Wear characteristics of plain carbon steel

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Plain carbon steel of nearly eutectoid composition (0.86 wt% C) has been subjected to annealing, normalising and quenching followed by tempering treatment to attain different microstructures, viz. coarse pearlite, fine pearlite and tempered martensite. The dry sliding wear characteristics of these heat-treated samples have been studied on pin-on-disc type wear testing machine under different loads and at constant sliding velocity. Analysis of the wear test data along with SEM of wear debris and worn surfaces reveal that the wear resistance depends on the microstructure and the morphology of the phases. Coarse pearlite, fine pearlite and tempered martensite structure exhibit the wear resistance to be in decreasing order. Analysis of the wear debris indicates that oxidative and metallic wear mechanisms are involved under different test conditions employed in the present investigation.

Introduction

Plain carbon steel which consist of about four-fifth of the total tonnage of steel produced, are economical as compared to alloy steels and find adequate application in many industrial components. Of the many failure modes associated with the steel components, wear presents a unique challenge to the designer and developer of mechanical components. Wear is a complex process as it is a system property and not a material property. Steel may wear out in different modes such as abrasion, adhesive, erosion, surface fatigue and erosion-corrosion. Out of these modes, adhesive and abrasive wear are commonly observed in steel components. Wear characteristics of steel components and their real life performance in different working conditions have been the subject of numerous investigations. With large number of variables like load, sliding speed, test geometry, composition, hardness, environment, etc., it is observed that controversies over the understanding of wear mechanism still exist. Apart from these variables, the type of microstructure also influences the wear resistance of steels. Though several investigations have demonstrated improved wear resistance of steel through surface treatment such as hardening or surface alloying but very few studies have been made to correlate the wear property of a steel with its microstructure. Studies on the effect of microstructure of a plain carbon steel on wear rate under dry sliding condition at relatively lower loads and a fixed sliding speed at room temperature are reported here.

Experimental Procedure

Plain carbon steel of nearly eutectoid composition (C 0.86, Mn 0.56, P 0.20, S 0.04 and Si 0.06 weight %) was taken and subjected to different heat-treatment processes to attain different microstructures. The wear characteristics of these heat-treated samples were studied as described below:

Sample preparation

Samples of size 30 mm length and 6.25 mm diameter were cut from a steel bar. Three sets comprising of five pins in each set were taken for carrying out heat-treatment. All the three sets of samples were kept in a tabular furnace at 840°C for a period of 45 min. These samples were covered with cast iron chips to avoid oxidation. After heating the samples for above-mentioned period, two sets of samples were taken out of furnace. The first set was allowed to cool in air to attain fine pearlitic structure and the second set was directly quenched in oil to attain martensitic structure. The oil-quenched samples were further subjected to tempering treatment at 450°C temperature for 2 h followed by oil-quenching resulting in tempered martensitic structure. The third set of samples was allowed to cool inside the furnace up to room temperature to attain coarse pearlitic structure.

Macrohardness of all the three sets of heat-treated samples was measured on Vickers hardness tester using diamond indenter and found to be: Annealed 350; Normalized 450; and, Tempered 550.
Metallographic preparation

The heat-treated samples were prepared for metallographic studies by grinding them on belt grinder driven by electric motor. These samples were further polished up to 4/0 grade of emery paper followed by cloth polishing using submicron size alumina paste. After polishing, the samples were etched with 2% nital solution and analysed under SEM.

Wear characteristics

For wear test, polished samples up to 4/0 grade emery paper were used. Before testing, these samples were cleaned in acetone and dried. Wear characteristics of these samples were studied on pin-on-disc type wear testing machine supplied by DUCOM, Bangalore (India). The test geometry is shown in Fig.1. It consists of stationary pin holder where pin is loaded normally against a rotating disc made of hardened EN-32 steel, having hardness of HRc 65. Before the conduct of every test, the surfaces of the specimen and the disc were cleaned with acetone to remove any dirt or grease. A digital electronic Mettler balance having an accuracy of $10^{-4}$ g was used to measure the weight loss of the pin after each run to estimate the volume loss during wear. Initially, the weight loss was measured after every 2 min of sliding up to 16 min and thereafter, at an interval of 15 minutes for a total sliding period of 3 h.

Results and Discussion

Microstructural characteristics

The heat-treated samples examined under scanning electron microscope (SEM) exhibited different features. Fig. 2 shows lamellar coarse pearlitic structure of annealed sample having interlamellar spacing in the range of 0.25 to 0.50 μm. The microstructure of the normalised steel as shown in Fig. 3 consists of fine pearlite with interlamellar spacing in the range of 0.10 to 0.25 μm. The microstructure of the oil-quenched steel followed by tempering at 450°C for 2 h is shown in Fig. 4. The

![Fig. 1 — Test geometry of Pin-on-disc wear testing machine](image1)

![Fig. 2 — SEM of annealed specimen showing presence of coarse pearlite](image2)

![Fig. 3 — SEM of normalised specimen showing presence of fine pearlite](image3)
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structure contains round shape cementite particles distributed almost uniformly in the ferrite matrix. The size of these cementite particles is observed to vary in the range 0.20 to 0.90 μm.

Wear characteristics

The wear characteristics of all the three heat-treated samples studied under normal loads of 2.5, 3.5 and 4.5 kg and at constant sliding velocity of 1 m/s exhibited a loss in volume with increasing load. The variation of wear volume with sliding distance for annealed sample is shown in Fig. 5. The data points were observed to lie primarily on two linear segments. Glasscott et al.\textsuperscript{18} also observed similar trends. The first segment corresponds to primary severe wear (run-in wear) and the second one for steady state wear. The best-fit lines were drawn for the two linear segments by least square method. The wear rates of the samples at different loads were determined from the slopes of these segments. Fig. 6 shows the variation of wear rate with load for both the linear segments. It is observed that the second linear segment has a lower wear rate as compared to first one for the same load. The wear rates in both the linear segments show an almost linear behaviour with increasing load.

![Fig. 4 — SEM of quenched and tempered specimen showing presence of round shape cementite in a matrix of ferrite](image1)

![Fig. 5 — Variation of wear volume with sliding distance at different loads for annealed specimen](image2)

![Fig. 6 — Variation of wear rate with load for annealed specimen corresponding to first and second linear segments](image3)

![Fig. 7 — Variation of wear volume with sliding distance at different loads for normalised specimen](image4)
The variation of wear volume with sliding distance for the normalised steel having fine pearlitic structure is shown in Fig. 7. Two linear segments are observed here also as in case of annealed sample. The variation of wear rate with increase in load for both the linear segments is shown in Fig. 8. The second linear segment shows a relatively lower wear rate as compared to the first linear segment for the same load. Wear rate in the second linear segment for normalised sample shows linear behaviour with increasing load, similar to those observed in annealed sample but the variation is nonlinear corresponding to wear rate observed in the first linear segment.

The variation of wear volume with sliding distance for quenched and tempered steel is shown in Fig. 9. It also exhibits two linear segments as observed for annealed and normalised steel. The wear rate at different loads observed for these linear segments are shown in Fig. 10. The variation of wear rate with load for both the first and second linear segments is similar to that observed in normalised steel.

The wear coefficients obtained at different loads for annealed, normalised and tempered samples are shown in Table 1. The wear coefficient is calculated using the Archard's wear law \( V = kWS/3H \), where \( V \) is the volume loss in wear, \( W \) the load applied, \( S \) the sliding distance, \( H \) the bulk hardness of the material and \( k \) the wear coefficient of the material\(^{19}\). To obtain the wear coefficients, wear rate \( (V/S) \) is divided by the contact area \( (W/H) \) estimated from the applied load and indentation hardness, and multiplying the result by the geometrical factor of three. The first linear segment is observed to have a higher wear coefficient as compared to second linear segment for all the steel samples at different loads.

**Nature of wear surface and debris**

The worn surfaces of the test pins examined under...
SEM are shown in Fig.11. Figs 11a and 11b represent the micrographs of annealed steel tested at 2.5 kg and 4.5 kg load, respectively, whereas Figs 11c and 11d for tempered steel tested at 2.5 kg and 4.5 kg load, respectively. Similar wear tracks were also observed for normalised steel. The samples tested at low load were observed to be smooth except a few deep grooves as shown in Figs 11a and 11c. SEM examination of these worn out surfaces showed cracking and spalling of wear track and oxide layer at higher load as shown in Figs 11b and 11d. Thus, it appears that more oxide is generated at higher load. Glasscott et al.\textsuperscript{18} in their studies observed that oxide debris generated during the process of wear build-up progressively in the wear track and the contact pressure increases. As more and more oxide is produced, the metal-metal contact reduces thus lowering the wear rate leading to transition from severe wear to mild wear.\textsuperscript{9} Micrographs of the worn surfaces also indicate the presence of scoring marks, craters and areas of rough grooves in the direction of sliding. In some places, adhesion effect is also visible [Figs 11b and 11d]. It appears that the material has been fragmented from craters. In some samples, a flake-type morphological feature in the debris sticking to surfaces was observed and their surface was scored. These types of features were also observed by other investigators.\textsuperscript{20,21} The debris were also sticking to the

<table>
<thead>
<tr>
<th>Sample</th>
<th>Linear segment</th>
<th>Wear coefficient ($k \times 10^{-4}$) calculated for different segments at different loads</th>
<th>Average wear coefficient ($k \times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.5 kg</td>
<td>3.5 kg</td>
</tr>
<tr>
<td>Annealed</td>
<td>First</td>
<td>6.22</td>
<td>6.03</td>
</tr>
<tr>
<td></td>
<td>Second</td>
<td>1.72</td>
<td>1.74</td>
</tr>
<tr>
<td>Normalized</td>
<td>First</td>
<td>6.97</td>
<td>7.52</td>
</tr>
<tr>
<td></td>
<td>Second</td>
<td>3.13</td>
<td>2.70</td>
</tr>
<tr>
<td>Tempered</td>
<td>First</td>
<td>8.98</td>
<td>8.01</td>
</tr>
<tr>
<td></td>
<td>Second</td>
<td>3.43</td>
<td>3.16</td>
</tr>
</tbody>
</table>

Fig. 11 — SEM of worn surfaces of the test samples
Fig. 12 — SEM of wear debris of the tested annealed sample

The wear debris at shorter sliding distances corresponding to first linear segments and long sliding distances corresponding to second linear segments were also examined under SEM. The debris examined under SEM reveals different morphological features. The presence of fine spherical particles, agglomerates and flakes in the debris is for the first linear segment which corresponds to severe wear as shown in Figs 12a and 12b for annealed steel tested at 2.5 and 4.5 kg load, respectively. At longer sliding distance as shown in Fig 12c corresponding to second linear segment for tempered steel, the presence of non-spherical particles along with coarse oxide powders represents a mild wear. The formation of metallic wear particles and the appearance of the wear pin surfaces at higher load confirm severe damage and plastic flow of material as shown in Fig. 12d. The cracking and distortion observed due to severe plastic deformation in the direction of sliding is the characteristic feature of worn out surfaces. The metallic lusture of the debris (Fig. 12c) with fine wear track mark on it indicates that the material has come out from the surface either from grooves or from craters. The presence of small particles along with larger ones indicate that these have formed in the process of fragmentation of large particles. Debris are fine powders of oxides, red and brown in colour. This shows that oxidative wear mechanism is operational at relatively low loads whereas the presence of metallic particles in the debris at higher load indicates that metallic wear dominates at higher load. Further, the debris collected from the test run in the present investigation confirms oxidative and metallic modes of wear. The results in the present investigation are in agreement with the earlier work observed by several investigators.

The wear rate of the first linear segment is consistently higher which may be attributed to: (a) the inclusion of run-in period in this segment, and (b) the
development of oxide cover commensurate with sliding condition. Once the extent of oxide cover reaches the dynamic equilibrium under a given sliding condition, the second linear segment develops. Thus, it is observed that the first linear segment has higher wear coefficient compared to that observed in the second linear segment as shown in Table 1. The two stage wear, i.e., primary severe wear followed by secondary mild wear, as observed in the present investigation, is in agreement with the work of Glasscott et al.\textsuperscript{18}. On the basis of wear coefficient, the coarse pearlite structure has the lowest wear coefficient and it increases in the order for fine pearlite and tempered martensite. From the results it appears that relatively coarse cementite plate in coarse pearlitic structure is able to hold better against sliding wear than the fine cementite plates in fine pearlitic structure. The masking of fine cementite plates by flow of ferrite could be a contributing factor to increasing wear. Matrix is not able to hold fine carbide particles in tempered martensitic structure as well as fine cementite plates in fine pearlitic structure. The superiority of pearlitic structure over tempered martensitic structure as observed in the present investigation confirms the previous works\textsuperscript{13,14,15,29}. Apart from the superiority of the pearlitic structure, the present investigation also establishes the superiority of wear resistance of coarse pearlite structure over fine pearlite structure.

Conclusions

The present investigations deal with the influence of microstructure and the morphology of phases in heat-treated 0.86 wt% C steel under dry sliding condition against the counterface of hardened steel. The volume loss in wear has been found to increase with sliding distance and can be described in terms of two linear segments. The wear rate in the first linear segment is higher than that in the second linear segment which has been attributed to run-in period in the first segment and progressive development of oxide cover in the second linear segment. The wear rate in both the linear segments has been found to vary with load over a limited range and does not even change significantly between certain intervals of load. At low load, oxidative wear mechanism is predominant whereas at higher load metallic wear mechanism dominates. The wear debris generated at higher loads contain larger amounts of oxide compared to those generated at lower load which may be due to higher frictional heating at higher load increasing the temperature at the sliding surface. On the basis of wear coefficients, both in the first and the second linear segments, the coarse pearlite, fine pearlite, and tempered martensite structure in 0.86 wt% C steel show the wear resistance in decreasing order.

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