Wear mode map evaluation of induction hardened 4140 and carburised 8617H steels on 1040 steel

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Abstract
This study was undertaken to evaluate the likely effect on the wear rate of changing the pinion material in a rack and pinion steering box from carburised SAE-AISI grade 8617 H steel to induction hardened SAE-AISI grade 4140 steel. Accordingly, pin-on-disc unlubricated wear tests were conducted using carburised 8617 H pins and through hardened 4140 pins. The surface hardness of the pins was approximately 60 HRC for both materials. The discs were made of SAE-AISI grade 1040 steel through hardened to a hardness of 45 HRC. The tests were conducted using a load of 2.2 kg and a rotational speed of 60 rpm and also under a load of 28.5 kg and a speed of 99 rpm. The results showed that both the pins and the discs wore more rapidly when the tests were carried out with 4140 pins. The data was evaluated using a wear mode map developed by Lim, Ashby and Brunton. This indicated that the wear mode was mild delamination wear at the lower load and speed but severe oxidational wear for higher load and higher speed.

Keywords
1040, steel, map, evaluation, mode, induction, wear, hardened, 4140, carburised, 8617h, steels

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Wear Mode Map Evaluation of Induction Hardened 4140 and Carburised 8617H Steels on 1040 Steel

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ABSTRACT

This study was undertaken to evaluate the likely effect on the wear rate of changing the pinion material in a rack and pinion steering box from carburised SAE-AISI grade 8617 H steel to induction hardened SAE-AISI grade 4140 steel. Accordingly, pin-on-disc unlubricated wear tests were conducted using carburised 8617 H pins and through hardened 4140 pins. The surface hardness of the pins was approximately 60 HRC for both materials. The discs were made of SAE-AISI grade 1040 steel through hardened to a hardness of 45 HRC. The tests were conducted using a load of 2.2 kg and a rotational speed of 60 rpm and also under a load of 28.5 kg and a speed of 99 rpm. The results showed that both the pins and the discs wore more rapidly when the tests were carried out with 4140 pins. The data was evaluated using a wear mode map developed by Lim, Ashby and Brunton. This indicated that the wear mode was mild delamination wear at the lower load and speed but severe oxidative wear for higher load and higher speed.

Introduction

Materials for gear applications, such as steering pinions, must have good wear resistance. Due to the substantial commercial significance, a very large amount of work has been done in examining wear. Studies have been carried out in essentially two different areas [1]. Some studies have focused on collection of performance data for materials selection while others have been directed towards improving wear resistance by developing a fundamental understanding of the wear mechanisms that occur. The hardness of the steel is very important for achieving wear resistance [2]. Wear mechanism maps can be generated which, by analogy with deformation mechanism maps, summarise data and models for wear, showing how the mechanisms interface and allowing the dominant mechanism to be identified [3]. For development of the maps the theoretical treatments are reduced to the simplest possible level with heat flow being approximated by the equivalent one-dimensional problem and rates of oxidation being calculated from the simplest kinetic model [3]. There are many types of wear, including adhesive wear, abrasive wear, fretting wear, fatigue wear and corrosive wear [4]. Adhesive wear occurs mostly in steels which have a smooth surface finish and where the sliding members have similar hardnesses. Sliding dry adhesive wear is one form of adhesive wear. It occurs in many machine parts, such as gears, when lubrication failure occurs [5]. The purpose of this work was to examine the likely effect of changing the pinion material in a rack and pinion steering box (with an SAE-AISI grade 1040 steel rack) from case hardened SAE-AISI grade 8617 H steel to induction hardened SAE-AISI grade 4140 steel. The tests were carried out unlubricated (dry) using the pin-on-disc wear test. They were conducted using a load of 2.2 kg (the self-weight of the test fixture) and a rotational speed of 60 rpm and also using a load of 28.5 kg and a rotational speed of 99 rpm. The type of wear was evaluated in each case using a wear map.

Experimental Methods

Characterisation of 8617 H and 4140 Pinions

Prior to undertaking the wear tests, metallurgical characterisation was carried out for a pinion made from the existing material, 8617 H, and a pinion made from...
the proposed alternative material 4140. The 8617 H pinion had been gas carburized, while the 4140 pinion had been induction hardened. The two pinions were sectioned longitudinally perpendicular to the case and metallographically polished to a 1 micron finish. Three microhardness traverses were made across the polished sections, starting at the surface, using a Leco M-400-H1 hardness testing machine with a 500 g load. The microhardness measurements were made at intervals of 0.05 mm. Case depth was determined as the depth at which the hardness dropped to 50 HRC (effective case depth) [6]. The samples were then etched in 2% Nital and their microstructure examined using an Olympus PMG 3 optical microscope.

### Wear Testing

Wear testing was carried out using a 4kW electrically driven pin-on-disc wear tester built by Challen [7]. During operation, the head of the wear testing machine remained stationary while the disc rotated in a clockwise direction. The pins thus contacted a circular path around the disc, along a circle 75 mm in diameter. This gave a path length of 236 mm/revolution [7]. Discs 100 mm in diameter by 9 mm thick were machined from a 100 mm diameter 1040 steel bar, while pins 23 mm long by 9.5 mm in diameter were manufactured from both 8617 H and 4140 steel. After machining, the 1040 discs and 4140 pins were through hardened, while the 8617 H pins were gas carburized. Prior to carrying out the wear tests, the prepared pins were weighed to an accuracy of 0.0001 g. After the tests, any loose wear debris was removed from the pins. They were then washed in alcohol, dried, then reweighed. The discs were also weighed at the start of each test and at the same intervals as the pins. As for the pins, any loose wear debris was removed and the discs were then washed in alcohol and dried before weighing. The discs were weighed to an accuracy of 0.01 g. The details of the various tests conducted are listed in Table 1.

### Metallographic Examination of Discs and Pins

Microhardness traverses were made on metallographically prepared sections taken perpendicular to the surface. For the disc, the microhardness traverse was made at 0.1 mm intervals while for the pins the traverse was made at 0.05 mm intervals. The measurements were made using a Leco M-400-H1 hardness testing machine with a load of 500 g. The samples were then etched in 2% Nital and their microstructure examined using an Olympus PMG 3 optical microscope.

### Examination of Wear

The disc and pins from Test # 3 and Test # 4 were examined after testing using a scanning electron microscope (SEM). The pins were examined using a JOEL JXA-840 SEM. However, for the disc, it was necessary to use a machine with a larger stage and, accordingly, SEM examination of the disc was carried out using a Hitachi 4500-II FESEM. A special fixture was constructed to hold the disc. Images of the discs and pins were recorded at 500x.

### Results

#### Characterisation of Discs and Pins

- **Hardness and Microstructure**
  - The surface hardness measured on the disc was 45 HRC. A microhardness profile through the surface of the disc is shown in Fig. 1. This indicates that the hardness is essentially constant over the distance measured having a value again of 45 HRC. This agrees well with the design hardness of the steering rack which was also 45 HRC. The microstructure of the disc can be seen in Fig. 2. The disc has a characteristic hardened and tempered microstructure of tempered martensite. Microhardness profiles through the surface of an unused 8617 H pin and an unused 4140 pin are shown in Figs 3(a-b). The surface hardness of the 8617 H pin was 57 HRC rising slightly to a value of 59 HRC at a position of 0.1 mm beneath the surface then decreasing progressively to a value of 50 HRC at a position of 0.6 mm beneath the surface. This profile is similar to that obtained for the 8617 H pinion. The surface hardness of the 4140 pin was 60 HRC but dropped progressively to an essentially constant value of 55 HRC at a position of 0.25 mm beneath the surface. The surface hardness was representative of that of the induction hardened pinion. The microstructure of the case of the 8617 H pin is shown in Fig. 4 (a). The microstructure was similar to that of the pinion. The microstructure of the 4140 pin is shown in Fig. 4 (b). The microstructure was found to be similar both near and remote from the surface, as would be expected since the pin was through hardened, and was similar to that of the induction hardened surface of the 4140 pinion.

![Figure 1. Surface hardness of unused 1040 disc.](image1)

![Figure 2. Microstructure of 1040 disc at 500x.](image2)

#### Table 1. Details of tests conducted

| Test No | Pin | Disc | Applied Load (kg) | Speed (rpm) | No of Cycles |
|---------|-----|------|-------------------|-------------|--------------|
| #1      | 4140| 1040 | 2.2               | 60          | 10000        |
| #2      | 8617 H | 1040 | 2.2               | 60          | 10000        |
| #3      | 4140| 1040 | 28.5              | 99          | 7000         |
| #4      | 8617 H | 1040 | 28.5              | 99          | 7000         |
Wear Testing

Wear Curves

Wear curves were prepared from the weight loss measurements for both the pins and the discs for Tests # 1-4. Pins Test # 1 was carried out with 4140 as the pin material. The wear rate was approximately constant for the first 1000 revolutions, but then decreased considerably. It was noted that the wear was more rapid for Pin 2 than for the other two pins. For the 8617 H pins, examined in Test # 2, the behaviour was generally similar to that for 4140 pins. The results from Test # 1 and # 2 are plotted together for the individual pins in Figs. 5-7. It can be observed that the wear is slightly less on the 8617 H pins than on the 4140 pins. For Test # 3, which was carried out with 4140 as the pin material, there was a smaller difference between the amounts of wear on the different pins, but it was noticed that, in all three tests, Pin 2 underwent the greatest amount of wear, while Pin 3 underwent the least. For the 8617 H pins examined in Test # 4, there was a difference in the amounts of wear at the three different pin positions, and again the wear was greatest for Pin 2 and least for Pin 3, as was found for the 4140 pins. The results from Tests # 3 and # 4 are plotted together for each of the individual pins in Figs. 9-11. It can be seen that the wear is again slightly more on the 4140 pins than on the 8617 H pins. In all cases the wear was essentially linear, i.e., steady state, after the first 1000 revolutions.

Discs

The wear curve for the disc for Test # 1 and # 2 are plotted together in Fig. 8. The wear rate for the disc tested with 4140 pins was rapid initially, but decreased substantially after 1000 revolutions. Similar behaviour was observed with the 8617 H pins, although the amount of wear was substantially less. The results for the discs from Tests # 3 and # 4 are plotted together in Fig. 12. The curves again show a rapid initial wear rate up to 1000 revolutions followed by a much slower and essentially linear wear rate. Again, the amount of wear was substantially more for the discs tested with 4140 pins than for those tested with 8617 H pins. Like the pins, the discs showed essentially steady state wear beyond 1000 revolutions in all the tests.
Characterisation of Wear

The disc and one of the pins from Test # 3 (4140 pins) as well as the disc and one of the pins from Test # 4 (8617 H pins) were examined at the completion of the wear test by scanning electron microscopy to establish the nature of the wear. SEM photographs of the worn surface on the 4140 and 8617 H pins are shown in Figs. 13 (a-b), respectively. The worn surfaces are similar on both pins. The surfaces have a smeared appearance which appears to be from metal being re-deposited onto the pins. The wear track on the 1040 disc is shown for the test conducted with the 4140 pins in Fig. 14 (a) and with the 8617 H pins in Fig. 14 (b). The appearance of the wear on the discs is quite different to that on the pins with the wear tracks exhibiting a coarse flakey appearance.

Discussion

Mode of wear

Fig. 15 shows the wear mode map for steel developed by Lim et al. [9]. The different modes of wear that can occur are restricted to specific fields of the wear mode map. The wear mode map is generated by plotting normalised pressure $F^*$ against normalised velocity $v^*$ using the following equations:

$$F^* = \frac{F}{A_nH_0}$$  \hspace{1cm} (1)

$$v^* = \frac{v}{\rho c \alpha}$$  \hspace{1cm} (2)

$$w^* = \frac{W}{A_n}$$  \hspace{1cm} (3)

where

- $F$ is the normal force on the sliding interface (N)
- $A_n$ is the nominal (apparent) contact area (m$^2$)
- $H_0$ is the room temperature true hardness of the softer sliding member (N/m$^2$)
- $v$ is sliding velocity (m/s)
- $\alpha$ is the thermal diffusivity (m$^2$/s = K/\rho c)$
- $ro$ is the radius of the contact area (m)
- $W$ is the wear rate i.e., volume lost per unit distance slid (m$^3$/m)

In the current study, the hardness of the softer sliding member (i.e., the disc) was 45 HRC which is equivalent to 466 HV [12]. The true hardness $H$ can be determined from the Vickers hardness (HV) number $HV$ by [8,13]:

$$H = 10.58 \frac{HV}{10^6} N/m^2.$$  

For the tests carried out with an applied load of 28.5 kg, the normal force $F = 279.3$ N. The test rig contained three equally sized pins 9.5 mm in diameter pins in contact with the disc giving a total contact area $A_n$ of $213 \times 10^{-6} m^2$. This gives a value of $F^* = 2.78 \times 10^{-4}$.

The wear track had a diameter of 75 mm, giving a path length of 0.236 m per revolution [7]. The tests were conducted at 90 – 100 rpm giving a sliding velocity of 0.354 – 0.393 m/s. Using a value of $2.1 \times 10^{-5} m^2/s$, for the thermal diffusivity of steel gives $v^* = 80 – 89$ [10,14].

The point corresponding to the values of $F^*$ and $v^*$ determined in Eq.1 and Eq. 2 is shown on the wear mode map for steel in Fig. 15 [9]. It can be seen that these values correspond to a point inside the transition between mild oxidational wear (type 2.1 (ii)), and severe oxidational wear (type 2.2 (ii)), but close to the zone of severe oxidational wear.
Lim et al. [9] point out that type 2.1 (ii) wear (mild oxidational wear) involves the formation of a thick, brittle oxide which is continuously generated by the high flash temperatures at the asperity contacts. Oxide fragments break away to produce wear debris but the oxide is continuously replenished so that direct metal-to-metal contact is prevented [9].

When the load is high enough, the oxide layer can be penetrated and metal to metal contact results, producing a transition to type 2.2 (ii) wear (severe oxidational wear). Deep tearing of the surfaces now occur giving severe metallic wear [9].

The micrographs of the wear tracks on the discs shown in Figs. 14 (a) and 14 (b) are consistent with this mechanism of wear, suggesting that the mode is principally severe oxidational wear.

For the tests, carried out with an applied load of 2.2 kg, $F = 2.15 \times 10^{-5}$. These tests were conducted at 60 rpm giving a value of $v^* = 53$. This point is also shown on Fig. 15 and is within the region of mild delamination wear. This is consistent with the low wear rate observed.

**Wear Curves**

The wear curves for both the pins and the discs exhibited a period of running-in wear followed by steady state wear. This is characteristic of sliding adhesive wear, the running-in wear produced a substantially higher wear rate than the steady state wear [8]. In the tests carried out using just the load produced by the self-weight of the fixture (2.2 kg), the steady state wear commenced after approximately 1000 revolutions for both the pins and discs, Figs. 5-7 for the pins and Fig. 8 for the disc. With the heavier loads (28.5 kg), the period of running-in wear was markedly reduced for the pins and extended to a maximum of only about 100 revolutions, Figs. 9-11 for the pins. However, the running-in in wear still continued to about 1000 revolutions for the discs, Fig. 12. The decrease in wear rate after the running-in stage has been attributed to reduction in the true contact pressure [9]. During running-in, smoothing out of the initial surface roughness occurs to give sliding surfaces which conform to each other at a microscopic level. As a result the true contact pressure decreases resulting in a reduction in the wear rate [9]. Martensitic formation, work hardening and the formation of oxide films can all occur during wear and at least some of these processes would be expected to reach steady state more slowly on the discs than on the pins [9]. This may explain the different running-in behaviour seen for the pins and the discs.

**Comparison of Wear Behaviour for 4140 and 8617 H Pins**

The results from the comparative tests conducted with 8617 H and 4140 pins showed that the wear was substantially more for the tests with the 4140 pins than for those with the 8617 H pins, Figs. 8 and 12. Much of the difference is in the running-in stage where the wear can be seen to be occurring much more rapidly in the tests conducted with the 4140 pins. However, the steady state wear rate can also be seen to be higher for the 4140 pins. For the tests conducted at the highest loading, the wear rate was $1.6 \times 10^{-5}$ for the 4140 pins compared with $9.6 \times 10^{-6}$ for the 8617 H pins. The amount of wear on the pins was also greater for the tests conducted using 4140 pins than for those using 8617 H pins, Figs. 5-7 and 9-11. In part, this difference was again due to a higher rate of wear during the running-in stage. However, again an increase was consistently seen in the steady state wear rate with average values at the higher loading being $5.0 \times 10^{-6}$ for the 4140 pins compared with $4.1 \times 10^{-6}$ for the 8617 H pins.

The higher wear rate for the 4140 pins is surprising in view of their slightly higher hardness of 60 HRC compared with 57 HRC for the 8617 H pins. It is noted however that the hardness of the
4140 pins decreased with distance beneath the surface, Fig 3 (b), while the hardness of the 8617 H pins increased, at least initially, Fig. 3 (a), suggesting the possibility of the relative hardnesses inverting as wear progressed. The difference is more likely due to differences in the pin composition and microstructure. The 4140 pins had a nominal composition of Fe-0.4%C-0.9%Mn-1%Cr-0.2%Mo whereas the 8617 H pins had a nominal composition of Fe-0.17%C-0.8%Mn-0.5%Cr-0.6%Ni-0.2%Mo. Moreover, the 8617 H pins were carburised so that the wear surface would have a carbon content of approximately 0.8%C, approximately twice that of the 4140 pins. The higher (surface) carbon content is almost certainly responsible for the lower wear rate observed for the 8617 H pins. While both pins were tempered to (essentially) the same surface hardness, the higher carbon in the 8617 H would mean that a greater amount of hard carbide would be present and this would impart better wear resistance [10]. The 8617 H pins also produced less wear on the 1040 discs than did the 4140 pins. In view of the relatively small differences in the chemical composition of the two pin materials it is unlikely that the different wear rates produced on the 1040 are due to differences in the physical properties of the two steels and again the differences in composition and microstructure must be responsible for the different rates of disc wear produced by the different pin materials. The mechanism of wear appeared to be localised welding. It would seem that the higher quantity of carbides in the 8617 H may have limited the amount of localised welding that occurred resulting in reduced wear on the disc, i.e., less metal transfer would have occurred in terms of Bowden and Tabor’s severe wear mechanism [11].

Conclusions

The present study compared the wear behaviour produced during unlubricated pin-on-disc wear testing using 4140 and 8617 H pins. The pins had a surface hardness of approximately 60 HRC. 1040 discs were used having a hardness of 45 HRC. The tests were carried out using a load of 2.2 kg and 28.5 kg and a sliding velocity of 0.35 - 0.4 m/s.

The results showed that both the pins and the discs wore more rapidly, in both the running in and the steady state stage, when the tests were carried out with 4140 pins. This is attributed to microstructural differences between the two materials. The carburised 8617 H pins had approximately twice the surface carbon content of the 4140 pins. This would result in a higher carbide content which would reduce the wear rate of the pins. The carbides in the 8617 H pins also appear to have reduced the level of localised welding thereby reducing the level of wear on the discs.

Evaluation of the results using Lim et al.’s wear mode map indicated that mild delamination wear occurred when using a low load (2.2 kg), while severe oxidational wear occurred when using a high load (28.5 kg).

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