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Research Paper

DRY SLIDING WEAR BEHAVIOUR OF HYPEREUTECTOID STEEL UNDER THE INFLUENCE OF MICROSTRUCTURES, SLIDING SPEEDS AND NORMAL PRESSURES

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The object of the present work is to investigate the effect of microstructure and operational parameters of normal pressure from 0.1249 to 0.8743 MPa with varying sliding speeds from 1 to 7 m/s for a sliding distance of 10,000 meters under unlubricated conditions of hypereutectoid steel on volumetric wear rate by Pin-on-disk wear tests type m/c in moist air was studied. Experimental results have shown that the microstructure of combined phases like cementite and pearlite gives better wear resistance than other phases under low operational conditions. The combined phases of cementite and martensite gives better wear resistance than other phases under high operational conditions. Also observed that, the volumetric wear rate of 1.5 wt % C of 100% martensite steels is low wear rate for all the operational conditions. SEM observation of the worn surface showed that three body and surface delamination were the dominant sliding wear mechanisms.

Keywords: Hypereutectoid steel, Microstructure, Normal pressure, Sliding speed

INTRODUCTION

In terms of volume of production and applications in many areas its contribution to various industries such as construction, manufacturing sector and railways is very high. However from the safety point of view many parameters are studied so that the failure rate is minimized. One of the important parameter is wear rate or wear behavior under different combinations of sliding speed and normal load. Wear may take place by various modes. The common mode of failure among these steels is found to be due to wear. Hence it is important to study the wear behavior of steels

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under different microstructure, work environment and operating conditions.

Wear can be defined as displacement or removal of material as a result of tribological processes. Tribology is the science and technology of interacting surfaces in relative motion. It is a broad field that includes friction, lubrication and various forms of wear (Rigney, 1990). Wear is an unavoidable progressively destructive complex phenomenon that leads to the deterioration.

The dissipation by wear impacts strongly the national economy and the life style of most people. So, the effective decrease and control of wear are desired, it is well known that Leonardo da Vinci studied a simple sliding bearing in ancient times. The scientific study of wear began in recent times and carried out in Germany, in particular, before World war II. Siebel reported a review paper on the early stages of the research. In the 1950s after World War II, steady progress was made in the field of wear research. Archard found an empirical law for sliding wear, where the wear volume is proportional to the vertical load and sliding distance and is inversely proportional to the hardness of a softer mating metal when two unlubricated metal surfaces are slide against each other in a mild wear regime. Thereafter, many studies on the wear process have been actively continued for various friction materials, and important technology and knowledge of wear control have been accumulated (Etsuo Marui *et al.*, 1997).

The mid-1970s was an excellent time to begin work in tribology. Instruments for local structural and chemical characterization of materials wear becoming widely available, so it was becoming easier to test the assumptions of friction and wear models and to reject those which were inconsistent with observations. At the same time, the new instruments provided a flood of new and sometimes bewildering information on the surface and subsurface of particular materials. Now and then one should try to review and digest some of this information. A Festschrift such as this one provides a stimulus and an appropriate opportunity for doing this. It is helpful to have a theme can be used to connect the results of many different experiments, and the many ways in which it influences sliding behavior of materials (Rigney, 1994).

History of Steel

Steels represent the most important group of engineering materials as they have the widest diversity of applications of any of the engineering materials. Generally, carbon is the most important element profoundly affecting the mechanical properties of the steels. Increasing the carbon content of steels increases the hardness and strength (Amit Gupta and Deep Narayan Mishra, 2013).

Ultrahigh-carbon (UHCS) steels, Hypereutectoid steels (1.0-2.1 wt% C) are commonly perceived as being too brittle at room temperature and have, therefore, generally been rejected by steel industry. The primary cause of the brittleness in the UHCS is the presence of brittle proeutectoid secondary carbide networks. However, these carbide networks can be broken up by thermo-mechanical processing. A UHCS treated by this method can achieve a microstructure containing fine equiaxed ferrite grains and spheroidal carbides and will thus possess an ultrahigh strength and good ductility at room temperature and high super-plasticity at elevated temperatures. Current studies mainly focus on spheroidization process, fracture toughness, mechanical properties, fracture mechanisms and super-plasticity in UHCS and so on (Chen *et al.*, 2010).

Ultrahigh-carbon steels (UHCS) exhibit ultrahigh strength and good ductility at room temperature and high superplasticity at elevated temperature. Sherby and co-workers have developed many processing routes for breaking up the pro-eutectoid carbide network, such as hot-and-warm working, a Divorced Eutectoid Transformation (DET), and a DET with associated deformation. Syn and co-workers have studied the correlation between the yield strength and the micro-structural parameters of UHCS (Zhan-Ling Zhang *et al.*, 2008).

The development of a modern family of steels-the ultrahigh carbon steel (UHCS)-this family has direct similarities in composition to certain ancient steels. The UHCS, which contains relatively large amounts of carbon (between 1 and 2 wt%), were developed at stand ford university from about 1975 to the present time. Their high carbon content was subsequently recognized to be similar to that found in Damascus steels and upon further studies, to other ancient steels, including the Japanese tama-hagane (a material of 1.6% C that is reduced to 1.0% C by folding) and English crucible steel (1.0%). Also, as laminated composites that in some case also contained high carbon steels (Jeffrey wadsworth, 2000).

A good understanding of the microstructure and its influence on wear resistance is of great importance to designers and engineers in selecting wear-resistant materials. Wear maps are useful for associating wear mechanisms with conditions in sliding wear. However, there are few reports relating mechanisms with microstructures of materials. ZumGahr has compared the wear resistance of different microstructures in a very simplified manner. The superior wear resistance of pearlitic structures compared with bainitic or tempered martensitic structures of equal hardness has been measured by Kalousek et al. on rail steel containing 0.72% C, 0.79% Cr and 0.21% Mo. According to their research, the favorable wear resistance of the pearlitic structure is attributed to its high work hardening in sliding contact (You Wang *et al.*, 1999).

It was reported that wear behavior of metal and alloys showed different behavior under different operating conditions. In spite of these investigations, the effects of normal pressure, sliding speed and different phases on volumetric wear rate yet to be clearly understood. Therefore in the study an attempt is made to investigate the effect of normal pressure, sliding speed and combination of different phases like martensite, pearlite and cementite on wear behavior of different hypereutectoid steels. It is expected that the applications of these results will contribute to the different concerned mechanical processes. Nowadays, different phase combinations are widely used for sliding applications where wear is required. Hypereutectoid steel having a microduplex structure might be applied to the construction, sliding parts of the machines etc. in industry in the near future. Therefore it is required to study the effect of the microstructure on the wear behavior of hypereutectoid steels. Due to these tribological applications, different phase combinations have been selected in this research study.

EXPERIMENTAL DETAILS

Selection of Steels for the Present Investigation

Considering the requirements of Pearlite, Cementite and Martensite phases of the experimental steels, the percentages of carbon present in them were selected. Approximately 1.0 and 1.6 percentage of carbon of the hypereutectoid steel respectively as shown in Table 1.

Heat Treatment of Sample

The hypereutectoid steel sample was subjected to different heat treatments to attain different microstructures. The changes in the microstructure and wear performance were studied as a function of cooling. Wear characteristics of these pin specimens were investigated. The samples of size 30 mm lengths and 10 mm diameter in the form of pins were used.

The specimens were heated at 775 °C (750+25), soaked for two hour for homogenization and cooled in resistance furnace, this process led to the formation of Pearlite and Cementite. The specimens were heated at 730 °C, soaked for one hour for homogenization and quenched in water, this hardening process led to the formation of Martensite and Cementite. The specimens were heated again to 950 °C and soaked for two hour for homogenization and quenched in water, this hardening process results to the formation of 100% Martensite.

Wear Test

A pin-on-disk type wear testing machine manufactured by DUCOM, Bangalore (India) was used as shown in Figure 1. Dry sliding wear test was carried out using a hardened counter face of a polished disk of EN-32 with a hardness of HRC 62-65 at a relative humidity of 50-70% at a room temperature of 32 °C. Wear tests were first performed at a normal pressure from 0.1249 to 0.8743 MPa with varying sliding speeds from 1 to 7 m/s for a sliding distance of 10,000 meters. The specimen is weighed before and after the wear test and the loss in weight is recorded. Hence wear volume and volumetric wear rate can be calculated as follows:

Wear volume loss = Weight loss/density (gm/mm^3)

Figure 1: Pin on Disk Machine

Table 1: The Chemical Composition of the Hyper Eutectoid Steel (wt-%)

S. No.	Grade	%C	%Si	%Mn	%P	%S
1.	EN-31 and SAE 52100	0.920	0.256	0.348	0.002	0.002
2.	AISI-D2	1.573	0.265	0.549	0.026	0.021

Volumetric wear rate = Volume loss per unit sliding distance (mm^3/m)

Metallographic Studies

Before the wear test, samples were prepared for metallographic examination by polishing, using polish papers of grade 4/0, 6/0 and then wet polishing was carried out using wet alumina paste of sub micron grade. Specimens were etched with 2% nital solution and analyzed under optical microscope as shown in Figures 2, 3 and 4 of 0.92 wt% of carbon samples are specimen-1, specimen-

Figure 2: 0.92% C Pearlite and Cementite

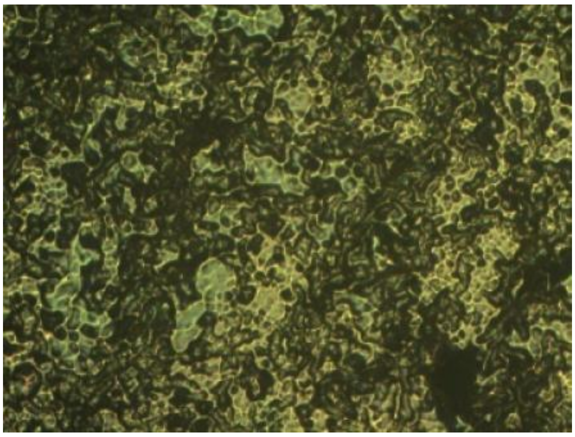


Figure 3: 0.92% C Martensite and Cementite

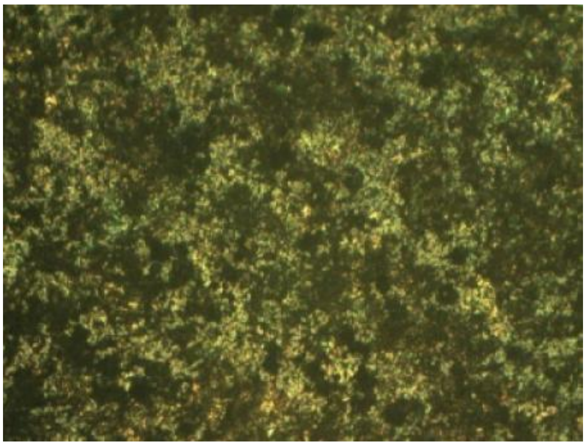


Figure 4: 0.92% C 100% Martensite

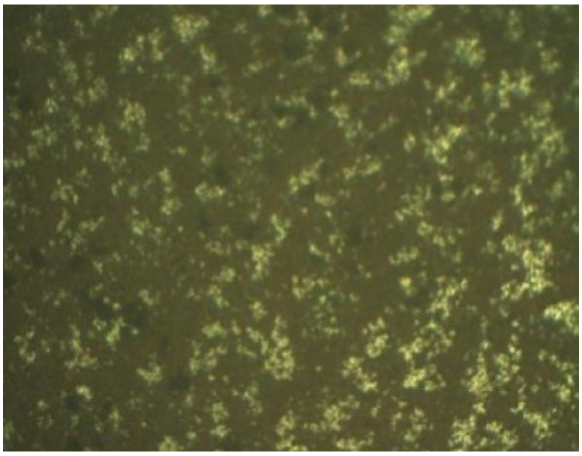


Figure 5: 1.57% C Pearlite and Cementite

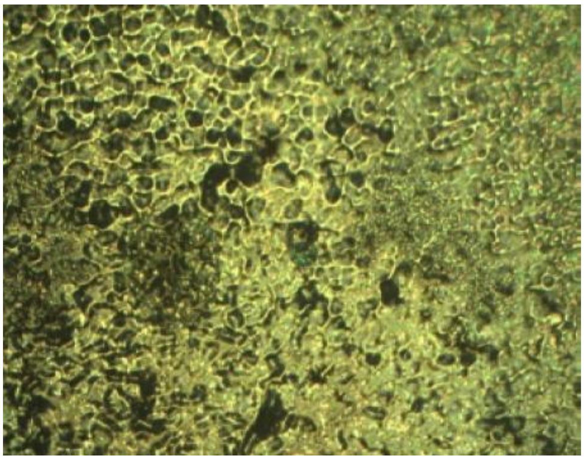


Figure 6: 1.57% C Martensite and Cementite

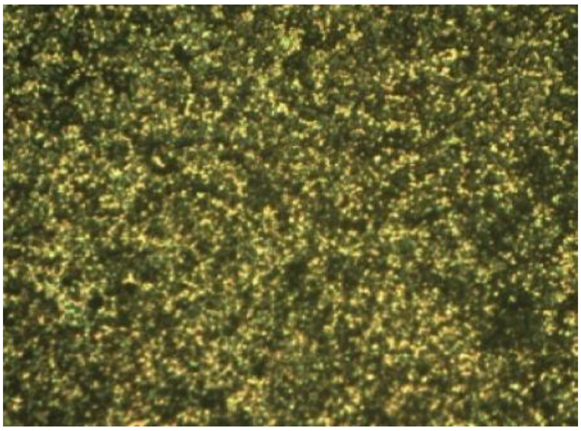
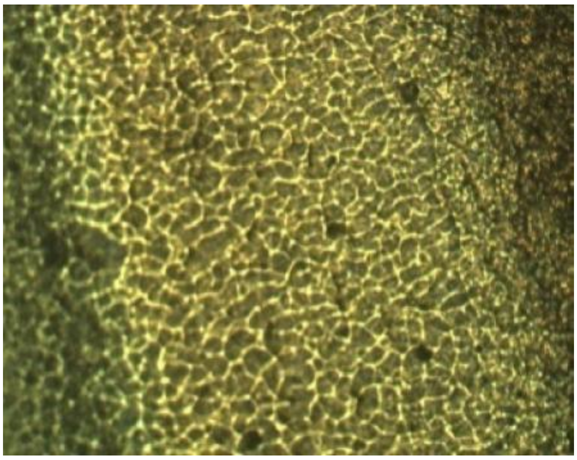


Figure 7: 1.57% C 100% Martensite



2 and specimen-3. And shown in Figures 5, 6 and 7 of 1.57 wt% of carbon samples are specimen-4, specimen-5 and specimen-6. After the wear test, worn out pin samples were coated with gold oxide to overcome the effect of oxidation and then studied under the optical microscopes.

Pearlite: Pearlite is a composite structure consisting of soft, ductile ferrite and hard brittle carbide in the form of lamellae. These are alternate bands of ferrite and carbide is the eutectoid mixture of ferrite and Cementite. It contains 0.8% C and is formed at 723 °C. It is very fine plate like or lamaller mixture of Ferrite and Cementite. It has a Ferrite matrix (background) and thin plates of Cementite on it. The phase mixture known as Pearlite, which occurs in steels, is characterized by the cooperative growth of Cementite (Fe_3C) and Ferrite at a common transformation front with the parent austenite. This leads to the development of a lamellar structure which in two-dimensional sections appears to consist of alternating layers of Ferrite and Cementite, which gives the mixture an iridescence that is associated normally with natural pearls or shells, and hence the name Pearlite (Pandit and Bhadeshia, 2012).

Cementite: Cementite is much harder but more brittle than ferrite. Thus, increase the fraction of Fe_3C in steel alloy while holding other microstructural elements constant will result in harder and stronger material. It is an interstitial compound of iron and carbon containing 6.67% C by weight and also it is the hardest phase in the iron-carbon system. This is also known as iron carbide (Fe_3C), It is considered a chemical compound because it contains 6.67% carbon by weight. It is crystalline in nature. Cementite is a very hard and brittle compound of low tensile strength but high compressive strength. The presence of Cementite greatly enhances the properties of steel. Cementite dissolution during heat-treatment processes in high-carbon, chromium-containing steels has been investigated experimentally and theoretically. It is found that for pearlite with a lamellar microstructure, the dissolution rate is controlled by the rate of diffusion of carbon in the early stage, and of the alloying element (chromium) in the later stage. The diffusion of chromium in cementite particles as well as in austenite is experimentally observed. This steel is widely used to make hardened components such as bearings, gears, transmission shafts, and loading struts of aircraft, due to its excellent properties. The properties are often obtained after a thermal treatment of a subAcm austenization followed by an isothermal bainitic annealing. Cementite dissolution during the subAcm austenization process is often regarded important with respect to the control of austenite grain growth, since the Zener's pinning (drag) force against the growth of austenite grains is proportional to the grain size of cementite particles (Zhao *et al.*, 2006).

Martensite: Martensite is the hardest and strongest and in addition, the most brittle, it has, in fact, negligible ductility. Its hardness is dependent on the carbon content. Martensite is a very hard needle-like structure of iron and carbon. It is formed by very rapid cooling from the austenitic structure. Need to be modified by tempering before acceptable properties reached. To accomplish the demands of light-weight construction all possible mechanisms as precipitation hardening, solid solution hardening and grain refinement have been used to develop high-strength steels. As martensite is generally known as a hard but brittle microstructure, its application was limited to tool steels or tempering steels. These steels require an additional, well defined tempering treatment to achieve an adequate toughness. Unlike plate martensite, its lattice was not tetragonal but cubic as no carbon distorts the lattice (Schulz-Beenken, 1997).

RESULTS AND DISCUSSION

Volumetric Wear Rate

From the Figure 8. It is observed that with increase in the normal pressure the volumetric wear rate is increased for all the specimens and for almost all the sliding speeds. Volumetric wear rate is decreased from 1 to 3 m/s, latter the same is increased with increase in the sliding speed for all the specimens for all the normal pressures. Volumetric wear rate is almost constant with increase in the normal pressure at the sliding speed of 3 m/s for all the specimens. Under the high operational conditions of 7 m/s and 0.8743 MPa, the volumetric wear rate is high when compared with the other operational conditions. Also from Figure, it is observed that, under low operational conditions volumetric wear rate is

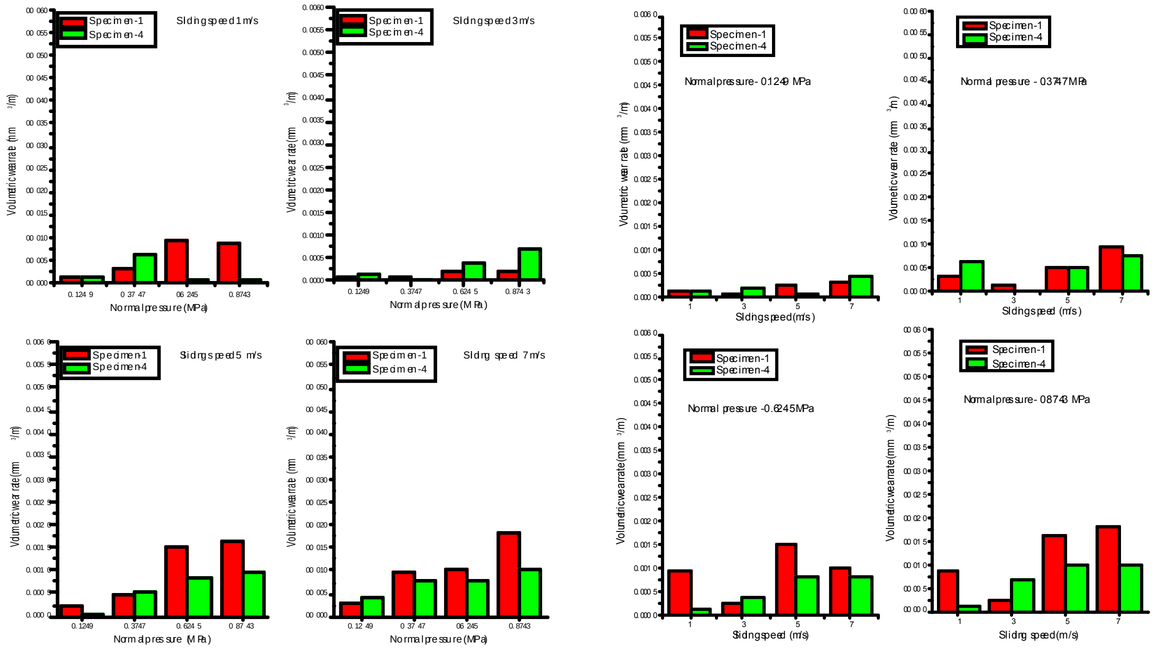


Figure 8: Effect of Volumetric Wear Rate on Normal Pressure and Sliding Speeds of Combination of Pearlite and Cementite Phases

low. But higher volumetric wear rate is observed under high operational conditions. Volumetric wear rate is increased with increasing the normal pressure. Combination of pearlite and cementite is nothing but combination of ferrite and cementite. Cementite is quite hard phase compared with the ferrite phase. Initially ferrite phase wears faster than the cementite. When, cementite phase comes in contact with the sliding disc, cementite breaks and overlays the wearing surface. Hence, volumetric wear rate is low when compared with the martensitic steel. Under high normal pressure, this broken cementite thrown away in the form of wear debris and again ferrite phase come in contact with the sliding disc. So the volumetric wear rate is increased with the normal pressure.

Effect of Pearlite and Cementite

0.92 wt% C steel has almost 100% pearlite steel whereas 1.57 wt% carbon steel has about 20% of cementite and remaining is pearlite. Pearlite is a mixture of ferrite and cemntite. Cementie is reinforcing in the ferritic matrix. Cementite is carbide which is hard material. As per the Archard equation volume loss is inversely proportional to the hardness of the material. Hardness of the 1.57 wt% carbon steel is high due the combination of cementite and pearlite.

Under low operational conditions normal pressures of 0.1249 and 0.3747 MPa, the volumetric wear rate of 0.92wt % carbon steel is low whereas under the high normal pressures of 0.6245 and 0.8743 MPa the volumetric wear rate is more. Under low normal pressures, the impact stress on the wearing surface due to the vibration of the disc is low and this impact stress is absorbed by the softer matrix of ferrite which is present in the pearlite. But under same operational conditions volumetric wear rate of high carbon steel is more. High carbon steel has cementite and pearlite phases. Cementite is hard and brittle. Brittle materials have low in shear strength and during wearing the material loss will takes place due to shearing action of the matting surfaces.

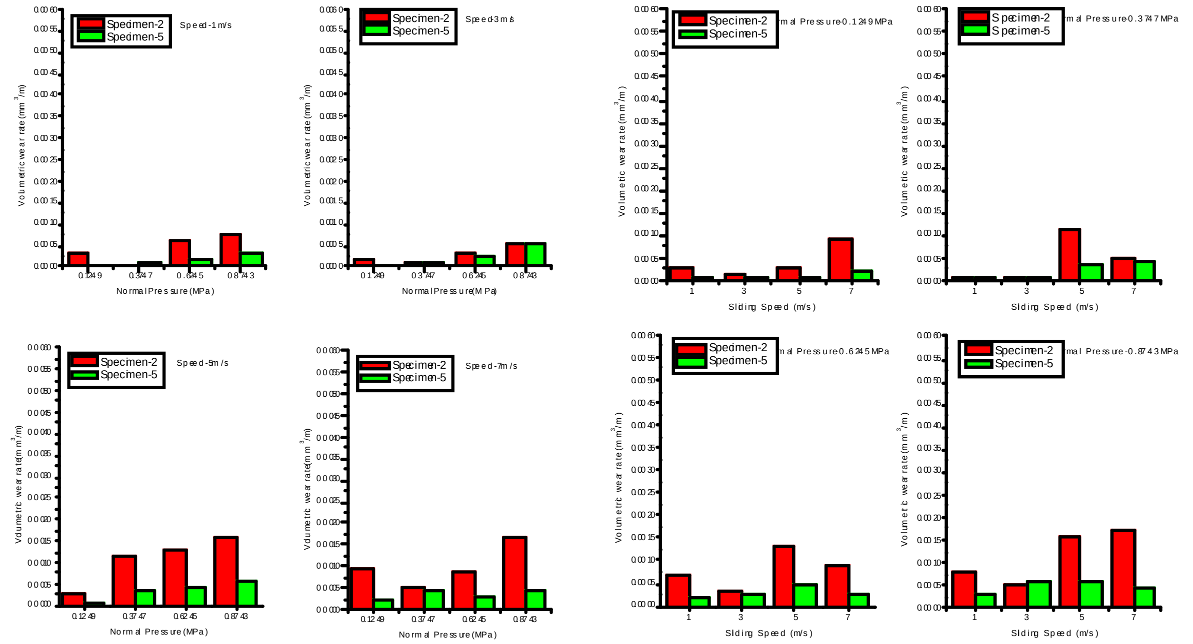
The same is reverse under high normal pressures of 0.6245 and 0.8743 MPa. Under high normal pressure, the cementite particles in the form of debris comes out and may embedded on the pearlitic phase and the whole surface behaves like cementie surface hence, the volumetric wear rate is low for high carbon steel under high normal pressures.

Parlite is a mixture of ferrite and cementie. Initially ferrite phase will wear and cementite will come in contact with the disc. When oxide layers generates, the oxide layers goes in the cavity of the ferrite layers and the whole surface behaves as almost fully oxidative layers so the volumetric wear rate is low. But for the high carbon steel volume fraction of cementite is more which is hard and brittle. The oxide layer almost forms on the pearlitic phase. The wear rate of cementite is more due to its low shear stress. Hence the volumetric wear rate is almost constant under sliding speed 3 m/s.

Effect of Martensite and Cementite

Cementite is a hardest phase among martensite, ferrite and pearlite. When cementite is combined with the martensite and pearlite which is a mixute of ferrite and cementite, the volumetric wear rate is low when compared with the only martensitic phase.

Figure 9: Effect of Volumetric Wear Rate on Normal Pressure and Sliding Speeds of Combination of Martensite and Cementite Phases



From the figures it is observed that volumetric wear rate of high carbon steel is low when compared with the low carbon steel. 0.92 wt% of carbon steel has 2% cementite and 98% martensite, also 1.57 wt% carbon steel has 13.63% cementite and 86.37% martensite. Due to more percentage of cementie in high carbon steel the volumetric wear rate is low under all operational conditions.

Effect of 100% Martensite

From the above Figures 10 it is observed that with increase in the operational conditions of normal pressures and sliding speeds the volumetric wear rate of both the steels have increased. Also it is observed that, volumetric wear rate of 0.92 wt% of carbon steels is high when compared with the 1.57 wt% of carbon steel. When the specimen is quenched from the austenitic temperature to get the martensitic micro structure, some percentage of austenite remained in the phase. This is called the retained austenite. This retained is more prone to the work hardening. This percentage of retained austenite is more in high carbon steel. So when wearing the surface becomes harder, when compared with the low carbon steel. Hence, the volumetric wear rate of 1.57 wt% carbon of 100% martensite steels is low wear rate for all the operational conditions.

SEM Studies

Wear of metals with low hardness and strength occurs by mechanism of adhesion, micro cutting and oxidation. From the Figure 11, it is observed discontinuous grooves on the wornout surface. These discontinuous groves are due to three body abrasive wear mechanism. During wearing, the asperities will break and slide between the wearing surfaces of pin and sliding disc. The free asperities will roll during the sliding and result in

Figure 10: Effect of Volumetric Wear Rate on Normal Pressure and Sliding Speeds of Combination of 100% Martensite Phases

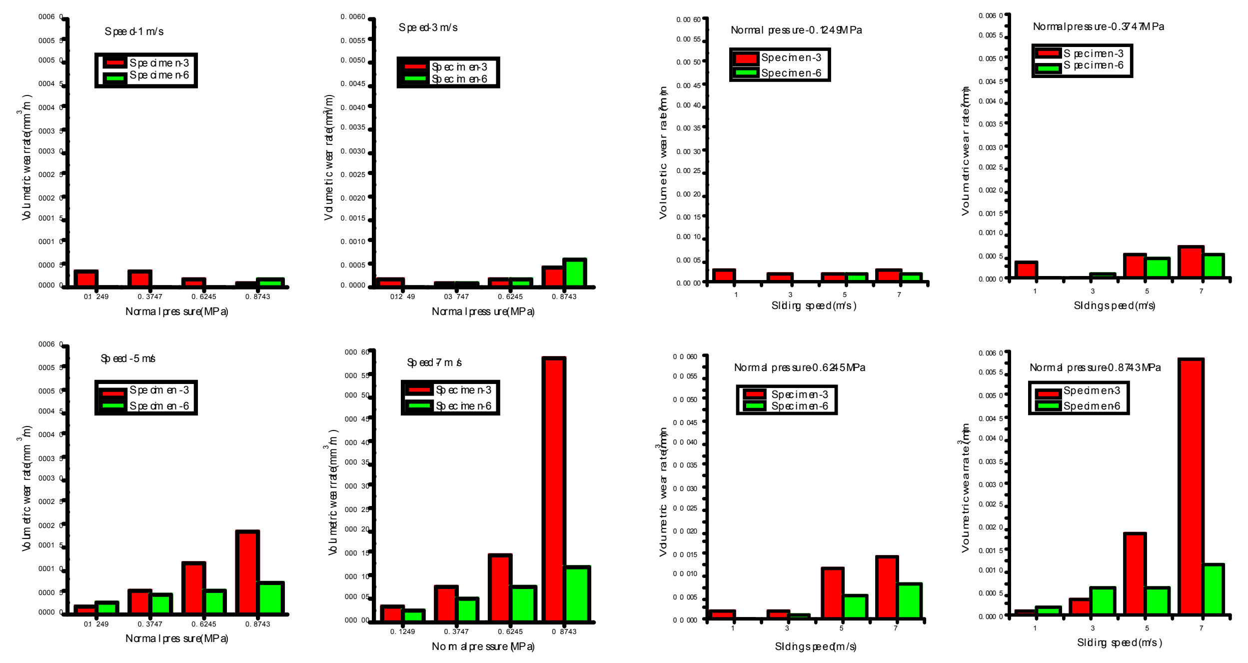
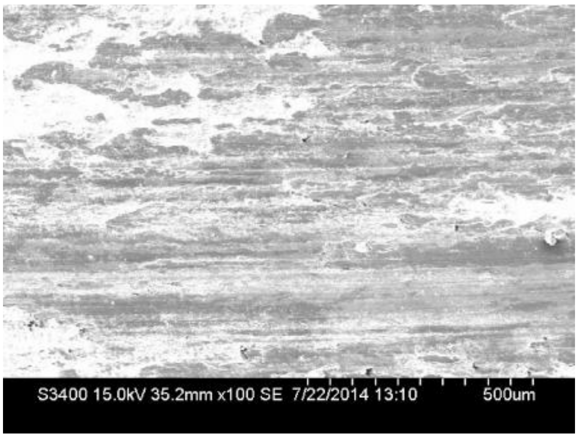


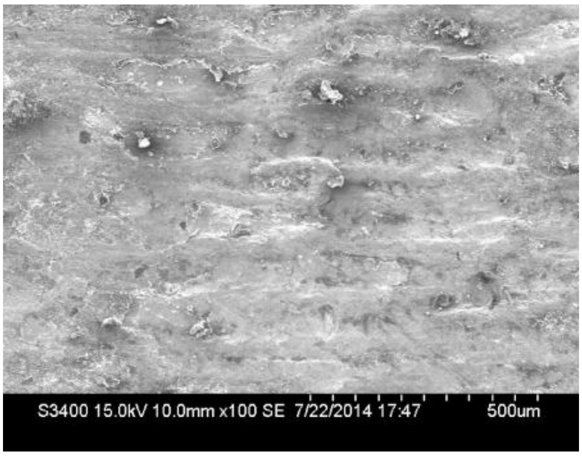
Figure 11: SEM Micro Graph of Sp-2, Speed-1 m/s, Normal Pr. 0.1249 MPa



discontinuous grooves. Due to this abrasive action volumetric wear rate is little high. In this case abrasive asperities would not always be much stronger than the mating surfaces. In the three body abrasive, the grooves are not continuous like two body abrasive. Hence in the SEM Micrographs discontinuous groove are observed.

From the Figure 12 the laminative and delaminative wear mechanisms is observed under the operational conditions of high sliding speed of 7 m/s and low normal pressure of 0.12149 MPa. Under high sliding speed, the frictional temperature is high. Due to this high frictional temperature the edges of the

Figure 12: SEM Micro Graph of Sp-5, Speed-7 m/s, Normal Pr. 0.1249 MPa



asperities will deform plastically and overlays on the wearing surface. Due to the generation of high frictional temperature and thus involving the massively deformed surface layers, the yield strength of the surface layer falls considerably and hence the same undergoes extensive plastic deformation of metal under normal pressure. For these reasons the corresponding wear surface will be in the form of laminates with surfaces partially oxidized. This partially oxidized occurs because of insufficient in-situ time required for the thorough oxidation of the massive laminates formed as shown in Figure 12. After plastic deformation, the over layer surface separates and forms a cavity and result in wear loss.

CONCLUSION

The hypereutectoid steels have been investigated. Based on the experimental observations, the following conclusions can be drawn.

1. The volumetric wear rate is mainly affected by combinations of phases.
2. The wear rate of contact surface after a change in normal pressure to a high level is affected by the rubbing history associated with the normal pressure and sliding speed.
3. In the transition regime, the volumetric wear rate is constant irrespective of normal pressure for all specimens.
4. Under low operational conditions combination of cementite and pearlite gives better wear resistance than other phases.
5. Under high operational conditions combination of cementite and martensite gives better wear resistance than other phases.
6. At the sliding speed of 3 m/s, volumetric wear rate is minimum and almost constant for all the phases under all operational conditions.
7. The volumetric wear rate of 1.57 wt% carbon of 100% martensite steels is low wear rate for all the operational conditions.

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