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Article

Impact Wear of Structural Steel with Yield Strength of 235 MPa in Various Liquids

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Abstract: The wear of pipelines, used in slurry transport, results in high costs for maintenance and replacement. The wear mechanism involves abrasion, corrosion, impact, and the interaction among them. In this work, we study the effect of impact on the wear mechanism and wear rate. Results show that when the effect of impact is small, the wear mechanism is dominated by electrochemically induced surface modification, which leads to a lower wear rate in a corrosive environment than in a non-corrosive environment. By contrast, when the effect of impact is large, the wear mechanism is drastically altered. In that regime plastic deformation is important. The influence of corrosion in the high impact regime can be neglected. Our findings show the importance of including impact effect in the distinction of wear of slurry pipes.

Keywords: wear; corrosion; impact; deformation; surface modification

1. Introduction

Dredging is involved in keeping waterways navigable or for the purposes of constructing new land in freshwater or seawater areas. In dredging engineering, the sedimented sands or other solids, mixed with water, need to be transported by means of pipelines. The pipelines wear due to the interaction among erosion, abrasion, and corrosion, resulting in high costs for maintenance and replacement of the pipelines [1–3].

Researchers have studied and reported the wear of pipelines for decades [4–10]. Truscott [11] reviewed the research findings of 20 years before 1972 and summarized three determinant factors of wear: the properties of the slurry, the regime of the flow and the materials. The properties of slurry mainly include the particle hardness, size, shape (sharpness), specific mass, concentration. The mode of flow in principle determines the particle dispersion and particle motion, which eventually determine the wear mechanism. The properties of materials mainly include chemical composition, microstructure and hardness. The erosion wear of slurry pipelines results from two mechanisms, particle impact and scouring, where the latter occurs as a result of a sliding abrasive wear. Several apparatuses have been introduced to study the wear mechanism of slurry pipes [12,13]. These apparatuses aim to study the influence of multiple factors like the flow concentration, the particle size, or the flow velocity.

However, the material surface change due to corrosion is rarely reported, yet extremely important. In a corrosive environment, especially electrochemical corrosion, the surface of the material changes and the change could potentially alter the original material properties like hardness, and therefore it influences the final wear rate. In a previous paper [14], the authors reported the micro-coupling effect, occurring in a multiphase material in an electrochemically corrosive environment. In that study, a pearlitic steel, consisting of ferrite and cementite, was exposed in seawater while subject to abrasive wear. The coupling between ferrite and cementite, due to their electrochemical potential difference, leads to the dissolution of ferrite and the protruding of cementite, and subsequently the redistribution of cementite due to abrasion. The altered surface is much harder than the original due to the enrichment of harder phase: cementite.

In actual slurry transport, however, no noticeable seawater wear rate decrease was observed and reported. In this study, impact is introduced to identify the wear mechanism. Various liquids are used to provide different corrosive environments. We will argue that impact dominates in slurry transport. This domination of impact wear explains the negligible difference in wear in seawater and fresh water.

2. Experimental

2.1. Material Preparation

The material, used in this study, is a structural steel: S235 [15]. This material, with minimum yield strength of 235 MPa and hardness of 183 $HV_{0.1}$ (±9.2), is widely used in dredging industry for its good combination of mechanical properties and welding properties. The sample used in this study are cylinders, 30 mm in diameter and around 8 mm in thickness. The preparation procedure consists of three stages. First, the sample was grinded with silicon carbide sandpaper from 80 to 2400 mesh (particle size equals roughly 10 μm). Then the grinded sample was polished with diamond containing polishing liquid from 3 μm to 1 μm until the surface was mirror-like. Finally, the polished sample was cleaned in acetone with ultrasonic, followed by rinsing with distilled water and dried with room temperature air.

2.2. Experimental Procedure with a Hammering Pin on Disc

A modified pin on disc, as shown in Figure 1, was used to perform experiments. A hammering module was incorporated. The module contains a retractable component, powered by compressed air to hit and lift the pin. The impact height can be measured during experiments by the pin on disc software (TriboX 1.0, CSM instruments, Buchs, Switzerland). The load was 1 N for all experiments but with various impact height, thereby various effect of impact, namely 0.2 mm, 1.0 mm, 2.0 mm, and 3.3 mm. The pin was lifted at a frequency of 1 Hz and in contact with the sample for a period close to 0.5 s. The pin hit the sample at a near but different place each time, forming a round wear track eventually. The radius was 8 mm, and the rotational speed was 2 Hz (corresponding linear speed is 0.1 mm/s) for each 2.75-h experiment. Three liquids were used to provide different corrosion condition, namely non-corrosive ethanol, corrosive deionized water, and severely corrosive seawater (simulated by a 3.5% NaCl solution). Each combination of impact height and liquid was repeated three times to obtain the variability of the experiment. The counterpart used in this study was an aluminum oxide ball with a diameter of 6 mm. After each experiment, the ball was either rotated or replaced to obtain fresh contact between the sample and the ball.

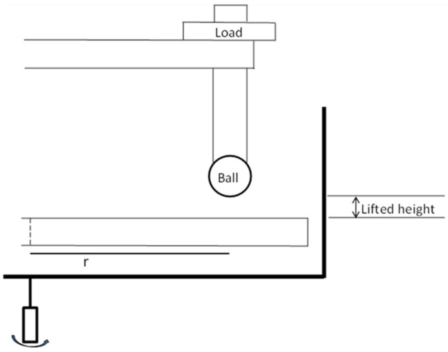

Figure 1. The diagram of the modified pin on disc. A lifted distance exists between tha ball and the sample surface. The distance is well controlled and measured by the software of pin on disc.

2.3. Characterization

After experiments, the wear track profiles of the samples were measured by white light interferometry (Bruker Contour GT-X, Bruker, Leiderdorp, The Netherlands). Specifically, four different places of each cross section of the wear track were measured, and the wear rate was calculated by multiplying the area of the cross section by the perimeter of the wear track, divided by the sliding distance [16].

3. Results

3.1. Wear Rate Comparison

Wear rate, overall, increased with increasing impact height from 0.2 mm to 3.3 mm, as shown in Figure 2a. For the case of 0.2 mm, the wear rate in deionized water was the largest, followed by wear in ethanol. In seawater, the wear rate was the smallest. This order is the same as was obtained in sliding wear in these liquids [14]. For higher impact heights, the wear rate difference among three liquids decreases. At 1.0 mm impact height, the wear rate in the three liquids is identical within the error of measurement. For higher impact heights the differences are even smaller. The net material loss, shown in Figure 2b, shows the same behavior, except that the wear rate increase with the increasing impact height is much smaller.

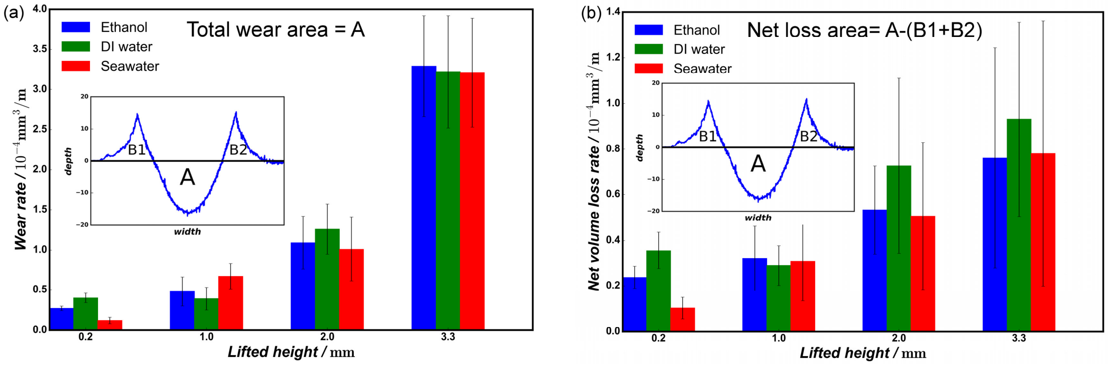

Figure 2. (**a**) Wear rate comparison at various impact heights; (**b**) Net volume loss comparison at various impact height. Ethanol, deionized (DI) water and seawater were used to vary corrosivity. The error bar stands for one standard deviation of three repeated results. The embedded small figure represents the cross section of the round wear track.

3.2. Wear Track Analysis

The wear track comparison at various impact height in three liquids is illustrated in Figure 3. As can be seen, for each liquid, with increasing impact height, the depth of the track increases as well, and when the impact height reaches 3.3 mm, the wear depth seems to be the same among all liquids, well corresponding to the wear rate comparison (Figure 2). The total volume loss due to wear has two components: material removal and deformation. The deformation part accounts for a large portion of the total wear when the impact height is beyond 1 mm. As shown in Figure 4, for all three liquids, the ratio of deformation to total wear is less than 20% for the impact height of 0.2 mm, by comparison, it reaches nearly 80% when the impact height is 3.3 mm. For 1 mm and 2 mm, the ratios are comparable. In seawater, the ratio change is the most dramatic from less than 20% to roughly 60%, when the impact height increases from 0.2 mm to 1 mm. Additionally, the wear track, overall, is smooth except for the situation where the impact height is the least, 0.2 mm, which shows a level of roughness, similar to the situation in pure sliding [14].

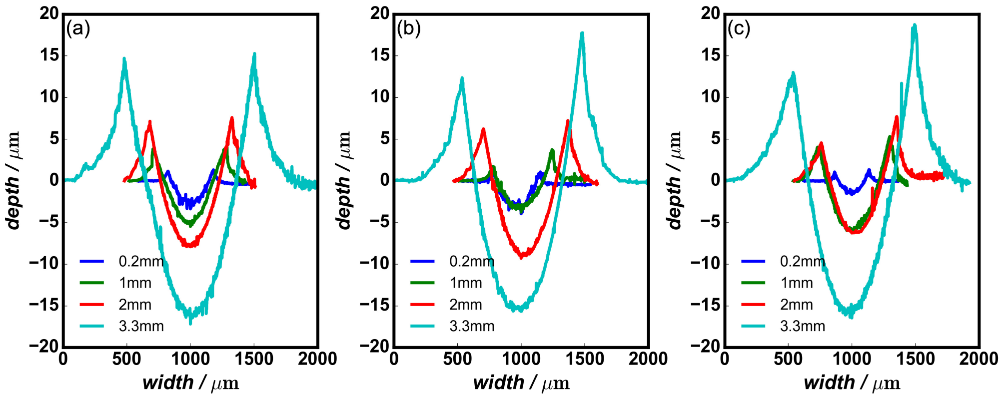

Figure 3. Wear track comparison at various impact heights in three liquids: (**a**) in ethanol; (**b**) in DI water; (**c**) in sea water. The average of three repetitive results was used for each situation. The wear track was moved to the center in order to be easily compared.

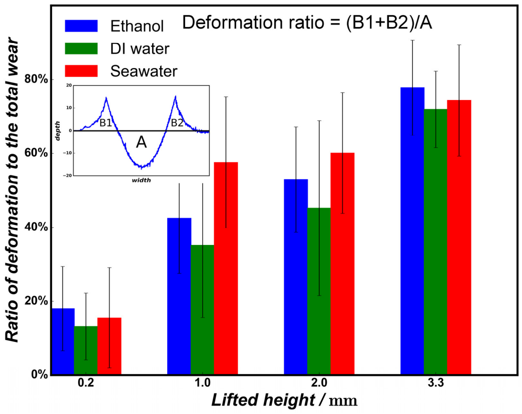

Figure 4. The ratio of plastic deformation to the total wear at various impact heights. Ethanol, DI water and seawater were used to vary corrosivity. The error bar stands for one standard deviation of three repeated results. The embedded small figure represents the cross section of the round wear track.

4. Discussion

In slurry transport, the pipes wear due to the combination of sliding, impact and corrosion [1]. The interaction among those factors determines the final wear. Typically, the interaction leads to a positive synergistic effect and results in higher wear rate. However, research has shown the beneficial effect of the interaction between corrosion and abrasion, where corrosion is able to modify the sample surface by dissolving the soft phase and leaving the hard phase protruding, and subsequently, abrasion redistributes the hard phase, increasing the wear resistance [14]. However, in real slurry transport situations, no noticeable wear difference between corrosive and non-corrosive mediums was observed and reported. Although the scale of the research in a lab is different from in real situation, the mechanisms should keep the same. In this study, impact shows a huge influence on the wear rate. At 0.2 mm, the wear rate in ethanol, DI water, and seawater shows a huge difference, and in seawater, the wear rate is the smallest. However, when the impact height increases to 1 mm, the wear rate difference is within the experimental uncertainty. From 1 mm impact height, the influence of corrosion is not able to dominate. At 0.2 mm, the impact is small, and the wear result is similar to the result found in pure sliding. In pure sliding, the modified surface is able to increase the wear resistance of the sample, showing a beneficial effect. From low impact to high impact, the wear mechanism changes from material removal to mainly plastic deformation, as shown in Figure 4. When deformation becomes the determining factor of wear, surface modification, which governs the wear mechanism in pure sliding wear, does not make a difference. The deformation also results in a rather smooth wear track, which is not typical in a corrosive environment. The smooth wear track implies that the influence of corrosion becomes a minor influencing factor.

5. Conclusions

In this study, the effect of impact on the wear of a structural steel S235 was studied in various liquids. When impact is small, corrosion plays a dominant role so that the sample in seawater wears the least due to the beneficial interaction with abrasion. However, when impact is large, the wear rates among three liquids do not show a noticeable difference, because the wear mechanism changes from material removal to mainly plastic deformation. The influence of corrosion becomes a minor influencing factor when subject to impact.

Supplementary Materials: The followings are available online at http://www.mdpi.com/2079-6412/7/12/237/s1, Figure S1: Estimated hitting speed of the pin: 0.2 mm; 1 mm; 2 mm; 3.3 mm; Figure S2: The micrograph of worn surfaces imaged with Scanning Electron Microscope; Table S1: Estimated hitting speed and angle of the pin on the sample for various lifted heights.

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Author Contributions: Yueting Liu and G.C.A.M. Janssen conceived the idea and designed the experiments. Yueting Liu performed the experiments and wrote the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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