Effect of Microstructures on Low-Stress Abrasive Wear of Steel Plates

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INTRODUCTION

Abrasive wear is a common and costly problem in the industrial areas of agriculture, mining, mineral processing, and earth moving whenever dirt, rock and minerals are handled. Depending on the stress level during abrasive wear, it is often categorized as being low-stress or scratching abrasion, high-stress or grinding abrasion, gouging abrasion and solid particle erosion. Among them low-stress abrasion occurs when lightly loaded abrasive particles impinge on and move across the wear surface, cutting and plowing material on a microscopic scale. During this event, the abrasive remains relative intact during abrasion, in contrast to high-stress abrasion, where the abrasive is crushed. A typical example of low-stress abrasion is the wear that occurs on a construction machine working with loose sand or dirt.

The abrasive wear resistance of a material has been related to a variety of material properties, including compositions, hardness, elastic modulus, yield strength, and microstructure, etc. Among them, material hardness has been considered the predominant factor. This can be explained by the micro-cutting mechanism, one of the wearing mechanisms that contribute to material removal during abrasion. By increasing material hardness, the particle has less penetration depth, therefore, less material is scratched off by the abrasive particle. This has been expressed in simple terms through Archard’s wear equation

\[ W_v = k_{ab} s \frac{F_N}{H} \]  

where \( W_v \) is the volume loss due to wear, \( k_{ab} \) is the abrasive wear coefficient, \( s \) is the sliding distance of the abrasive under normal load \( F_N \), and \( H \) is the hardness of the material. Heat treated steel plates are widely used as abrasion resistant materials. The steel grades are usually classified based on their hardness levels - from 360 up to 600 HBW. When even higher abrasion resistance is needed, materials with extremely high hardness, such as tungsten carbide and chromium carbide are applied to create hard faces on steels to address some of the most severe abrasive wear environments.

Beside hardness, the microstructure of the material plays a critical role in its wear performance. For example, Tylczak mentioned that when hardness is the same, austenite and bainite are more abrasion resistant than ferrite, pearlite or martensite due to higher strain-hardening capacity and ductility of austenite. The study of Xu and Kennon indicated that for steels with carbon content less than 1.0 wt%, at the same hardness level, bainitic microstructures had the highest wear resistance, followed by quenched and tempered microstructures, then annealed structures, and spheroidized structures. The effects of microstructures on abrasive wear performance were also reported in other literature. Zum Gahr summarized the effects of steel hardness and microstructures on wear resistance and gave a chart as shown in Figure 1. This chart implies that a pearlitic steel with a hardness of 200-250 HV could provide equivalent wear resistance to a hardened steel with a hardness of 400-500 HV. Such results have been supported by the laboratory and field observations from Hagen, Prasad and Kulkarni, Burdick and Fernandez and Kiser.
In the recent years, such studies have been further extended to wear performance of low- to ultralow-carbon steels, where soft microstructures such as ferrite are predominant. The study by Sundström et al. indicated that steels of ferrite/pearlite/bainite microstructures, with hardness around 300 HV, gave equivalent impact abrasion resistance as steels of martensitic microstructures with hardness of 450-500 HV. The studies by Chen and Liu et al. indicated that as-rolled low-carbon microalloyed steels, with ferrite/pearlitic microstructures, give similar low-stress abrasion resistance to heat treated steels with a hardness of 400 HBW. The investigation by Rendon and Olsson with low- to ultralow-carbon steels also indicated that steel hardness, varying from 190 to 390 HV, does not have significant impact on the material wear performance under high-stress abrasion and impact abrasion.

This study investigates the effects of microstructure and hardness of steels on wear resistance during low-stress abrasion. Five steels were selected for investigation, including two as-rolled low-carbon steels, a hardened low-carbon steel, a hardened medium-carbon alloy steel and an as-rolled high-carbon steel. The wear resistances of these steels were evaluated by dry-sand-rubber-wheel (DSRW) wear test, and the wear data were correlated to the microstructures and mechanical properties of the steels.

**EXPERIMENTAL**

Five steels were selected for this study denoted A, B, C, D and E. Steel A is a thermomechanically rolled low-carbon microalloyed steel. Steel B is a hot-rolled low-carbon steel. Steel C is a hardened low-carbon steel. Steel D is a hardened medium-carbon alloy steel. Steel E is a hot-rolled high-carbon steel. Except Steel D, which is a Caterpillar Inc. proprietary steel, all other materials are commercial steel grades. The chemical compositions (in wt%) are given in Table I.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Al</th>
<th>B</th>
<th>Ti</th>
<th>Zr</th>
<th>Nb</th>
<th>V</th>
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<tbody>
<tr>
<td>A</td>
<td>.092</td>
<td>1.224</td>
<td>.016</td>
<td>.007</td>
<td>.11</td>
<td>.13</td>
<td>.04</td>
<td>.01</td>
<td>.32</td>
<td>.024</td>
<td>.0002</td>
<td>.013</td>
<td>.003</td>
<td>.00</td>
<td>.06</td>
</tr>
<tr>
<td>B</td>
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<td>1.157</td>
<td>.012</td>
<td>.001</td>
<td>.05</td>
<td>.16</td>
<td>.12</td>
<td>.05</td>
<td>.28</td>
<td>.030</td>
<td>.0001</td>
<td>.014</td>
<td>.003</td>
<td>.00</td>
<td>.01</td>
</tr>
<tr>
<td>C</td>
<td>.123</td>
<td>1.209</td>
<td>.020</td>
<td>.000</td>
<td>.39</td>
<td>.02</td>
<td>.27</td>
<td>.01</td>
<td>.01</td>
<td>.040</td>
<td>.0011</td>
<td>.024</td>
<td>.002</td>
<td>.01</td>
<td>.01</td>
</tr>
<tr>
<td>D</td>
<td>.428</td>
<td>0.811</td>
<td>.012</td>
<td>.015</td>
<td>.61</td>
<td>.09</td>
<td>.11</td>
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<td>.0028</td>
<td>.053</td>
<td>.003</td>
<td>.00</td>
<td>.10</td>
</tr>
<tr>
<td>E</td>
<td>.754</td>
<td>1.017</td>
<td>.008</td>
<td>.004</td>
<td>.32</td>
<td>.07</td>
<td>.20</td>
<td>.02</td>
<td>.21</td>
<td>.004</td>
<td>.0002</td>
<td>.005</td>
<td>.002</td>
<td>.00</td>
<td>.01</td>
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</table>

The microstructures of the steel grades are characterized using light optical microscopy on polished and etched metallographic samples, and the micrographs are given in Figure 2. Steel A and Steel B have ferritic/pearlitic microstructures. The pearlite content in Steel A is less than Steel B due to its lower carbon content, and it has finer grain sizes due to thermomechanical processing. The microstructure of Steel C is martensitic/bainitic, although the amount of bainite is hard to determine from the optical micrographs. Steel D has martensitic microstructure. The microstructure of Steel E is essentially 100% pearlite.
The hardness of the steel grades was evaluated using two different techniques including Vickers hardness and scratch hardness. The scratch hardness test was conducted per ASTM G173-03. Spherical scratch test indenter with 200μm radius was used to create the scratches. The load was set at 30 N. The tip travelled at a speed of 10 mm/min to a distance of 10 mm. The hardness results are given in Table II. Steel A and B have the lowest hardness (137-148 HV), consistent with as-rolled low-carbon steels. The as-rolled high-carbon Steel E has a hardness of 243HV. With the application of a quench and temper heat treatment, the hardness of low-carbon Steel C reaches 406 HV, and Steel D achieves a hardness of 657 HV.

Table II. Hardness and scratch hardness of the steel grades evaluated.

<table>
<thead>
<tr>
<th>Steel</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (HV)</td>
<td>137</td>
<td>148</td>
<td>406</td>
<td>657</td>
<td>243</td>
</tr>
<tr>
<td>Scratch hardness (kg/mm²)</td>
<td>153</td>
<td>184</td>
<td>353</td>
<td>719</td>
<td>329</td>
</tr>
</tbody>
</table>
The abrasion resistance of the steel grades was evaluated using DSRW wear test per ASTM G65-04 (2010). The apparatus is shown in Figure 3a. The test samples have a size of $76 \times 25.4 \times 12.7$ (in mm). AFS 50/70 silica sand was used for the test. An image of the sand is given in Figure 3b showing that its shape is quite rounded. The sand flow rate was set at 370 g/min. The load on the steel sample was set at 130 N. A 228 mm diameter (nominal) rubber wheel was used for this test. The wheel rotating speed was set at 200 rev/min. A total travel distance of 6000 revolutions was used for each sample. The sample weight was measured before and after wear testing with a scale to an accuracy of $10^{-4}$ g. The actual wheel diameter was also measured after each test to offset the size change during tests. The weight loss of the sample was then converted into volume loss (in mm$^3$), assuming a density of 7.80 g/cm$^3$. The wear loss of Steel C was used as the baseline. The data from other steels were normalized to the average volume loss of Steel C for comparison.

![Figure 3. The DSRW wear test apparatus a) and the image of the abrasive b) per ASTM G65-04.](image)

The abrasive wear resistance of the steels was further evaluated through a field wear study. Three different steel plates were tested. Two of these plates were of the same grade as Steel A and Steel C but from different heat lots, and will be designated as Steel AA and Steel CC. The third plate evaluated was a martensitic, heat treated plate having a hardness of 265 HV, which will be designated Steel F. Steel AA and Steel CC were placed on the bottom of an excavator bucket as shown in Figure 4a. Steel AA and Steel F were placed side-by-side inside of the bucket as liner plates (Figure 4b). The bucket was tested in sandy soil conditions, and therefore is expected to present a similar wear mode to that of the DSRW test. Wear measurements were performed on bottom wear plates and liner plates after a prescribed number of hours of field service. Multiple measurements were taken at three different locations along the length of each plate. The amount of wear on the steel plates was evaluated by the change in thickness.

![Figure 4. Location of wear plates place on an excavator bucket for field tests: (a) Steel AA and Steel CC were placed side-by-side on the bottom of the bucket, and (b) Steel AA and Steel F were placed side-by-side as liner plates within the bucket.](image)
The DSRW wear test results are shown in Figure 5a. The as-rolled Steel A and Steel B have the highest wear loss. The wear loss from Steel C is only slightly less than Steel A and B, despite its higher hardness imparted by heat treatment. The wear loss of Steel D is about 50% less than that of Steel C. For Steel E the wear loss is about 25% less than Steel C, despite its lower hardness.

Figure 5b shows the normalized wear loss data plotted against the hardness of the steel samples. The separation in data trends between hardened steels (Steel C and D) and non-hardened steels (Steel A, B and E) is clear. Very similar results have been obtained from previous studies. This set of data agrees well with the chart given by Zum Gahr in Figure 1, taking into consideration that Figure 1 is a plot of wear resistance and Figure 5b plots relative wear.

![Figure 5](image.png)

**Figure 5.** DSRW wear test data for (a) the five experimental steels normalized to Steel C, and (b) the normalized DSRW wear test data (showing individual test data points) plotted as a function of hardness.

The wear loss data (in mm) from field test are given in Figure 6. For the bottom wear plates, the hardened Steel CC and non-hardened Steel AA have comparable wear loss at the bottom of the bucket (Figure 6a). For the liner plates, the as-rolled Steel AA showed significantly less wear loss than the hardened Steel F (Fig. 6b). The field test results further confirm the laboratory testing observations that as-rolled plate steels can provide comparable wear performance to significantly harder heat treated plates under certain wear circumstances.

![Figure 6](image.png)

**Figure 6.** Field wear measurements on (a) bottom wear plates and (b) liner plates, showing the as-rolled Steel AA, had similar or better wear performance to the heat treated, martensitic plates, Steel CC and Steel F with hardness around 265 HV.

The DSRW wear surfaces are displayed in Figure 7. Scratching patterns can be seen on all the wear surfaces. Besides the differences in length and depth of the wear slots between these steel samples, the wear surfaces of Steel A and B appear to be dull as compared to the other three steels. The upper edges of the micrographs in Figure 2 are the cross-section of the wearing surfaces. Little increase in surface roughness is noted resulting from the wear process. Consistent with past observations, little discernable plastic deformation can be seen at or near the wearing surfaces.
The wear surfaces were further investigated using a scanning electron microscope (SEM), as shown in Figure 8. The images were taken under both secondary electron image (SEI) mode (on the left column) and backscattered electron image (BEI) mode (on the right column). For the two hardened steels (Steel C and D) and the hot-rolled high-carbon steel (Steel E), the scratching wear pattern can be clearly seen in both SEI and BEI images. For Steel A and B, however, the wear pattern is quite different. Instead of scratching wear, the wear surfaces of these two steels are composed of pits and very fine scratches. The wear pattern is more close to “indentation” rather than “scratching”. This observation is surprising, since scratching wear, whether the scratches were created by microcutting or microplowing mechanisms, has been well recognized as the dominant wearing mechanism for DSRW wear tests according to literature and previous studies. This result indicates that a different wear mechanism was involved for the two low-hardness steels during DSRW wear test. The shift of wear mechanisms from high-hardness steels to low-hardness steels will be discussed in details in the following section.

DISCUSSIONS

During DSRW wear testing, pressure is applied on the sand particles by the load (130 N in this case) on the rubber wheel. Under this pressure, the sand particles are partially imbedded in the rubber wheel, and partially penetrated into the metal surface, as illustrated in Figure 9a. The depth of the penetration into the metal surface is dependent on the hardness of the metal. The penetration will be deeper on a soft material and shallower on a hard material. The rotating movement of the rubber wheel drives the sand particles to slide against the steel sample and create scratches on the metal surface.

The driving force \( F_d \) for the sand particle movement comes from the rubber wheel, which must be high enough to overcome the resistance from the metal to create grooves on the metal surfaces. The resistance of the metal \( F_r \) can be expressed by:

\[
F_r = A \tau_c = F_N \mu_g
\]

where \( A \) is the cross-section area of the material being moved during grooving and \( \tau_c \) the shear strength of the material. \( F_N \) is the load applied on an abrasive particle and \( \mu_g \) is the grooving term of coefficient of friction. For grooving wear, Zum Gahr\(^5\) derived an equation as the following:

\[
\mu_g = \frac{4}{5\pi K R^2 H_{def}} \frac{F_N \sin \alpha}{R^2 H_{def}}
\]

Equation 2

Equation 3
Figure 8. SEM images of DSRW wear surfaces from the five experimental steels. Left – SEI mode image. Right – BEI mode image.
where $R$ is the tip radius of the abrasive particle. $\alpha$ is the attacking angle of the particle tip. $H_{\text{def}}$ is the material hardness after severe deformation, which is usually measured on wearing debris. In this study we consider $H_{\text{def}}$ is close to the scratching hardness of the material. $K = H_{\text{def}}/\tau_c$. It has been found that $K$ could be considered as a constant depending on the available slip systems of the wearing material. $K$ is about 5 for cubic metals and may be greater than 5 for hexagonal metals$^5$.

Equation 3 implies that $\mu_g$ increases strongly with the decrease of $H_{\text{def}}$. Since $F_N$ is fixed for a test, the grooving resistance for materials with lower $H_{\text{def}}$ hardness is greater than that for materials with higher $H_{\text{def}}$ hardness. This is because of the deeper penetration of the abrasive on softer materials, thus, more material being moved during grooving wear.

If the driving force for abrasive particle movement is greater than the material grooving resistance, the abrasive particle will cut through the part surface. Since soft materials lead to deeper groove penetration, the movement of abrasive particles will cause more material being moved by microcutting or microplowing on a softer material than that on a harder material. This is the situation observed in most wearing studies, especially for high-stress abrasion and gouging wear, where the driving force for abrasive particles is much larger than material grooving resistance.

However, the driving force for abrasive particle movement is limited during low-stress abrasion. The driving force could be lower than the material grooving resistance. In this case, the abrasive particle can no longer create a continuous groove on the metal surface. Instead, the particle may penetrate into part surface to a certain depth, but then tumble through the rubber-metal interface, leaving a series of dents or pits on the wear surface. This mechanism is illustrated in Figure 10.

Steel C, D and E have higher hardness and scratching hardness than Steel A and B. The grooving resistance for these three steels is relatively small due to shallower penetration depth. The driving force from the rubber wheel is sufficient to drive the abrasive particles to slide on the metal surfaces, leaving a number of grooves on the wearing surface. For the two softer materials (Steel A and B), the grooving resistance is significantly larger due to deeper penetration depth. The driving force from the load on the rubber wheel is no longer sufficient to drive the abrasive particles to cut across the metal surfaces. This prevents sand particles from sliding. The continuing movement of the rubber wheel caused the sand particles to tumble at the rubber/steel interface. The result of this type of wear is similar to micro-pitting or an indentation wear process. Less material is removed from the metal surface during this process as
compared to pure sliding, as observed in the harder materials. The change in wear mechanism can be used to explain why the soft Steel A and Steel B give comparable wear loss as the hardened Steel C under low-stress abrasion conditions.

It should be emphasized that this mechanism change is limited to low-stress abrasion, where the driving force for grooving of abrasive particles is not sufficient to overcome the material grooving resistance. It is expected that once the driving force exceeds the material groove resistance, the wearing mechanism will change into sliding, resulting in a dramatic increase in wear loss.

**SUMMARY**

In the present study the abrasion resistance of five industrial steels were investigated with DSRW wear testing and field tests under low-stress abrasive wear situations. The main results can be summarized as follows:

1) Both material hardness and microstructure play important roles in material wear resistance during low-stress abrasion. Up to a certain hardness level, the wear resistance of a hardened steel with martensitic microstructure can be matched by a non-hardened steel with pearlitic/ferritic type of microstructures.

2) For hardened steels and as-rolled high-carbon steels, the wearing mechanism is grooving during low-stress abrasion. For as-rolled low-carbon steels, the wearing mechanism is predominantly micro-pitting or indentation. The shift of the wear mechanisms is due to the limited driving force for abrasive particle movement during low-stress abrasion. Soft materials result in deeper particle penetration, thus higher grooving resistance. When the driving force is not sufficient to overcome grooving resistance, the particle cannot slide. Instead, the abrasive particles tumble across the metal surface. The change in wearing mechanism for soft steels results in reduced material loss during wearing process.

**REFERENCES**