Surface coatings for 3-piece freight bogie centre bearings

Matthew J. Franklin
University of Wollongong
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Chapter 6: Wear observations

Some of the results included in this Chapter have been presented previously at the Conference On Railway Engineering, Melbourne, 2006 (Conference paper #2).

6.1 Experimental

6.1.1 Samples

The Australian rail industry have provided a worn polyethylene centre bowl liner, two (2) worn cast AISI 1053 medium carbon steel top centres and five (5) worn Hadfield steel centre bowl liners. These components have been given sample identification codes as listed in Table 10. The polyethylene centre bowl liner was from a 90 tonne 3-piece freight bogie, whilst the seven (7) steel components were from 50 tonne 3-piece freight bogies. The polyethylene liner was in service for around 8 years. The service periods for the steel components are not known, however they are typical of components in service for eight (8) to ten (10) years. The TC1 top centre and CB5 centre bowl liner were mating components from the same vehicle, however it is not known how long they were mated together. All the components were used in the un lubricated condition, and the steel components were not used with polymer liners.

The manufacturer data sheet for the polyethylene centre bowl liner is listed in Table 11. The typical mechanical properties of AISI 1053 medium carbon and Hadfield steels are listed in Table 12. The Hadfield steel hardness value was measured on a new cast and machined centre bowl liner at 20 µm depth (near surface).
Table 10 List of worn centre bearing components, material types, and nominal new dimensions.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Component</th>
<th>Material</th>
<th>Nominal new rim wall thickness (mm)</th>
<th>Nominal new inside diameter (mm)</th>
<th>Nominal new outside diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB1</td>
<td>Centre bowl liner</td>
<td>High density polyethylene</td>
<td>6.35</td>
<td>404.0</td>
<td>-</td>
</tr>
<tr>
<td>CB2</td>
<td>Centre bowl liner</td>
<td>Hadfield steel</td>
<td>305.5-306.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TC1</td>
<td>Top centre</td>
<td>Cast AISI 1053 steel</td>
<td>-</td>
<td>299.8 +2.4/-0.8</td>
<td></td>
</tr>
<tr>
<td>TC2</td>
<td>Top centre</td>
<td>Cast AISI 1053 steel</td>
<td>-</td>
<td>299.8 +2.4/-0.8</td>
<td></td>
</tr>
<tr>
<td>CB3</td>
<td>Centre bowl liner</td>
<td>Hadfield steel</td>
<td>N/A</td>
<td>304.8 +0 / -1.6</td>
<td>-</td>
</tr>
<tr>
<td>CB4</td>
<td>Centre bowl liner</td>
<td>Hadfield steel</td>
<td>304.8 +0 / -1.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CB5</td>
<td>Centre bowl liner</td>
<td>Hadfield steel</td>
<td>304.8 +0 / -1.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CB6</td>
<td>Centre bowl liner</td>
<td>Hadfield steel</td>
<td>304.8 +0 / -1.6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 11 Manufacturer data sheet for high density polyethylene centre bowl liner [47].

Table 12 Typical mechanical properties of AISI 1053 medium carbon and Hadfield steels.

<table>
<thead>
<tr>
<th></th>
<th>Hardness</th>
<th>Yield strength, $\sigma_y$ (MPa)</th>
<th>Ultimate tensile strength, $\sigma_{uts}$ (MPa)</th>
<th>Approximate yield strength in shear, $\tau_y$ (MPa)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast AISI 1053 medium carbon steel</td>
<td>230 HV</td>
<td>325</td>
<td>620</td>
<td>188</td>
<td>[48]</td>
</tr>
<tr>
<td>Cast and machined Hadfield steel</td>
<td>300 HV</td>
<td>380</td>
<td>820</td>
<td>196</td>
<td>[49]</td>
</tr>
</tbody>
</table>

NB: The Hadfield steel hardness value is an actual near-surface (20 µm depth) measured value of a new cast and machined centre bowl liner.
6.1.2 Testing

Table 13 summarises the testing completed on each of the worn components. These testing procedures are described in more detail in sections 6.1.2.1 and 6.1.2.2 below.

**Table 13 Overview of testing schedule.**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Method of measuring worn dimensions</th>
<th>Other test methods</th>
<th>Microhardness profiles (Yes/No)</th>
<th>Microstructural profiles (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB1</td>
<td>Micrometer</td>
<td>differential scanning calorimetry</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CB2</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>TC1</td>
<td>Vernier caliper</td>
<td>atomic emission spectroscopy</td>
<td>Yes</td>
<td>Yes (OM + SEM)</td>
</tr>
<tr>
<td>TC2</td>
<td>Touch sensor</td>
<td>-</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CB3</td>
<td>Vernier caliper</td>
<td>-</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CB4</td>
<td>Vernier caliper</td>
<td>-</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CB5</td>
<td>Vernier caliper</td>
<td>atomic emission spectroscopy</td>
<td>Yes</td>
<td>Yes (OM only)</td>
</tr>
<tr>
<td>CB6</td>
<td>Touch sensor</td>
<td>-</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

6.1.2.1 Polyethylene sample

The worn surface of the polyethylene liner was observed and photographed. There are no records of the actual original dimensions of the sample. The worn rim wall thickness of this liner was measured using a micrometer and is compared to the nominal new thickness. The measurement positions were located on plane B-B or 18 mm above the plate contact surface (refer to Figure 58) and at angular increments of 22.5° from the longitudinal direction providing sixteen (16) positions in total. A qualitative value of specific gravity was determined. The melting point and approximate crystallinity of the polyethylene samples were determined using differential scanning calorimetry (DSC Q100, TA Instruments). The samples were heated from –20 to 180 °C using a heating
rate of 10 °C/min. For these experiments the crystallinity is calculated as the ratio of the heat of fusion obtained using differential scanning calorimetry divided by the heat of fusion of 100% crystalline polyethylene (293 J/g) [78, 79].

### 6.1.2.2 Steel samples

The worn surfaces of all the steel samples were observed. Top centre sample, TC1, and centre bowl liner sample, CB3, have been photographed. The worn surfaces of the photographed samples are visually similar to the other steel samples.

There are no records of the actual original dimensions of the steel samples. The worn diameters of centre bearing components: TC1, CB3, CB4, CB5 were measured using vernier calipers. Sample CB2 had been plasma cut so it’s dimensions were not measured. The measurement positions were located on plane B-B (refer to Figure 58) and at least eight (8) equi-distant positions around the rim wall (22.5° increments from the longitudinal direction). The measured dimensions are compared to the nominal new dimensions.

The worn dimensions of centre bearing components: TC2, and CB6 were measured using a touch sensor attached to a milling machine. The measurement positions were located on plane B-B (refer to Figure 58) and on around 150 positions around the rim wall. The origin or centre points of these components have been determined. The measured dimensions are compared to the nominal new dimensions.

The chemical compositions of the steel samples: TC1 and CB5 were determined using atomic emission spectroscopy.

The worn centre bowl liner: CB2 was sectioned for hardness profile determination. Samples were sectioned from one longitudinal, one 45° direction and one lateral
direction at four positions: 14, 19, 24 and 29 mm above the level of the plate contact surface, similar to the sampling scheme shown in Figure 58 a. Samples for microhardness measurements were polished to 3 μm finish and etched in 2.5% nital for 5 seconds to reveal the microstructure of the coatings. Microhardness measurements for hardness-depth profiles were made using a Leco microhardness tester at a load of 100g.

The worn mating centre bearing components: TC1 and CB5 were sectioned for cross-sectional microhardness measurements and optical microscopy observations. Samples were sectioned from the longitudinal and lateral directions, at three positions: 11, 18, and 25 mm above the level of the plate contact surface (Figure 58 a), and in 2 orientations: parallel and perpendicular to the plane of bogie rotation (Figure 58 b). Samples for metallographic examination were polished to 3 μm finish and etched in 2.5% nital for 5 seconds to reveal the microstructure of the coatings. Microstructural observations were made using Leica optical microscope. Cross-sectional samples perpendicular to plane of rotation from component: TC1 were examined using the Leica Stereoscan 440 SEM at 18 mm above plate contact surface position. Microhardness measurements for hardness-depth profiles were made using a Leco microhardness tester at a load of 100g.
Figure 58 (a) Location, and (b) orientation of cross-sectional samples taken from the worn AISI 1053 steel top centres and Hadfield steel centre bowl liners.
6.2 Results

6.2.1 Photographs

A photograph of the worn polyethylene centre bowl liner is shown in Figure 59. The rim wall and plate sections were mostly covered in a black film that on some parts of the plate section, where it was peeling off, had a thickness of up to 0.2 mm.

Photographs of the top centre sample, TC1, and centre bowl liner sample, CB3, are shown in Figures 60 to 61, and Figures 62 to 63, respectively.

Figure 59 Photograph of worn polyethylene centre bowl liner, sample ID: CB1.
Figure 60 Photograph showing clearly the worn longitudinal surface of AISI 1053 medium carbon steel top centre, sample ID: TC1.

Figure 61 Photograph showing clearly the worn lateral surface of AISI 1053 medium carbon steel top centre, sample ID: TC1.
Figure 62 Photograph showing clearly the worn longitudinal surface of Hadfield steel centre bowl liner, sample ID: CB3.

Figure 63 Photograph showing clearly the worn lateral surface of Hadfield steel centre bowl liner, sample ID: CB3.
6.2.2 Worn dimensions

The worn dimensions of the samples CB1, TC1, CB3, CB4, CB5, TC2, CB6 are shown in Figures 64 to 70. The worn radii, as determined through touch sensor measurements, as a function of angle from longitudinal direction for top centre sample, TC2, and centre bowl liner sample, CB6, are shown in Figure 71.

During curve negotiation the top centre is in contact with the centre bowl liner at the rim wall. To calculate the approximate contact conditions, the top centre sample, TC2, has been hypothetically moved longitudinally. In the first case, it is by +7.5 mm. The new radii from origin point to the perimeter of the moved sample are calculated. In Figure 72, the new radii for the moved top centre sample, TC2, and the worn radii for centre bowl liner sample, CB6, are plotted against the angle from the longitudinal direction over the range 90 to 270°. In the second case, the top centre sample, TC2, is moved -5.7 mm longitudinally. In Figure 73, the new radii for the moved top centre sample, TC2, and the worn radii for centre bowl liner sample, CB6, are plotted against the angle from the longitudinal direction over the range from 270°, through 360°, to 90°.

In Table 14 the total wear depth from both longitudinal edges of the measured steel components is determined. The wear depth rate per year is also presented. In Table 15 the worn volume, wear co-efficient and normalized wear rate have been calculated for samples TC2 and CB6. The assumptions for the normalised wear rate calculation were: rim wall load equals 31 kN (50 ton wagon load), sliding distance equals 3,172 m (equivalent to 10 years on Goonyella track (refer to Table 6)), and for the wear co-efficient calculation were the same plus the hardness of the softer steel (AISI 1053 medium carbon steel) was 300 HV or 550 MPa (approximate yield strength).
CB1 – Centre bowl liner

Figure 64 Worn rim wall thickness of HDPE centre bowl liner - CB1. NB: Not to scale - exaggerated for effect.
Figure 65 Worn dimensions of AISI 1053 medium carbon steel top centre - TC1. NB: Not to scale - exaggerated for effect.
Figure 66 Worn dimensions of Hadfield steel centre bowl liner - CB3. NB: Not to scale - exaggerated for effect.
<table>
<thead>
<tr>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worn ( \text{dia.} = 307.4 \text{ mm} )</td>
<td>Worn ( \text{dia.} = 305.4 \text{ mm} )</td>
</tr>
<tr>
<td>Nominal ( \text{dia.} = 304.8 \text{ mm} )</td>
<td>Nominal new diameter (max. tolerance)</td>
</tr>
</tbody>
</table>

Figure 67 Worn dimensions of Hadfield steel centre bowl liner - CB4. NB: Not to scale - exaggerated for effect.
CB5 – Centre bowl liner

Figure 68 Worn dimensions of Hadfield steel centre bowl liner – CB5. NB: Not to scale - exaggerated for effect.
Figure 69 Worn radii of AISI 1053 medium carbon steel top centre – TC2. NB: Not to scale - exaggerated for effect.
CB6 – Centre bowl liner

Worn radius = 154.3 mm

Nominal radius = 152.4 mm

Figure 70 Worn radii of Hadfield steel centre bowl liner – CB6. NB: Not to scale - exaggerated for effect.
Figure 71 Worn radii as a function of angle from longitudinal direction for samples TC2 and CB6.
Figure 72 Worn radii of sample CB6. Radii from origin point to perimeter of sample TC2 moved +7.5 mm longitudinally to make theoretical contact with the rim wall of centre bowl liner sample, CB6.
Figure 73 Worn radii of sample CB6. Radii from origin point to perimeter of sample TC2 moved -5.7 mm longitudinally to make theoretical contact with the rim wall of centre bowl liner sample, CB6.
Table 14 Total wear depth and wear rate.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total wear depth (mm)</th>
<th>Wear depth rate (mm depth/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TC1</td>
<td>7.4</td>
<td>0.74</td>
</tr>
<tr>
<td>TC2</td>
<td>7.1</td>
<td>0.71</td>
</tr>
<tr>
<td>CB3</td>
<td>1.6</td>
<td>0.16</td>
</tr>
<tr>
<td>CB4</td>
<td>2.6</td>
<td>0.26</td>
</tr>
<tr>
<td>CB5</td>
<td>5.0</td>
<td>0.50</td>
</tr>
<tr>
<td>CB6</td>
<td>3.9</td>
<td>0.39</td>
</tr>
</tbody>
</table>

NB: Total wear depth is equal to sum of wear from both longitudinal edges of component. Wear rate is based on 10 years service life.
Table 15 Worn volume, wear co-efficient and normalized wear rate for samples TC2 and CB6.

<table>
<thead>
<tr>
<th></th>
<th>Area of plane B-B - New nominal (mm²)</th>
<th>Area of plane B-B - worn component (mm²)</th>
<th>Worn area (mm²)</th>
<th>Rim wall contact height (mm)</th>
<th>Worn volume (mm³)</th>
<th>Wear co-efficient, κ</th>
<th>Normalised wear rate (m³/m.N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC2 – top centre</td>
<td>70,592</td>
<td>68,991</td>
<td>1,600</td>
<td>34</td>
<td>54,422</td>
<td>3.0 x 10⁻⁴</td>
<td>5.7 x 10⁻¹³</td>
</tr>
<tr>
<td>CB6 – centre bowl liner</td>
<td>72,583</td>
<td>73,806</td>
<td>1,222</td>
<td>34</td>
<td>41,554</td>
<td>2.3 x 10⁻⁴</td>
<td>4.4 x 10⁻¹³</td>
</tr>
</tbody>
</table>

NB: Rim wall load equals 31 kN (50 ton wagon load) which is half the 60 kN load quoted for 96 tonne wagon load [6]. Prevailing rail track was varied. Assume sliding distance = 3,172 m, which is equivalent to 10 years on Goonyella track (refer to Table 6). For wear co-efficient calculation, the softer material was AISI 1053 medium carbon steel top centre with hardness equal to 300 HV or 550 MPa (approximate yield strength).
6.2.3 Material analysis

The polymer centre bowl liner sample, CB1, floated on water, thus it’s specific gravity is less than 1.00 g/cm³. The melting point and heat of fusion of this sample, as determined by differential scanning calorimetry, was 136.3 °C and 141.9 J/g, respectively. The degree of crystallinity is 48.4 %.

The chemical composition of the worn AISI 1053 medium carbon steel top centre sample, TC1, and mating Hadfield steel centre bowl liner sample, CB5, are listed in Table 16.

Table 16. Chemical composition (in wt%) of Hadfield and AISI 1053 medium carbon steels.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadfield</td>
<td>1.19</td>
<td>12.65</td>
<td>0.73</td>
<td>0.045</td>
<td>0.008</td>
<td>0.35</td>
<td>0.063</td>
<td>0.055</td>
<td>0.025</td>
<td>84.70</td>
</tr>
<tr>
<td>AISI 1053</td>
<td>0.53</td>
<td>0.95</td>
<td>0.65</td>
<td>0.011</td>
<td>0.015</td>
<td>0.15</td>
<td>0.11</td>
<td>0.024</td>
<td>0.003</td>
<td>97.44</td>
</tr>
</tbody>
</table>

6.2.4 Microhardness and microstructural profiles

The microhardness-depth profiles for the worn Hadfield steel centre bowl liner, CB2, are presented in Figures 74 to 77.

The microhardness-depth profiles and cross-sectional microstructures for the worn AISI 1053 medium carbon steel top centre, TC1, and Hadfield steel centre bowl liner, CB5, are presented in Figures 78 to 83. Higher magnification SEM images of the worn AISI 1053 medium carbon steel top centre, TC1, are presented in Figures 84 to 88. Higher magnification optical micrographs of the worn Hadfield steel centre bowl liner, CB5, are shown in Figure 89a. and Figure 89b.
Figure 74 Microhardness profiles for Hadfield steel centre bowl liner sample, CB2, in longitudinal, 45°, and lateral positions at 14 mm above plate surface.
Figure 75 Microhardness profiles for Hadfield steel centre bowl liner sample, CB2, in longitudinal, 45º, and lateral positions at 19 mm above plate surface.
Figure 76 Microhardness profiles for Hadfield steel centre bowl liner sample, CB2, in longitudinal, 45º, and lateral positions at 24 mm above plate surface.
Figure 77 Microhardness profiles for Hadfield steel centre bowl liner sample, CB2, in longitudinal, 45°, and lateral positions at 29 mm above plate surface.
Figure 78 Wear observations. Longitudinal - 11 mm above plate surface

Centre bowl liner: **Hadfield steel**

Top centre: **AISI 1053 steel**

**Depth below surface (µm)**

**Hadfield (austenitic) steel**

**AISI 1053 (pearlitic) steel**

Parallel to plane of rotation

- Work hardening
- Worn surfaces

Perpendicular to plane of rotation

- Hardness indentations
- Bakelite specimen mount material (black and grey colour)
Figure 79 Wear observations. Longitudinal - 18 mm above plate surface

Centre bowl liner: Hadfield steel
Top centre: AISI 1053 steel

Depth below surface (µm)

Hadfield (austenitic) steel
AISI 1053 (pearlitic) steel

Parallel to plane of rotation

Work hardening twins

Perpendicular to plane of rotation

Strain hardened layers at surface

Microhardness (HV 100g)
Figure 80 Wear observations. Longitudinal - 25 mm above plate surface

Centre bowl liner: **Hadfield steel**
Top centre: **AISI 1053 steel**

Depth below surface (µm)

**Hadfield (austenitic) steel**

**AISI 1053 (pearlitic) steel**

Parallel to plane of rotation

Perpendicular to plane of rotation

Work hardening twins

Strain hardened layers at surface
Figure 81 Wear observations. Lateral - 11 mm above plate surface

Centre bowl liner: **Hadfield steel**

Top centre: **AISI 1053 steel**

**Depth below surface (µm)**

**Hadfield (austenitic) steel**

**AISI 1053 (pearlitic) steel**

Heavily strain hardened layers at surface and deep into the subsurface

Strain hardened layers at surface
Figure 82 Wear observations. Lateral - 18 mm above plate surface
Centre bowl liner: **Hadfield steel**  Top centre: **AISI 1053 steel**

Depth below surface (µm)

**Hadfield (austenitic) steel**
- Parallel to plane of rotation
  - Work hardening twins

**AISI 1053 (pearlitic) steel**
- Perpendicular to plane of rotation
  - Strain hardened layers at surface
Figure 83 Wear observations. Lateral - 25 mm above plate surface

Centre bowl liner: Hadfield steel  
Top centre: AISI 1053 steel

Depth below surface (µm)

Hadfield (austenitic) steel  
AISI 1053 (pearlitic) steel

Parallel to plane of rotation

Work hardening twins

Perpendicular to plane of rotation
Figure 84 Cross-sectional SEM image of AISI 1053 steel top centre – TC1, longitudinal direction – perpendicular to plane of rotation. Figure 84b. is the same location but higher magnification than in Figure 84a.
Figure 85 Cross-sectional SEM image of AISI 1053 steel top centre – TC1, longitudinal direction – perpendicular to plane of rotation. Higher magnification than in Figure 84b.
Figure 86 Cross-sectional SEM image of AISI 1053 steel top centre – TC1, lateral direction – perpendicular to plane of rotation. Figure 86b. is the same location but higher magnification than in Figure 86a.
Figure 87 Cross-sectional SEM image of AISI 1053 steel top centre – TC1, lateral direction – perpendicular to plane of rotation. Figure 87b. is the same location but higher magnification than in Figure 87a.
Figure 88 Cross-sectional SEM image of AISI 1053 steel top centre – TC1, lateral direction – perpendicular to plane of rotation. Same location but higher magnification than in Figure 87b.
Figure 89 Cross-sectional optical micrographs of Hadfield steel centre bowl liner – CB5 (NB: micron bars = 20 µm):

a. longitudinal direction – perpendicular to plane of rotation. Same location but higher magnification than in Figure 79.

b. lateral direction – perpendicular to plane of rotation. Same location but higher magnification than in Figure 82.
6.3 Discussion

6.3.1 Polyethylene sample

There are only two polymers used in dry rubbing bearing applications that have a specific gravity less than water. These are polypropylene (0.93 g/cm³) and polyethylene (0.91-0.965 g/cm³). The melting point of the sample was 136.3 ºC. The melting point of polypropylene and high density polyethylene (HDPE) are 165ºC and 130-136 ºC, respectively, thus the sample is confirmed to be HDPE [80]. The degree of crystallinity for HDPE is normally between 40-80 % [81]. In this case it was 48.4 %.

The polyethylene liner was not greased prior to or during service. The black film observed could be coal dust and/or a polyethylene wear product. At this stage this was not determined. However, it is important to recognize that this film could affect the coefficient of sliding friction compared to the original product without the film. The full-scale frictional moment testing of a modified UHMW polyolefin polymer liner by Richmond also observed fine powder wear debris which spread into thin platelets over the surface [2].

There was no obvious evidence of wear to the HDPE centre bowl liner. The measured rim wall thickness was greater than nominal. This is consistent with the fact that the rail industry surveyed did not report any failures of polymer centre bowl liners due to wear.

6.3.2 Steel samples

The wear for all steel samples measured was greatest in the longitudinal direction. The wear in the lateral direction was negligible. This is also consistent with industry experience. It is thought that during the life of the centre bearing, the frequency of contact between the top centre and centre bowl liner in the longitudinal direction is
several orders of magnitude greater than the lateral direction. I am not sure how the rim loads compare in the longitudinal and lateral directions. Some trains tend to operate in mainly in one direction, so the leading edge may have greater wear than the trailing edge, which may have been the case for AISI 1053 steel top centre - TC2 (Figure 69).

The average wear depth rate for AISI 1053 steel top centre samples and Hadfield steel centre bowl liner samples were approximately 0.72 and 0.33 mm/year, respectively. The significance of this was discussed briefly in the selection of alternative materials in Chapter 3.

The calculated wear co-efficient for AISI 1053 steel top centre sample – TC2, and Hadfield steel centre bowl liner sample – CB6, were 3.0 x 10^{-4} and 2.3 x 10^{-4}, respectively. Thus, the wear can be classified as moderate [40]. The wear co-efficient values are consistent with the dry sliding wear of metallurgically compatible or partially compatible materials [43].

6.3.2.1 Work hardening of Hadfield steel centre bowl liners – CB2 and CB5

This part of the discussion is based on the hardness profile results presented in Figures 74 to 77, and Figures 78 to 83, respectively. The measured near-surface (20 μm depth) microhardness of a new cast and machined Hadfield steel centre bowl liner was 300 HV (100g). The microhardness at 20 μm depth varied from 400 to 650 HV (100 g). The hardness in the lateral and 45° directions ranged from 520 to 650 HV (100g). For sample CB2, the hardness in the longitudinal direction was 420 to 480 HV (100g), with the exception of the value measured at 29 mm above the plate surface of 300 HV which did not show any significant work hardening. This point was close to the top of the rim wall, so may have had limited contact. For sample CB5, the hardness in the longitudinal
direction was 500 to 550 HV (100g). It is clear that the Hadfield steel centre bowl liners have work hardened appreciably in all directions – longitudinal, 45° and lateral, for the three different heights above the plate contact surface compared to the nominal new hardness of 300 HV 100g. Similar hardening has been reported in Hadfield steel elsewhere via the following loading conditions: shot peening [82], dynamically loaded abrasive wear test [83], combined impact and sliding wear test [84], in the cutting zone of turning process [85], and near the fracture of tensile test specimens [86].

6.3.2.2 Microstructure of Hadfield steel centre bowl liner – CB5

The microstructures of all Hadfield steel samples as shown in Figures 78 to 83, and Figure 89a. and Figure 89b., showed evidence of intersecting deformation twins. A similar microstructure in Hadfield steel has been reported elsewhere due to the following loading conditions: shot peening [82], in the cutting zone of turning process [85], near the fracture of tensile test specimens [86], samples subject to tension [87, 88], and samples subject to compression [88, 89].

Hadfield steel is an austenitic steel having the face centred cubic (fcc) structure. It is a stable austenite, compared to medium manganese austenitic steels which are metastable. Subsequently, there was no strain- or friction-induced martensite present in the samples. This is in agreement with the work of others who also did not observe martensite phase in strain-hardened Hadfield steel. [82, 86, 87, 88, 89].
6.3.2.3 Microstructural and microhardness profiles of AISI 1053 medium carbon steel top centre – TC1

This part of the discussion is based on the results presented in Figures 78 to 83. The microstructural results show plastic flow of the pearlite grains near the surface towards a direction parallel to the surface. This plastic flow occurred in both the longitudinal and lateral directions, and parallel and perpendicular to the plane of rotation. Typically it was to a depth of around 50 µm. The core microhardness of the sample was 230 HV (100g). The microhardness was in the range of 230 to 300 HV 100g, with the exception of the measurement at longitudinal – 25 mm above plate surface which was 400 HV 100g. In most, but not all cases, there was some strain hardening.

6.3.2.4 High magnification microstructure of AISI 1053 medium carbon steel top centre – TC1

This part of the discussion is based on cross-sectional scanning electron microscopy of the AISI 1053 medium carbon steel top centre – TC1 as presented in Figures 84 to 88. The white cementite lamellae and grey ferrite matrix are highlighted in Figure 85. The micrographs (Figures 84 to 88) show the presence of surface cracks, and subsurface voids and cracks.

6.3.2.5 Wear mechanisms

A summary of the key features relating to wear of the components and subsequent comments / inferences are listed in Table 17. The hard surface of the Hadfield steel centre bowl liner when in sliding contact with the softer surface of the AISI 1053 steel top centre causes the surface and near subsurface of the AISI 1053 steel to plastically strain. The depth of plastic strain at the end of the component life was around 50 µm. It
is not clear whether the strain hardened layer causes shakedown, that is it contains residual protective stresses that upon re-loading at subsequent sliding events could result in the load being carried entirely elastically rather than plastically [39], during the component life. In any case, the micrographs (Figures 84 to 88) show the presence of subsurface voids and cracks, and surface cracks. The cementite lamellae are relatively hard particles in the pearlite microstructure. During plastic strain these can break. This could explain subsurface crack formation [25]. Figure 87b. appears to show voids that are becoming elongated due to shear deformation [25]. The large subsurface void highlighted in Figure 88 may have grown due to void coalescence. Also in Figure 88, it appears in that there is a crack adjoining a void. The large tensile stresses at the trailing edge of a dry sliding contact can assist opening of surface cracks present [35]. In summary, the wear mechanism for AISI 1053 steel top centre appears to be plastic strain accumulation in conjunction with surface crack-initiated and subsurface crack- and void-initiated low cycle fatigue.

Plastic strain has been accumulated in the Hadfield steel by twinning (Figures 78 to 83, Figure 89a. and Figure 89b). The Hadfield steel centre bowl liner has a lower wear rate compared to the AISI 1053 steel top centre due to the former having a significantly harder strain-hardened surface, i.e. higher shear yield strength. It is possible that the surface has reached the shakedown limit and most of the load was carried elastically. Assuming this is so, then subsurface crack- and void-initiated low cycle fatigue would be the wear mechanism. Surface cracking, that would suggest otherwise, was not observed in images taken by optical microscopy. Figures 78 to 83 show that the depth of detached wear particles from the surface appears to be of the order of 10 µm.
<table>
<thead>
<tr>
<th></th>
<th>AISI 1053 steel – top centre</th>
<th>Hadfield steel – centre bowl liner</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear co-efficient, K</td>
<td>3.0 x 10^-4</td>
<td>2.3 x 10^-4</td>
<td>Moderate wear</td>
</tr>
<tr>
<td>Normalised wear rate</td>
<td>5.7 x 10^-13</td>
<td>4.4 x 10^-13</td>
<td>Typical of unlubricated medium carbon steel (Figure 39) [53]</td>
</tr>
<tr>
<td>(m3/(N.m))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface hardness (HV 100g)</td>
<td>300</td>
<td>550</td>
<td>Hadfield steel work hardened in service and is significantly harder than AISI 1053 steel.</td>
</tr>
<tr>
<td>Surface and subsurface</td>
<td>Plastically strained surface to a depth of around 50 µm + subsurface voids/cracks</td>
<td>Work hardening twins at surface</td>
<td>Plasticity index, Ψ &gt; 1.0 [23], and μ &gt; 0.3-0.33 [35, 90].</td>
</tr>
<tr>
<td>microstructure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative surface</td>
<td>Rough</td>
<td>Smooth</td>
<td>Hadfield steel is well-known to provide a smooth work hardened surface.</td>
</tr>
<tr>
<td>roughness</td>
<td></td>
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</tbody>
</table>
6.4 Conclusions

Wear observations of a worn polyethylene centre bowl liner, AISI 1053 steel top centres, and several Hadfield steel centre bowl liners have been made. The conclusions that can be drawn from these wear observations are that:

1. the Hadfield steel centre bowl liner work hardened significantly in service and provided a smooth worn surface, and

2. the wear of the AISI 1053 top centre was due to plastic strain accumulation in conjunction with low cycle fatigue.