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Wear performance of quenched wear resistant steels in abrasive slurry erosion

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ABSTRACT

Three commercially available quenched wear resistant steel grades were compared with a structural steel and four elastomer materials to reveal the differences in their behavior in slurry erosion conditions and to find the best solutions for demanding applications. A slurry-pot tester, allowing simulation of various wear conditions with different minerals, particle sizes (up to 10 mm), abrasive concentrations, and sample angles were used to simulate different industrial slurry applications. In this study, granite and quartz with concentrations of 9 and 33 wt% were used as abrasives in tests conducted at 45° and 90° sample angles. The performance of the studied steels was evaluated with respect to their material properties such as hardness and microstructure. Furthermore, the cross-sections and wear surfaces of the test samples were analyzed to reveal the possible differences in the mechanical behavior of the materials during slurry erosion. The wear surface analyses show that abrasion is the dominating wear mechanism already for the smallest particle size of 0.1/0.6 mm. In low-stress abrasive slurry erosion with the smallest particles, the elastomers showed better wear resistance than the steels, whereas in demanding high-stress abrasive slurry erosion conditions the quenched wear resistant steels can well compete with elastomers in wear resistance. The relative wear performance of the steels increased with increasing abrasive size, while for the elastomers it decreased.

1. Introduction

Slurry is generally defined as a mixture of liquid and solid particles that can be transported by pumping. Transporting minerals or moving solids as a slurry is an increasingly viable alternative in many industrial applications ranging from dredging and pumping concrete at a construction site to large mining projects. In mines the slurry transportation of minerals is both an economical and environmentally friendly alternative, whereas for transferring concrete to its destination at large construction sites, pumping is generally the only option. The main factor related to the expenses of such pumping projects is wear. The wear environment, including mechanical wear and corrosion, dictates the initial capital costs and useful lifetime of the pipelines. [1–4] Size of the particles inside the slurry is one of the major factors affecting the wear in the process. In heavy duty slurry pumping the particle size can be up to several centimeters [5], while in fine particle mineral processes the particle sizes are typically between 100 and 250 μm [6,7].

Wear related problems cause significant economic and environmental losses in applications involving abrasive and erosive wear, such as pumps and pipelines in slurry transportation or pumps and crowns in dredging. Mainly due to corrosion, quenched wear resistant steels are not widely used in piping. However, the good mechanical wear resistance that steels can offer may have a greater effect on the pipe lifetime than their relatively poor corrosion resistance, when highly abrasive slurries are handled. The particles in the slurry can be large and sharp and the speed of the flow high, causing abrasive slurry erosion. In these conditions, understanding the active wear mechanisms is essential for the use and further development of new materials.

The slurry pipeline technology is relatively young. The first slurry pipeline was implemented in the 1960s and the first long distance pipeline in the 1990s [2]. Currently elastomer lining materials, such as rubbers or polyurethanes, have become a standard choice for combined wear and corrosion protection in slurry pipelines transporting minerals. However, such linings can

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be rather expensive and also quite sensitive to surface defects. In addition, they are known to suffer from problems related to adhesion and thermal expansion in pumping and pipeline transport applications, which all will promote mechanical wear. For example for polyurethanes, Zhang et al. [8] suggested a two times increase in the erosion rate from room temperature to 60 °C, and a three times increase to 100 °C. Furthermore, as the trend is towards higher production volumes and slurry transportation is also expanding into new application areas possibly with coarser particles, mechanical wear resistance is becoming more and more important [2].

In very demanding pumping or transporting applications abrasive wear becomes even more dominant, as the high flow speed of the slurry and high abrasiveness of the particles inside the slurry leads to a subtype of slurry erosion called abrasive slurry erosion [9,10]. Currently in the industrial field the fine particle slurry pumping represents the low-stress abrasive slurry erosion, whereas dredging and large particle slurry pumping represents the high-stress abrasive slurry erosion. Only few publications have been published about the latter conditions, i.e., abrasive slurry erosion caused by large particles [9,11]. Additionally, it has been shown that with such also the role of corrosion becomes smaller [12,13]. Such a change in the wear environment requires new material solutions and in-depth research to better understand the wear mechanisms and performance of different materials.

Amongst the published studies related to the slurry erosion of steels [13–23], just a few have included quenched steels, and only two articles were found where steels had been compared with elastomers. Clark and Llewellyn [14] compared several commercial plate and pipe steels using fine particles and zero degree sample angle. In these tests, the steels were ranked according to their surface hardness, the best wear performance being obtained with the hardest steel. Xie et al. [23] compared steels and elastomers, as well as some other material types, using fine particles and different low-stress wear test devices. They concluded that during slurry transportation the impact angles of the particles are random and that with fine particles and low-stress conditions elastomers have an excellent wear resistance. Madsen [21] compared elastomers and metal alloys both in laboratory and in-service conditions. He concluded that with fine quartz slurry the elastomers have an advantage over the tested metals, but in the field studies white cast iron was the best or on par with the elastomers. Also wear resistant steels were in the field tests often better than elastomers.

Considering all the aforementioned and the results of Stachowiak and Batchelor [24], showing that the change in the particle size, even from very fine particles of 9 μm to fine particles of 127 μm, can cause fundamental changes in the wear mechanisms, it is worthwhile to study the slurry erosion performance of the quenched wear resistant steels and to compare them with the current wear resistant elastomers using an application oriented test method in test conditions ranging from low-stress abrasive slurry erosion with fine abrasive particles to high-stress abrasive slurry erosion with larger particles.

Gupta et al. [18] have shown that the pot testers are suitable for predicting slurry erosion in the in-service applications. They used a whirling arm slurry-pot, where two vertical samples were on the same level, to compare the results from laboratory studies to the results obtained from a 60 m long slurry pipeline pilot plant. They used different slurry concentrations, ranging from 15 to 45 wt%, and velocities of 4–8 m/s with particle sizes less than 0.5 mm, to compare the wear performance of brass (hardness 120 HV) and mild steel (hardness 160 HV) in both test environments. They concluded that the slurry-pot can be successfully used to simulate a pipeline application. However, they did not include any harder steels or larger particles sizes in their study.

In this work, three commercially available quenched wear resistant steel grades were compared with a structural steel and four elastomer materials to reveal the differences in their behavior in abrasive slurry erosion conditions and to find the best solutions for demanding applications. A slurry-pot tester was used as it allows the simulation of various wear conditions with different minerals, particle sizes and slurry concentrations in different industrial applications. The performance of the steels was evaluated with respect to the material properties such as hardness and microstructure. Furthermore, the cross-sections and wear surfaces of the test samples were analyzed to reveal the possible differences in the mechanical behavior of the test materials during abrasive slurry erosion.

2. Materials and methods

Application oriented wear tests with the high speed slurry-pot wear tester [9] at the Tampere Wear Center were performed for four steel and four elastomer materials. In this study, the test parameters were selected to simulate demanding industrial slurry applications, such as dredging and slurry transportation.

The primary test materials were three quenched wear resistant steels with hardness grades of 400, 450 and 500HB. A 355 MPa structural steel, with hardness of 180 HV, was also tested as a reference material. Table 1 presents the measured surface hardness values, and the other mechanical properties as typical values and nominal compositions of the tested steels reported by the manufacturer. The nominal alloying of the untempered quenched steels was similar, as seen in Table 1. In the tests, a natural rubber with 40 shA hardness and three polyurethanes with hardness in the range of 75–90 shA represented the currently used materials in the slurry transportation applications and were therefore selected as comparison materials for the quenched steels. The tested polyurethanes are also available for slurry pump wear protection. Table 2 presents the typical mechanical properties of

Table 1
Mechanical properties and nominal compositions of the studied steels.

Material	355 MPa	400HB	450HB	500HB
Hardness [HV10, kg/mm^2]	180 ± 3	405 ± 3	475 ± 11	560 ± 10
Yield strength [N/mm^2]	355	1000	1200	1250
Tensile strength [N/mm^2]	470–630	1250	1450	1600
A5 [%]	20	10	8	8
Density [g/cm^3]	7.8	7.85	7.85	7.85
C [max%]	0.12	0.23	0.26	0.3
Si [max%]	0.03	0.8	0.8	0.8
Mn [max%]	1.5	1.7	1.7	1.7
P [max%]	0.02	0.025	0.025	0.025
S [max%]	0.015	0.015	0.015	0.015
Cr [max%]	–	1.5	1	1
Ni [max%]	–	1	1	1
Mo [max%]	–	0.5	0.5	0.5
B [max%]	–	0.005	0.005	0.005

Table 2
Typical properties of the studied elastomers.

Material	NR	PU1	PU2	PU3
Hardness [ShA]	40	75	85	90
Tensile strength [N/mm^2]	25	23	42	37
Density [g/cm^3]	1.04	1.05	1.21	1.11
Isocyanate type	–	MDI	MDI	TDI
Polyol type	–	Polyether	Polyester	Polyether