Tests on Wear of Various Metals due to Ice Friction

S. Kioka¹, and T. Takeuchi²

¹Civil Engineering Research Institute for Cold Region, Sapporo, Japan
²Hachinohe Institute of Technology, Sapporo, Japan
*kioka@ceri.go.jp

Tests involving ice friction-related wear/abrasion on various metals such as carbon steel, stainless steel and titanium were carried out to clarify the characteristics of deterioration in steel structures such as sheet piles in ice covered areas. Each metal test piece was placed in contact with artificial saline ice under certain levels of pressure using an oil jack [0.01–1.62 MPa], and reciprocating motion was introduced at a sliding speed of 1–15 cm/s by the rotation of a ball screw under AC servo motor control. The tests were performed in a cold room at a temperature of −10°C. The amount of wear sustained by the carbon steel increased linearly with the sliding distance (or time). Although wear also increased with higher levels of contact pressure, the rate of increase fell at pressure values of around 0.6 MPa or more. Conversely, the wear amounts sustained by stainless steel and titanium were close to zero, despite the minimal difference between the Brinell hardness values of the metals. Accordingly, it can be concluded that the main factor influencing this type of deterioration in carbon steel is corrosive wear rather than adhesive wear. Further, because the wear rate per unit time for carbon steel increased linearly with the sliding speed, it can be concluded that ice action promote the corrosion of steel by stimulating its surface.
1. Introduction

In sea areas covered with ice where active sea ice movement is seen (such as the Arctic Ocean and the Sea of Okhotsk), The degradation/deterioration of marine and coastal structures has been caused by wear, abrasion, deformation, peeling and other types of damage stemming from ice-related impact and friction. In addition to the interaction with sea ice, deterioration in steel structures can be severe because ice-infested sea waters may be relatively high corrosive due to the prevailing conditions of low temperature, high oxygen. It has been reported that the wear rate of steel materials in such areas is twice as high as that in normal areas (Smuta-Otto, 1986). In one case, concrete wear totaling approximately 14 cm in 20 years was reported (Janson, 1989). In Japan, significant deterioration in elements of steel sheet pile-type seawalls and training walls due to wear/impact with sea ice (Photo 1), and peeling of concrete surfaces and the exposure of reinforcements of concrete structure due to wear/abrasion have been confirmed. In particular, recent sea ice reduction due to the influence of climate change may have resulted in intensified sea ice movement and drift velocity and caused accelerated structural damage/deterioration. This may include the facilitation of corrosion and wear/abrasion to surface of structural materials due to impact with ice masses and contact/friction with sea ice. In coastal areas of Hokkaido, some studies focusing on external forces have been conducted, including analysis of ice loads acting on seawalls and canal walls, on-site measurement of wall contact pressure (Kawai et al., 2010) and a study into the dynamic behavior and contact loads of drift ice floes based on numerical calculation (e.g. Kioka et al., 2010). From the viewpoint of material wear, many studies concerning concrete wear caused by sea ice (e.g. Hoff, 1988; Nawwar et al., 1988; Houvinen, 1990; Itoh et al., 1994; Hanada et al., 1996; Friorio, 2005) have clarified the wear mechanism and proposed practical methods for related estimation (e.g. Itoh et al., 1994; Hanada et al., 1996). However, it is difficult to assess wear on surface of metal materials because the phenomenon involves composite deterioration with the simultaneous progress of corrosion, and very few quantitative studies have addressed this. Although there are many causes of wear (loss of material), the focus of this study was primarily on the possibility of mechanical wear (adhesive wear) of metal material surfaces caused by sea ice friction, and its contribution was examined by conducting a sliding wear test involving artificial sea ice with various metal materials (mainly SS400). This report also includes a summary of a deterioration survey of the Monbetsu Okhotsk Tower, which is a concrete structure protected with titanium-clad steel against the action of drift ice floes.

Photo 1. An example of deterioration in steel sheet piles of a training wall facing the Sea of Okhotsk.

2. Causes of Wear on Metal Materials

First, as general background on the phenomenon of wear between metal materials, adhesive wear is known as a typical form of wear. Material surfaces usually have microasperities, and areas
where actual contact takes place (referred to here as real contact areas) are often very small. Increased pressure on contact areas causes plastic deformation (adhesion), and if this is combined with movements between materials, shearing fracture occurs near the adhered part and results in transfer to other surfaces. If this is repeated, the build-up of transferred substances eventually causes a discharge of wear debris from the contact surface. This is the process behind the mechanism of wear. Another typical type of wear besides adhesive wear is abrasive wear, which is defined as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface. As with adhesive wear, this phenomenon can often be explained using Holm's wear equation:

\[ W = k \frac{P}{P_m} L \]

Here, \( W \) is the wear volume for the case of wear with distance \( L \) under load \( P \), \( P_m \) is the indentation hardness (or plastic flow pressure) of the softer side, and \( k \) is a constant known as the wear coefficient. It is known that the wear amount is proportional to the wear distance and load in the case of concrete wear caused by sea ice (Itoh et al., 1994; Hanada et al., 1996), and a calculation equation in a form similar to the above is proposed to estimate the wear amount. Another possibility is corrosive wear (as seen with the mechanism of sand erosion), which damages steel material surfaces in sea areas. In this process, rust layers stemming from corrosion are removed by the action of sand, resulting in exposure of the surface beneath and further corrosion (Abe et al., 1998). In the case of sea ice, the removal of rust layers by impact and friction can also accelerate corrosion and wear-related damage. It is further presumed that component deterioration originally caused by ordinary seawater corrosion may develop into critical damage due to the action of sea ice (e.g. friction and impact). Other factors to be considered include concentrated corrosion due to cell formation caused by potential differences depending on temperature, and facilitation of corrosion fatigue by repeated sea ice action. While various factors of wear are possible and are presumed to act in combination, this study focused on the risk of adhesive wear (a basic form of wear) via a component test.

3. Sliding Wear Test

3.1 Test Device and Experiment Method Overview

While many forms of friction/wear test are known, surface contact-type sliding (block on plate) was used for the same reason as that given by Ito et al. (1994). As shown in Fig. 1, a metal sample (specimen) representing a structure was placed in contact with an artificial ice prism (Kioka et al., 2009) (8 cm wide, 5–10 cm high, 70 cm long) contained in a steel case by applying reasonable pressure with a hydraulic jack. The friction surface was made parallel to the growth direction of the ice and the friction direction was made perpendicular to the growth direction to simulate conditions considered common in actual cases. The metal sample was plate-shaped and 10 cm in the friction direction, 8 cm in width (the same width as the ice prism) and 14 mm in thickness (contact area with ice: 10 × 8 cm). As shown in the figure, it was fixed to a holder and then attached to the hydraulic jack. To prevent the ice from being cut by the edges of the metal sample, a chamfer of approximately 5 mm was applied to them. As a result, the apparent contact area with the ice was 9 × 8 cm. The sample surface was finished by face-milling it to a roughness of 6S. Next, using downward pressure, friction was applied to the ice-containing case with a
reciprocating motion at a certain speed (amplitude distance: 30 cm). The basic principle of the motion was realized by rotating a ball screw with an AC servomotor, thereby creating a mechanism to allow stable sliding friction over a long distance. After the application of an appropriate friction distance, the wear amount was estimated by measuring the mass change with an electronic balance (precision: 1 mg; A and D Co., Ltd.; separate-type even balance AD4212A-1000). However, because a certain amount of rust had adhered to the sample (as detailed below), measurement was made immediately after the rust was removed with a soft brush to an extent that would not damage the sample surface itself. As other measurement items, the load in the horizontal and vertical directions and displacement in the friction direction were measured to support the estimation of friction force and contact pressure.

**Figure 1.** Schematic diagrams showing the sliding wear tester and the wear test method.

### 3.2 Experiment Conditions

Table 1 shows the main experiment conditions. The test was conducted in a condition-controlled low-temperature chamber at –10°C. While the metal sample used for the experiment was made of rolled structural steel (SS400), stainless steel (SUS304) and titanium (Ti) were also used in limited experiment conditions (standard). The average Vickers hardness values of the SS400, SUS304 and Ti materials used as metal samples were 132, 163 and 218, respectively. The apparent contact pressure (found by dividing the vertical load by the apparent contact area) ranged from 0.01 to 1.6 MPa, with 0.6 MPa as a standard value. Few reports to date have detailed the measurement of contact pressure (i.e., pressure perpendicular to the movement direction of the ice) in coastal areas of Hokkaido. However, based on the results of measurement relating to the side walls of the canal forming the second entrance to Lake Saroma facing the Okhotsk sea (Kawai et al., 2010), pressure was estimated to be lower than the standard value (0.6 MPa) set in this experiment even at its highest, and the range of contact pressure was considered to be sufficiently practical. The movement speed ranged from 0.01 to 0.15 m/s with approximately 0.06 m/s as a standard value. A wear test using freshwater ice was also conducted to examine the indirect contribution of corrosion to the wear amount. The maximum friction distance was approximately 50 km, except for one case in which the value was 125 km. However, the distance was limited to around 26 km in the case with the highest pressure because damage to
the artificial sea ice itself was severe. While the experiment was made only once due to time constraints, it was conducted twice with the standard test condition.

**Table 1. Main experiment conditions.**

<table>
<thead>
<tr>
<th>Sample material (specimen)</th>
<th>SS400, SUS304, Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric temperature (°C)</td>
<td>-10</td>
</tr>
<tr>
<td>Contact(friction) pressure (MPa)</td>
<td>0.01 – 1.62 (0.6)</td>
</tr>
<tr>
<td>Movement speed (m/s)</td>
<td>0.01 – 0.15 (0.06)</td>
</tr>
<tr>
<td>Max. wear distance (km)</td>
<td>26.7 – 125 (50)</td>
</tr>
<tr>
<td>Amplitude distance (m)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Notes:
- Values in parentheses indicate standard condition.
- SUS and Ti were tested under standard condition.
- Each sample surface was finished by face-milling.
- The Vickers hardness values for SS400, SUS304 and Ti are 132, 163 and 218, respectively.

### 4. Experiment Results and Discussion

#### 4.1 Relationship between Friction Distance and Wear

Fig. 2 shows the relationship between the friction distance and the average wear amount at a movement speed of 0.06 m/s with the standard condition. Average wear is defined as the value found by dividing the mass loss of the sample by its density and the apparent contact area, and is represented by a length value (mm). In other words, it can be considered as the average wear depth. This section first explains the basic form of sliding wear development in general materials. As shown in Fig. 3, three patterns are commonly seen. When the wear rate changes gradually from the start of sliding and becomes uniform later, the state of the changing rate is called initial wear, and the state of the uniform rate is called steady wear. As in the case of Type A, the wear rate is often higher in the initial (severe) wear state and lower in the steady (mild) wear state. The initial wear state is also known as the running-in period, in which significant projections originally present in surface roughness are crushed or removed by friction. As the structure of the surface layer changes at the same time, sliding between the materials can be achieved in a mutually advantageous manner. In the case of friction between metal materials (especially for transition elements), ongoing friction on the same part of the surfaces in a severe friction state causes repeated contact and separation of the surfaces (adhesive wear), resulting in their mechanical activation due to atmospheric gas adsorption. In such cases, films of chemically adsorbed oxygen form, and the real contact area in direct solid contact decreases dramatically. As a result, the size of transfer elements decreases, leading to the miniaturization of wear particles and a dramatic decrease in the specific wear rate. Type C is wear that progresses linearly. The cases shown in Fig. 2 resemble those of Type C, as their progress is almost linear. However, as the initial friction distance is very short in some cases of Type A and severe-mild wear transition is likely to occur, Type C can be seen as a subset of Type A. The known characteristics of friction between metal materials suggest that such transition is likely when the pv value (the product of apparent contact pressure and friction velocity) is small and at least one of the two solids is a transition metal. Severe-mild wear transition is considered to occur at an early stage for the materials used in this experiment because Ti is a transition metal and SS and SUS contain Fe, Ni and other transition metals. This may be the case if adhesive wear is dominant in material wear in experiments, and transition is thought to occur with an extremely
short friction distance. While it has been reported that concrete wear caused by sea ice generally takes the form of Type A (Itoh et al., 1994), the initial friction distance may be as short as several kilometers.

![Graph showing relationship between friction distance and average wear.](image)

**Figure 2.** Relationship between friction distance and average wear.

![Graph showing basic types of wear development.](image)

**Figure 3.** Basic types of wear development.

### 4.2 Influence of Contact Pressure on Wear

The previous section showed that wear amount is almost proportional to friction distance. Therefore we define the linear gradient of the wear amount versus the wear friction distance shown in Fig. 2 as wear rate (mm/km). Fig. 4 and Table 2 summarize the relationship between apparent contact pressure and the wear rate (mm/km). While Holm's equation is commonly used to treat sliding wear, it was confirmed that with concrete wear due to sea ice, the wear amount is also proportional to the friction distance as mentioned before, and is directly proportional to the load (contact pressure) (Itoh et al., 1994). However, in this experiment, while the wear rate tended to increase with greater pressure, no directly proportional relationship was seen, and the rate of increase seemed to drop off. No significant increase was seen especially around and after 0.5 MPa, meaning that Holm's equation is not applicable in this case. Although we did not measure ice hardness this time, values for the Brinell hardness of single-crystal pure ice would suggest that it was mostly in the order of 1 to 10 (depending on the ice temperature, the direction of the c-axis and other factors) (Butkovich, 1958), and the value was presumed to be one order smaller than that of metal. It may therefore be easy to presume that the real contact area (i.e., the
ratio of the load to the plastic flow pressure of the softer material) reached saturation over most of the apparent contact area at an early stage and caused the increase in the wear rate to slow down. However, this is unlikely because the above-mentioned value of 0.5 MPa is far smaller than the pressure in the order of 10 to 100 MPa presumed in this case. It is also unlikely that wear-related damage is the adhesive or abrasive type because ice is much softer than metal, and its shear strength is also extremely low (Tushima, 1978). In fact, the main cause of wear-related damage is thought to be corrosion, as outlined below. This changing tendency of the wear rate with pressure is considered to stem from a combination of increased shear force (leading to more corrosion), which is caused by increased pressure and in turn causes peeling of rust and the exposure of a new active surface, and reduced corrosion resulting from a low oxygen (dysoxic) conditions. Further, it may also be due to increased moisture content by pressure melting of ice and the release of brine, more detailed studies are necessary in the future.

**Figure 4.** Relationship between contact pressure and average wear rate.

**Table 2.** Wear rate in each experiment.

<table>
<thead>
<tr>
<th>Ice</th>
<th>Sample material</th>
<th>Contact pressure (MPa)</th>
<th>Wear rate (mm/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>0.007</td>
<td>1.22×10⁻⁴</td>
</tr>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>0.12</td>
<td>1.59×10⁻⁴</td>
</tr>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>0.35</td>
<td>2.75×10⁻⁴</td>
</tr>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>0.60</td>
<td>2.81×10⁻⁴</td>
</tr>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>0.67</td>
<td>3.09×10⁻⁴</td>
</tr>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>1.14</td>
<td>3.38×10⁻⁴</td>
</tr>
<tr>
<td>Saline</td>
<td>SS400</td>
<td>1.62</td>
<td>3.51×10⁻⁴</td>
</tr>
<tr>
<td>Fresh</td>
<td>SS400</td>
<td>0.58</td>
<td>9.41×10⁻⁶</td>
</tr>
<tr>
<td>Saline</td>
<td>SUS304</td>
<td>0.61</td>
<td>4.44×10⁻⁶</td>
</tr>
<tr>
<td>Saline</td>
<td>Ti</td>
<td>0.61</td>
<td>-2.5×10⁻⁶</td>
</tr>
</tbody>
</table>

Note: The terms saline and fresh represent artificial seawater and freshwater ice, respectively.

4.3 Influence of Corrosion

Fig. 5 shows the surface status immediately after the maximum friction distance was reached under each condition (at the end). As shown in (a), with an SS sample and artificial sea ice, the
SS often became corroded during the friction test, and its red rust adhered to the ice. However, this phenomenon was not seen with SUS or Ti samples as observed in Fig. 5 (b), in which the surface of the freshwater ice does not seem very different from those of the artificial sea ice (saltwater) samples in Fig. 5(a). However, the amount of rust adhering to the ice was considerably smaller. In other words, minimal rust formation was a characteristic seen with freshwater ice. The wear rates for freshwater ice and SS and for saltwater ice and SUS/Ti seem to be almost zero in Fig. 3. Fig. 2 was therefore enlarged, and the relationship between the friction distances and average wear amounts are shown in Fig. 6. Table 2 also shows that these wear rates are smaller by a factor of two or more compared to those in the above cases. This may be explained first by differences in the indentation hardness (or plastic flow pressure) of the samples. Although the Vickers hardness values of SS400, SUS304 and Ti are 132, 163 and 218, respectively, and those of SUS and Ti are greater than that of SS (Table 1), this does not sufficiently explain the difference. While the value for titanium is negative (Table 2), it can be regarded as almost zero because the result is highly likely to be an error caused by measurement accuracy issues. In addition, when freshwater ice (FW) was used for the same SS, the wear rate decreased dramatically and was in a similar order to that of SUS. No clear influence of contact pressure on the apparent surface status is seen in Fig. 5(a). It is also interesting that corrosion products appear as belt-like patterns parallel to the friction direction. It is not known whether this is because they were extended in the movement direction during a state of separation into anode and cathode components or whether the phenomenon stems from other factors. Either way, further studies on a more microscopic scale are planned for the future. The above results and the discussion in the previous section suggest that the conditions required for adhesive wear to occur are relatively rare, and that the main cause of wear in this experiment was corrosion, as hardly any wear was seen in corrosion-resistant materials.

(a) Comparison of SS sample friction surfaces with changes in pressure. The friction distance was displayed after the completion of the experiment

(b) Comparison of friction surface conditions for other materials

Figure 5. Examples of sample friction surface conditions.
Figure 6. Relationships between friction distance and average wear (enlargement of Fig. 2). From the left, SS400 vs. freshwater ice, SUS304 vs. artificial seawater ice, Ti vs. artificial seawater ice.

4.4 Influence of Friction Velocity

Fig. 7 shows the relationship between the average friction velocity and the average wear rate when the contact pressure was approximately 0.6 MPa. The black circles represent wear rates per unit distance (mm/km) as in Fig. 4, and the white circles represent wear rates per unit time (mm/day) when the cause of wear is assumed to be corrosion. In the former case, the maximum value appears to have been reached when the wear velocity was around 1 cm/s. In the latter, the hourly wear rate increased almost in proportion to the wear velocity. If this assumption is true in a strict sense, the former would be uniform regardless of friction velocity. It is especially interesting that the wear amount is zero and there is no corrosion when the friction velocity is zero and only pressure is applied. Looking at the wear rate per unit time (mm/day), although the reason for the higher values seen with increased velocity is unknown, the cause is assumed to be increased oxygen supply because the ice or metal surfaces is stimulated and oxygen adsorption into those surfaces become active in addition to increased friction heat or something. Another cause may be the melting of ice (i.e., the release of brine) due to increased friction heat. While the ice surface was always slightly wet, no clear difference relating to velocity variations was seen, and further studies are necessary in the future.

Figure 7. Relationship between average friction velocity and average wear rate.

5. On-site Deterioration Survey

The Okhotsk Tower (Photo 2) is a sea ice observation facility in Okhotsk coast of Hokkaido. As it is subject to the action of drift ice floes in winter, the concrete near the water surface is protected using steel clad with 1-mm thick titanium. In March 2010, the surface thickness of this steel clad was measured, and an appearance inspection of the surface conditions was also made.
The inspection was conducted visually from on board a survey ship over the range of M.L.W.L. +0.4 to +5.5 m (the top end of the steel clad plate) above the water, and by divers for M.L.W.L. +0.4 to -1.5 m (the bottom end of the steel clad plate) below the water. Thickness measurement of the plate was conducted for the range of +2.0 m (splash zone) to -1.5 m (the bottom end of the steel clad plate) using an electromagnetic coating thickness meter (5 points in the depth direction and 8 in the circumferential direction).

Although more than 15 years had passed since the structure was built, wear as revealed by the thickness survey was almost zero. Adhesion of rust fluid thought to be from the upper steel material was found, but no corrosion was seen above or below the water, and the appearance was extremely sound (Photo 3). It was presumed that wear was almost zero due to the absence of corrosion in addition to the relatively high material strength of titanium.

6. Conclusion and Future Prospects

In this study, focus was first placed on the possibility of adhesive wear (one of mechanical wear) caused by sea ice, and a sliding wear test was conducted using artificial sea ice and a variety of metal materials. The main findings were as follows:

- Wear tended to increase in almost linear proportion to the friction distance.
- While the wear rate (mm/km) increased with contact pressure, no significant increase was seen when the pressure was around 0.5 MPa or higher, and the results did not follow Holm's equation well expressing the (adhesive) wear properties of metal materials.
- The wear rate of SUS was smaller than that of SS by a factor of two. That of Ti was almost zero, which could not be explained only by the difference in hardness with SS.
- From the above results, it was presumed that the contribution of corrosion was much greater than that of mechanical wear (adhesive or abrasive).
- This assumption is also supported by the fact that wear per unit time was proportional to friction velocity (no wear in a stationary condition) and related to the activation of material surfaces or fluctuations in atmospheric (oxygen) supply.
- The deterioration survey results for the Okhotsk Tower (protected with titanium-clad steel against the action of drift ice floes) revealed that there was no wear-related damage and that an extremely healthy condition was maintained even 15 years after construction.
As a mixture of sand in sea ice has been found in some surveys at sites with severe wear-related damage, the contribution of abrasive wear caused by interposed particles is also considered possible. In some cases, sand was not only present at the surface of ice floes, but also penetrated to the inside. An abrasive wear test with interposed sand is also currently being conducted. Sand is considered a major cause of abrasion because wear amounts caused by sand are greater than those caused by corrosion in the current test, the results will be reported in a future report. The next publication will also include further interesting results from the current study concerning the examination of friction force and friction coefficients, which are inextricably associated with wear. While the current test was conducted in air with a focus on adhesive wear, underwater friction experiments including on-site exposure tests are scheduled for the future in consideration of the significant influence of corrosion. It is also considered necessary to conduct further studies from a variety of viewpoints because deterioration may be inhibited in some cases, such as those where thin ice layers forming on a material surface inhibit corrosion and where moderate rust layers inhibit adhesive or abrasive wear.

**References**


Smuga-Otto, I., 1986. Factors influencing corrosion of vessels and offshore structures in Arctic seawater, Corrosion 86.