80 and 97% in 45 min tests and between 66 and 82% in 270 min tests, depending on the sample angle. A larger sample angle caused a stronger edge effect.

In a previous [6] study, marked differences in particle embedment were observed between steels and elastomers, but also between different abrasives. For the steels, the embedment was only sticking of individual abrasives on the steel surface or occasional tribolayer formation by mixing of the two materials. For elastomers, however, a much stronger embedding tendency was observed with X-ray computer tomography, which revealed that although the particles penetrated only the very surface of the material, the particle concentration on the surface was high.

After the pioneering work of Hutchings [29] on particles deforming ductile materials, particle embedment has been studied in numerous studies [30–39]. In recent years, these studies have been much focused on numerical modeling, such as the work by Hadavi et al. [40]. The published results about the particle size effect have shown differences between metals and elastomer. For example, Getu et al. [38] reported that the particle size had no effect with the tested polymer materials, while for example Hadavi et al. [39] reported that embedment increases with the particle size in the case of aluminum. In these studies, Getu et al. used particles below the size of 200 μm, and Hadavi et al. below the size of 300 μm. Lathabai et al. [32] and Getu et al. [37] observed that with particles below the size of 700 μm and polymer materials, the embedded particles can protect the surface and reduce the wear rate. About the influence of larger particles, no information is available other than the observations done by Ojala et al. with steels and elastomers in the previous study [6]. In particular, the influence of the embedment on the ranking of different materials has not been studied before.

In demanding slurry applications, the abrasive wear mechanism dominates, as the abrasivity of the slurry is usually high because of the high slurry flow speeds and/or large particles inside the slurry. This wear type is generally called abrasive slurry erosion [6,41], where also corrosion is less significant [20,42]. In this work, the high speed slurry-pot wear tester was used with edge protected samples to simulate the wear conditions in industrial slurry applications where edge wear is limited or nonexistent, such as tanks and pipelines. The test materials included two wear resistant steels and two elastomers. The same materials were tested in the previous work [6] without edge protection, and therefore the edge effect could be evaluated by comparing the results of these two studies. The edge effect was studied with both fine and large particles. The wear performance of the materials was evaluated based on the wear tests and wear surface characterizations.

Table 1
Test materials.

Steels	400HB	500HB	Elastomers	NR	PU
Hardness [HV10]	414 ± 4	554 ± 2	Hardness [ShA]	40	75
Yield strength [N/mm^2]	1000	1250	Tensile strength [N/mm2]	25	23
Tensile strength [N/mm^2]	1250	1600	Density [g/cm^3]	1.04	1.05
A5 [%]	10	8	Isocyanate type	–	MDI
Density [g/cm^3]	7.85	7.85	Polyol type	–	polyether
C [max%]	0.23	0.3			
Si [max%]	0.8	0.8			
Mn [max%]	1.7	1.7			
P [max%]	0.025	0.025			
S [max%]	0.015	0.015			
Cr [max%]	1.5	1			
Ni [max%]	1	1			
Mo [max%]	0.5	0.5			
B [max%]	0.005	0.005			

2. Materials and methods

The test parameters were set to simulate the demanding conditions in slurry pipelines. The test device was the high speed slurry-pot wear tester [5] at the Tampere Wear Center. The test materials, presented in Table 1, included two wear resistant steels with hardness grades of 400 and 500 HB, and two wear resistant elastomers, i.e., a natural rubber and a polyurethane. All materials are commercially available. In the table the hardness values of the steels were measured, while the other values are typical values reported by the manufacturers. The nominal alloying of the steels was similar, but there were small differences in their microstructure. Both steels had an auto-tempered martensitic microstructure. The grain size of the 400HB steel was smaller than that of the 500HB steel. Small white areas seen in Fig. 1 are untempered (white) martensite.

The steel samples were 6 mm thick and the elastomer samples 5 mm thick. Otherwise all samples were 35 × 35 mm square plates. Edge protection was done with window plates having a 33 × 33 mm opening. 1 mm thick shim plates were placed under the elastomer samples to assure tight fitting inside the sample holder. The test setup was the same as used in the previous study [6] with unprotected plate samples. The wear tester is a pin mill type slurry-pot, where the samples are attached to a vertical rotating main shaft in horizontal positions at different height levels. Two lowermost sample levels and two sample angles, 45° and 90°, were used in these tests, as presented in Fig. 2.

The test preparations were as follows: the samples were first attached to the sample holders, the shaft was lowered into the pot, and the slurry was added. After that the samples were spun at 1500 rpm in the pot. The test time was first 20 min, after which the test was continued for another 60 min. Every test, lasting 20 or 60 min, consisted of four 5 or 15 min cycles. The sample rotation test method [5] was utilized, in which the sample positions are switched and the slurry is renewed after every cycle. Sample rotation assures that all samples have experienced similar conditions when the test is completed. Moreover, it minimizes the scatter in the results caused by the possible differences in the test conditions between the different sample positions. After the tests, the wear rates were determined by weighing and the volume losses were calculated using material densities. Comminution of the abrasives was evaluated by sieving the used abrasives after the tests.

Table 2 presents the test parameters selected on the basis of the previous study [6]. The largest and the finest abrasives used in the