Influence of sliding velocity on wear behaviour of different microstructures of Ni-Cr-Mo-V steel

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The effect of sliding velocity on wear property of six microstructural states of Ni-Cr-Mo-V crane wheel steel under 4 kg load has been studied and discussed in detail. The steel with 0.35 wt.% C, 0.68 wt.% Mn, 0.30 wt.% Si, 0.014 wt.% S and P, 0.68 wt.% Cr, 3.10 wt.% Ni, 0.40 wt.% Mo, 0.11 wt.% V, balance iron was hardened and tempered at 225, 350, 450 and 550°C to develop martensite and various hardened and tempered martensite microstructures. With the help of controlled furnace cooling, a bainitic structure was also developed. It was found that an increase in the tempering temperature increased percentage elongation and reduction in area but decreases the tensile strength. It was observed that increasing the velocity increased the wear rate but beyond a certain sliding rate, wear decreased with an increase in sliding velocity. Wear mechanism changed from mild/oxidative to severe/metallic and then to oxidative with increasing the sliding velocity. Hardened martensite showed highest wear resistance compared with various tempered martensite. Martensite tempered at a lower temperature possessed a higher wear resistance as compared to martensite tempered at a higher temperature. The bainitic microstructure showed the highest wear rate in all cases irrespective of velocity.

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Wear is an unavoidable progressively destructive complex phenomenon that leads to the deterioration\textsuperscript{1,2} of sliding surfaces that are mating under industrial operating conditions. Mating surfaces dislodge and transfer materials due to mechanical action which is also assisted by prevailing environmental conditions. A large number of machine components are fabricated with various types of steels which wear and tear in course of time due to adhesion, abrasion, erosion surface fatigue or erosion-corrosion. Adhesion and abrasion modes of wear are very frequently encountered in industrial conditions specially in steel plants. Wear and tear of machine components is affected by a variety of conditions\textsuperscript{3-13} which are created due to intrinsic and extrinsic characteristics, constitution, chemical composition, mutual solubility and surface finish of the mating surfaces, along with operating pressure, sliding velocity, temperature, lubrication and design aspects of the machine components. Out of the above, microstructures\textsuperscript{14-18} have a dominant influence on the surface life of the machine parts, specially those operating under high sliding velocities.

Keeping the above in view, experiments were carried out to study the wear characteristics of different microstructural states of a Ni-Cr-Mo-V steel under different sliding velocities, but at a fixed load of 4 kg. Wear testing may be used to grade the different structures of the Ni-Cr-Mo-V steel or select them for a particular application. Such a test also provides a proper understanding of the basic modes and mechanisms of wear and hence may help in controlling the same.

\textbf{Experimental Procedure}

Heat treatment and mechanical properties

Ni-Cr-Mo-V steel (0.35 wt.% C, 0.68 wt.% Mn, 0.30 wt.% Si, 0.014 wt.% S and P, 0.68 wt.% Cr, 3.10 wt.% Ni, 0.40 wt.% Mo, 0.11 wt.% V, and balance Fe) was heated in an electrical resistance heating furnace capable of a temperature control of ±1°C. Sample (15×15×60 mm) were heated at 875°C for 45 min and then quenched in oil that was subjected to vigorous stirring. Hardened samples were tempered at different temperatures (225, 350, 450 and 550°C) for a period of 1 h followed by water quenching. Transmission electron microscope was employed for the study of microstructures.

Tensile properties and hardness for each structure were determined at room temperature. For each structure three test samples were tested and average values of test results were summarized in Table 1.
Wear test

A pin-on-disc wear testing machine\textsuperscript{13,18} was used for wear property evolution under various sliding velocities at a constant load of 4 kg. Cylindrical wear test pins of 8 mm diameter and 35 mm length were machined from the heat-treated steel samples. Before the test, a surface finish of \( \sim 0.40 \mu \text{m} \) (c.l.a.) of both the test pin and the hardened (60-62 RC) steel disc flat surfaces were made. The surfaces were thoroughly cleaned and dried before the start of a test. Test pins were initially weighed on a single-pan-electrical balance, that had a least count of \( 10^{-7} \) kg. At the end of each test, specimens were cleaned and reweighed. The difference in the two weights gave the weight loss for which the wear volume was determined. Wear rate and wear volume per unit sliding distance were also calculated.

The wear rate has also been studied as a function of sliding velocity in case of all steel samples under a constant load of 4 kg. All the wear experiments were carried out under dry sliding conditions at a relative humidity of approximately 70% and a room temperature of \( 25 \pm 3 \)°C.

Results and Discussion

Table 1 presents the various heat treatments employed, the developed microstructures and some mechanical properties.

### Table 1 — Mechanical properties of Ni-Cr-Mo-V steel with different microstructures\textsuperscript{13}

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Heat treatment*</th>
<th>Microstructure</th>
<th>UTS (Mpa)</th>
<th>0.2% TYS (Mpa)</th>
<th>% Elongation</th>
<th>% RA</th>
<th>Hardness (HV 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Hardened 875°C (45 min) OQ</td>
<td>Martensite laths with some retained austenite</td>
<td>1898.8</td>
<td>1593.6</td>
<td>5.40</td>
<td>6.98</td>
<td>558.0</td>
</tr>
<tr>
<td>2.</td>
<td>Hardened 875°C (45 min) OQ Tempered 225°C (1 h) WQ</td>
<td>Martenite laths with fine cementite plate</td>
<td>1728.4</td>
<td>1464.7</td>
<td>8.10</td>
<td>8.76</td>
<td>486.0</td>
</tr>
<tr>
<td>3.</td>
<td>Hardened 875°C (45 min) OQ Tempered 350°C (1 h) WQ</td>
<td>Martensite laths with coarse cementite plates</td>
<td>1517.3</td>
<td>1254.6</td>
<td>8.70</td>
<td>10.24</td>
<td>403.8</td>
</tr>
<tr>
<td>4.</td>
<td>Hardened 875°C (45 min) OQ Tempered 450°C (1 h) WQ</td>
<td>Martenite laths with coarse cementite plates</td>
<td>1459.6</td>
<td>1168.1</td>
<td>9.76</td>
<td>14.20</td>
<td>361.6</td>
</tr>
<tr>
<td>5.</td>
<td>Hardened 875°C (45 min) OQ Tempered 550°C (1 h) WQ</td>
<td>Martensite laths with coarser cementite plates</td>
<td>1370.9</td>
<td>1048.6</td>
<td>11.98</td>
<td>15.80</td>
<td>350.5</td>
</tr>
<tr>
<td>6.</td>
<td>875°C (45 min) controlled furnace cooling @ 30°C/h</td>
<td>Baninite in the form of needles (coarse plate shaped cementite in ferritic matrix of high dislocation density)</td>
<td>1185.2</td>
<td>878.4</td>
<td>13.3</td>
<td>27.60</td>
<td>328.7</td>
</tr>
</tbody>
</table>

OQ (Oil Quenching); WQ (Water Quenching)

Influence of sliding velocity

Figure 1a shows the variation of wear rate with sliding velocity at a constant load of 4 kg for different microstructural states of the Ni-Cr-Mo-V steel. The wear rate increased and reached a peak value, but beyond a certain sliding rate it decreased in all the cases. Similar results were obtained by Nikajima and Mizutani\textsuperscript{19} when they investigated the variation of wear rate with respect to sliding velocity at a constant load, in steels containing 0.10, 0.30 and 0.40% carbon. It is also clear from Fig. 1a that there is a distinct transition velocity for each structure above which its wear rate starts decreasing. The transition velocity of martensite and martensite tempered at \( 225 \pm 3 \)°C was found to be \( 1.45 \text{ ms}^{-1} \), while that of martensite tempered at \( 450 \pm 3 \)°C and the annealed structure (bainite) was found to be \( 1.27 \text{ ms}^{-1} \). In general, the transition velocity is more in structures having high hardness and yield strength. This is in accordance with the observation of Moore and Tagart\textsuperscript{20} who found that friction decreased as the hardness and/or yield strength increased.

Wear rate (Fig. 1a) first increases slowly up to a certain point, for the structure of martensite and martensite tempered at \( 225 \pm 3 \)°C and \( 350 \pm 3 \)°C, above which it increases rapidly to a peak value, before decreasing further with increase in sliding rate. On the other hand, in the last three structures, viz., martensite
tempered at 450°C and 550°C and annealed structure (bainite), the wear rate first rapidly increases up to point, slows down a bit and then increases rapidly to the transition point above which the wear rate decreases with increasing sliding rate. The wear mechanisms in the first three structures were found to be oxidative when wear rate increased slowly, oxidative and more metallic (when it increased rapidly up to the transition point) and again oxidative when it decreased with increasing sliding rate. However, in the last three structures, the wear mechanisms were found to be oxidative plus some metallic, signifying the first rapid increase (after which it slows down), oxidative plus predominantly metallic (accounting for rapid increase up to the transition point) and oxidative (when it decreases). These are in agreement with the reported results of Yamazaki and Hayama\textsuperscript{21} who also found three stages in the wear process, though in a phosphor-bronze.

Figure 1b shows the variation of wear rate with sliding velocity at a constant applied load of 10 kg. Here also the wear rate increases, reaches a peak value, after which it decreases. The results are in agreement with those of other investigators\textsuperscript{19,21,22}. Again, the transition-velocity (at which the wear rate starts decreasing) is much less at a load of 10 kg, in comparison to that for a load of 4 kg. For example, the transition velocity for martensite and martensite tempered at 225°C at a load of 10 kg was 1.27 ms\textsuperscript{−1} (Fig. 1b). In the case of lower load (4 kg), it was 1.45 ms\textsuperscript{−1}. Similarly, transition velocity for remaining four structures (martensite tempered at 350, 450 and 550°C) and annealed structure (bainite) is 1.09 ms\textsuperscript{−1} in the case of higher load of 10 kg (Fig. 1b) while it was 1.45 ms\textsuperscript{−1} for martensite tempered at 350°C and 1.27 ms\textsuperscript{−1} for remaining three structures (martensite tempered at 450, 550°C and annealed) in the case of the lower load (4 kg). Here again this is in accordance with the observation of Moore and Tagart\textsuperscript{20}.

An increase in the sliding velocity results in the enhancement of frictional heating and hence a corresponding rise in specimen temperature. An iron-constantan thermocouple is fitted in contact with the test specimen pin at 1 mm above the mating interface of pin and disc and this is connected to a potentiometer via an ice bath to facilitate measurement of the temperature rise of the specimen near the interface due to frictional heating. It may be thus approximately used as indirect measure of the frictional resistance between the mating surfaces. Fig. 2 shows the variation in test pin temperature rise.
with increasing sliding velocity for different structural states of Ni-Cr-Mo-V steel. A direct variation between the two variables is obvious for all the structures. This is in agreement with Bowden and Riddler\textsuperscript{13,23} who reported a linear increase in temperature of the surface with increasing load and sliding velocity. The rise in temperature was not large and the structures that are relatively hard and strong display a lower rise in temperature than the softer ones. This is also in accordance with the observation of Moore and Tagart\textsuperscript{20} who found that friction decreased as the hardness and/or yield strength of a material decreased.

Metallographic evidences

The wear-debris formed at different sliding velocities under 4 kg load were subjected to X-ray analysis. Fig. 3 shows the constituents present in the debris. It is seen that mostly oxides are dominating.

Results of stereomicroscopic examination of wear-debris-particles of three structures namely the bainite, martensite tempered at 550\degree C and 225\degree C at low (0.54 ms\textsuperscript{-1}) high (1.09 ms\textsuperscript{-1}) and higher sliding velocities (2.0 ms\textsuperscript{-1}) are also shown in Figs 4, 5 and 6. Presence of oxides, in a predominant manner, in case of all the
three structures at low sliding velocity of 0.54 m/s is shown in Figs 4a, 5a and 6a. Appearance of some shining metallic particles, which decreases as the hardness of structure increased could also be seen. The oxides relate to the mild oxidative wear region of Fig. 1. On the other hand, the wear debris analysis, in the case of sliding velocity of 1.09 m/s, show the formation of metallic particles for all the three structures as shown in Figs. 4b, 5b and 6b. The amount of metallic particles was found to increase

Fig. 5 — Stereomicrographs of the wear debris of hardened and tempered martensitic (tempered at 550°C) structure of Ni-Cr-Mo-V steel at different sliding velocities under a constant load of 4 kg (x40): (a) 0.54 m/s; (b) 1.09 m/s; (c) 2 m/s

Fig. 6 — Stereomicrographs of the wear debris of hardened and tempered martensitic (tempered at 225°C) structure of Ni-Cr-Mo-V steel at three different sliding velocities under a constant load of 4 kg (x40): (a) 0.54 m/s; (b) 1.09 m/s; and, (c) 2 m/s
with an increase in sliding velocity up to the transition point, for all the three structures. However, at the velocity of 1.09 m/s\(^{-1}\), as in the present case the metallic particles decreased indicating lower deformation, with increase in strength of the structures. These relate to severe wear region of Fig. 1. The formation of oxides in a predominant manner, was also observed with a higher sliding velocity of 2 m/s\(^{-1}\), for the above mentioned three structures, viz. bainite, martensite tempered at 550°C and 225°C and are shown in Figs 4c, 5c and 6c. This causes decrease in the wear rate.

The fact that a mild wear at low speeds (0.36 m/s\(^{-1}\)), metallic/adhesive wear at high speeds (0.91 m/s\(^{-1}\)) and oxidative wear at higher speeds (2 m/s\(^{-1}\)), occurred, was also confirmed by the SEM examination of the wear-debris produced at these speeds. Fig. 7a shows the fine coagulated oxide powders at a low speed (0.36 m/s\(^{-1}\)) for martensite tempered at 550°C. Metallic nature of the wear-debris, at a speed of 0.91 m/s\(^{-1}\) is once again revealed by Fig. 7b, for martensite structure, tempered at 225°C, by SEM examination. Scanning electron microscopic examination of the wear debris produced for the structure of tempered martensite, tempered at 450°C was carried out and the results are shown at a magnification of 200 and 2500, in Figs 8a and b respectively. Debris generated at higher speed (2.0 m/s\(^{-1}\)) consists of oxide constituents along with metallic particles. Oxidative mode of wear dominates which causes the low rate of wear.

**Worn-surface topography**

Influence of sliding velocity on the worn surface of specimens containing bainitic structures at low (0.36 m/s\(^{-1}\)), high (1.09 m/s\(^{-1}\)) and higher velocity (2 m/s\(^{-1}\))
are shown in Figs 9a, 9b, 10a, 10b, 11a, and 11b, respectively. Mild scratching, minor ploughing of the worn-out surface, along with slight smearing of oxides is evident at low speed (Fig. 9a and 9b) of 0.36 ms$^{-1}$. Massive deformation consisting of cracking, ploughing, cavity formation, delamination is evident at high speed of 1.09 ms$^{-1}$ (Figs 10a and 10b). Larger extent of smeared oxides on the surface along with their shearing, cracking and even then sticking to the surface is evident at higher speed of 2 ms$^{-1}$ (Figs 11a and 11b).

**Mechanisms of wear**

From the results of this investigation it may be said that the wear of Ni-Cr-Mo-V steel, under the influence of increasing velocity occurs in three distinct regions. Mild or oxidative wear under low velocity, severe or metallic wear under high velocity and oxidative wear with decreasing wear rate under higher velocity. In between mild and severe wear a transition was also observed. When the sliding velocity is very low, a thin and tough oxide layer prevents direct metal-to-metal contact between the asperities of the sliding surfaces. Since the layer of oxide formed, thus, is thin and tough, it gets deformed elastically and is usually not ruptured during sliding with low velocity. Fine powdered oxide is generated from this thin oxide layer and oxidised small metallic fragments. As soon as the surface oxide is removed, the damaged surface is quickly reoxidised preventing further metal-to-metal contact between sliding surfaces. This may be the reason for mild wear to be purely oxidative because of the ability of the surface material to oxidise under ambient conditions. In the present case, smooth wear tracks were produced and low wear rates were obtained, because oxide layers prevented adhesive/metallic wear, though some minor metallic particles were observed, which indicate adhesive wear occurs but a very less extent. Further, the wear debris produced during mild wear consisted of fine powders of smaller size than the metallic particles.

![Fig. 9 — Scanning electron micrographs of the worn out surface of Ni-Cr-Mo-V steel having bainitic structure, sliding with 0.36 ms$^{-1}$ velocity (4 kg load): (a) Low magnification, and (b) High magnification](image1)

![Fig. 10 — Scanning electron micrographs of the worn out surface of Ni-Cr-Mo-V steel having bainitic structure, sliding with 1.09 ms$^{-1}$ velocity (4 kg load): (a) Low magnification, and (b) High magnification](image2)
induced under adhesion conditions. X-ray diffraction analysis\(^1\) confirmed the composition of the powder to be made of different oxides, along with some metallic particles. Wear rate increased with increase in sliding velocity. The thin oxide layer is ruptured under high velocity, metal-to-metal contact occurs which results in severe wear. Strains, accumulated in the sub-surface layer, help in cracks nucleating growing and finally connecting with each other on further sliding. These sub-surface cracks break out to give plate-like debris. Thus under high velocity pin sub-surface becomes soft enough and deforms easily which leads to formation of cracks, their nucleation and growth and finally joining each other to produce plate like debris. This severe wear is caused by the process of adhesion and delamination, and also abrasion by hard particles of the debris. However, at higher sliding velocities with increased interfacial temperatures, oxide is continuously generated by high flash temperatures at the asperity contact. More oxidation replenishes the losses due to break away of oxide fragments as wear debris. This prevents metal-to-metal contact, leading to reduction in wear rate. Thus, from this study it is inferred that sliding velocity also gives rise to similar wear mechanisms as in case of applied load viz. mild/oxidative, severe/metallic/adhesive and oxidative with decreasing wear rate, as the speed is increased from low to high to higher.

Conclusions

Following conclusions are drawn from the present investigation.

1. The wear rate increases with an increase in the sliding velocity, attains a maximum value and then decreases.
2. All the six structures of Ni-Cr-Mo-V steel exhibit mild wear at low, severe/metallic/adhesive wear at high and oxidative wear, with decreasing wear rate at still higher sliding velocities.
3. Transition velocity, where severe wear changes to oxidative wear with decreasing wear rate depends on yield strength and hardness of the structure. A structure having a higher yield strength and hardness has a higher transition velocity.
4. Rise in surface temperature of the Ni-Cr-Mo-V steel pin sample with increasing velocity is dependent upon the strength and hardness of the structure.

References