Evaluation of Surface Changes under Twin Disc Tests

Pär-Johan Lööf, Lucas Dambreville\textsuperscript{a,c}, Zlate Dimkovski\textsuperscript{a}, Per H. Nilsson\textsuperscript{b}, B.-G. Rosén\textsuperscript{a}

\textsuperscript{a}Halmstad University, Box 823, 301 18 Halmstad, Sweden (par-johan.loof@hh.se)
\textsuperscript{b}Volvo Group Trucks Technology, Gothenburg, Sweden
\textsuperscript{c}École Nationale d'Ingénieurs de Saint-Etienne, Saint-Etienne, France

Abstract:

In order to choose the right manufacturing process in terms of costs and component performance, three differently manufactured surfaces were investigated: brushed, multiple shot-peened and phosphated surfaces. In-house twin disc tribometer was used to test the wear and fatigue performance of the different surfaces. The evolution of the surface topography has been evaluated by in-line stylus and microscope image measurements as well as interference measurements of replicas taken at various test intervals. The form changes has been assessed by stylus measurements.

The results have shown that the surface roughness played the major role to wear and fatigue performance

Keywords: Twin disc, surface manufacturing, surface evolution, in line measurement

1. Introduction

In order to cope with new legislation demands, the automotive industry needs to improve the performance and durability of the components. More and more accent is put on the reduction of the fuel consumption which means reduction of the frictional losses of the components. 7-18% of the frictional losses come from the transmission systems from which about 55% is from the gear friction [1].

For gear designers, there are some basic design parameters in the macro scale that mainly affects the performance of a gear pair, and the micro scale effects of the surface in form of friction is taken into account in elastohydrodynamic lubrication (EHL) models to calculate efficiency. Although, the problem is often that high efficiency designs is performing poorly in means of noise, tooth breakage and pitting [2,3]. The second issue for a gear designer is to create a durable gear-design in the perspective of the surface to resist e.g. wear and pitting due to the rolling sliding motion between gears under high torque levels. Several models to predict and calculate [4,5,6] those fatigue problems for gear contacts operating under mixed elastohydrodynamic lubrication conditions exist, and one of the most important factors here is the manufactured surface. The properties of the manufactured surface is not given only from the chosen manufacturing method, e.g. grinding or shaving, but also from mechanical or chemical surface modification processes like phosphating to coat the surface with a protective layer of soft crystals and create oil-pits, or shot peening to induce compressive residual stresses improving performance [7,8,9,10]. Not to be forgotten is that those modification processes are not only adding surface properties, they are also removing traces from the original manufacturing process, like grinding streaks.

In the case of pitting, one of the most influencing factors is the real contact area and pressure spikes after run-in [4]. Usually, the smoother surfaces perform better [19,20], but the manufacturing cost increase with the finer surface finishes. It is therefore of interest to investigate how different alternative surface finishes manufactured by commonly used processes affect the performance.

The main goal of this paper is to screen the performance of brushed, multiple shot-peened and phosphated surfaces by using an in-house twin disc tribometer. For that, development of a procedure for in-line surface analysis is needed to better understand surface changes. The objectives to be fulfilled are to: (i) Rank the surfaces, (ii) Evaluate the wear performance (by monitoring the contact width), (iii) Evaluate the fatigue performance (by monitoring the pitting area).
2. Materials and methods

The samples used in this study were chosen to represent a base-surface and two commonly used surface modification methods, Multi Shot-Peening (MSP) and Manganese phosphating. For the Twin Disc test the dimensions of the two specimens are chosen to create a standardized reference contact scenario, possible to find in a real gearbox. The steel test material used is taken from gear manufacturing process but with a cylindrical geometry instead of the gear involute shape. Heat treatment and other processes is performed as for the real gear manufacturing.

2.1. Surface samples

In total three surface types were used in this study representing some of the most important manufacturing methods available in the gear manufacturing industry. The samples, manufactured from the same batch of material to the same macro-geometry, represents differences in both topography and mechanical properties in the initial state. Table 1 defines the sample types, and Figure 1 represents the initial surface.

Table 1. Sample combinations.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Base surface</th>
<th>Main effect of process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brushed – Brushed</td>
<td>Hard-turned</td>
<td>Very smooth surface</td>
</tr>
<tr>
<td>Multiple Shot-Peened - Multiple</td>
<td>Brushed</td>
<td>Characteristic structure, compressive residual stresses</td>
</tr>
<tr>
<td>Shot-Peened</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese phosphate – Manganese</td>
<td>Brushed</td>
<td>Etched dimples, crystal coated surface</td>
</tr>
<tr>
<td>phosphate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Initial sample surfaces. Top images are USB microscope photos and lower are profiles extracted from CSI measurements. From the left: Brushed, Multi Shot Peened and Phosphated

According to Table 1 the initial state of the samples is a hard turned and abrasive brushed surface. The purpose of this brushed surface is to mimic the ground surface currently used in gear production.

- Brushed gear surfaces typically has a linear pattern with a direction connected to the manufacturing process. This pattern, consisting of peaks and microvalleys is linked to the formation of micropitting, either through the plastically strained surface or stress concentration [10].
- Shot-peened gear surfaces has a directionless, continuous pattern. The (multi) shot-peening process induces compressive residual stresses increasing fatigue life. The level of induced stresses, and the pattern (including roughness) is depending on process parameters like media size and pressure [9,11,12].
- Manganese phosphated gear surfaces is initially covered with a layer of relatively soft crystals. Depending on process parameters like concentration of chemicals and process time the amount of etching of the surface varies removing the initial manufacturing i.e. grinding. An important impact on the surface is also the creation of dimples, able to retain oil into the contact area [13].
2.2. In-House Twin disc tribometer

The use of Twin disc testing to evaluate gear surface performance is a common practice [14,15]. Some of the benefits by using this simplified test method are the standardized geometry instead of a complete gear giving better control of contact conditions and the speed control.

The Halmstad In-house Twin disc (industrial scale) tribometer, fig 2., is designed to be able to handle medium sized samples, resisting high load and temperature during long test runs. Controllable parameters, see table 2, are relative speed for the two axes, incoming oil temperature, load between axes. The datalogging is done for rotational speed (sliding speed) and number of revolutions, load, temperature and torque.

To improve conditions, a spring package is included in the setup enabling small movements between upper and lower part. Not shown in fig 2. is the controllable external oil heating and filtering system.

![Fig. 2. Central area of Tribometer.](image)

2.3. Running conditions and procedure

Testing gear components using the Twin Disc method to simulate (chosen) conditions in a gear box requires a connection to the real world. In the tests performed, except for the different surfaces to be investigated, the steel is the same as in a typical commercial gear. The oil used is the base oil for gearbox oils commonly used but without additives, and the temperature for the incoming oil is kept at a temperature of 60 °C.

The geometry (radii 1 and 2 on test specimen) is defined to give the desired pressure according to Hertzian contact model.

The test cycle consists of a quite gentle running-in cycle (running-in is considered to be an factor affecting the overall performance [4,16]), i.e. gradually increasing the sliding velocity and load.

The inspection of the surfaces was done after stopping the test at shorter intervals in the beginning and longer intervals afterwards.

A summary of the conditions for the tests in this study is presented in Table 2 – Twin Disc parameters.
Table 2. Twin Disc Parameters.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main diameter of samples</td>
<td>80 mm</td>
</tr>
<tr>
<td>Initial contact width</td>
<td>1 mm</td>
</tr>
<tr>
<td>Load</td>
<td>4 kN</td>
</tr>
<tr>
<td>Oil, incoming temperature</td>
<td>SAE 90 base oil, 60 °C</td>
</tr>
<tr>
<td>Rotational speed slow/fast sample</td>
<td>600/900 rpm</td>
</tr>
</tbody>
</table>

2.4. Surface characterization

For the documentation and evaluation of the evolution of the surfaces during Twin Disc testing three different in-line technologies were used: profilometer, CSI on replica and USB microscope, see Fig. 3.

- **In-line profilometer**
  In-line 2D profile measurement was enabled using a portable profilometer (Mitutoyo Surftest) on a purpose built stand using a 2 µm/60° tip. The 2D profile can follow the form (wear/contact zone) and surface roughness.

- **CSI on replica**
  Using Coherence scanning interferometer [15] (MicroXam, ADE Phase Shift Technologies) in-line is only possible with the help of polymer replicas creating a 3D impression of the instantaneous surface structure. Measurements were performed using a 5X objective giving a measured area of 1652 x 1251 µm and a resolution of 2.2 µm in X, 2.6 µm in Y and 10 nm in Z. The pitting area, Sa and Svk was evaluated using the MountainsMap v.7 from Digitalsurf [17].

- **USB-Microscope**
  Portable USB microscopes from DinoLite gives a good overview, booth of the complete surface as well as smaller areas. Possible to evaluate using image analysis – but mainly a good way to give the human eye an understanding of the surface and its current state.

The measurement strategy was to keep track of four areas on each specimen (0°, 90°, 180°, 270°) under increasing intervals between stops. In Table 3 all the evaluation parameters are presented.
Table 3. Evaluation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lx</td>
<td>Contact width [µm]</td>
<td>Stylus</td>
</tr>
<tr>
<td>Ra / Sa</td>
<td>Arithmetic Mean Deviation of the roughness amplitude [µm]</td>
<td>Stylus / CSI</td>
</tr>
<tr>
<td></td>
<td>(According to ISO 4287:1 for profile and ISO 25178:2 for areal)</td>
<td></td>
</tr>
<tr>
<td>Svk</td>
<td>Reduced valley depth (roughness depth of the valleys) [µm]</td>
<td>CSI</td>
</tr>
<tr>
<td></td>
<td>(According to ISO 25178:2)</td>
<td></td>
</tr>
<tr>
<td>Rq</td>
<td>Root-Mean-Square (RMS) Deviation of the roughness profile [µm]</td>
<td>Stylus</td>
</tr>
<tr>
<td></td>
<td>(According to ISO 4287:1)</td>
<td></td>
</tr>
<tr>
<td>Pitting area</td>
<td>Part of measurement area identified as damaged [%]</td>
<td>CSI / USB microscope</td>
</tr>
</tbody>
</table>

3. Results

The measurements of the three different combinations evaluated in this study can be divided into two main parts, surface evolution and techniques for inline measurement of twin disc testing. Below the results are presented under the measurement technique used.

3.1. In-Line profilometer

Table 4 shows a summary of the results from profile analysis, initial value (1) and final value (2). The profiles have been zoomed into the contact zone and high-pass filtered using Gaussian filter (λc 0.25 mm). The analysis of the contact zone, table 4 and figure 4 is representing the change of form and contact width. The MSP surface presents the largest changes in terms of wear and roughness.

Table 4. Summary of profile analysis.

<table>
<thead>
<tr>
<th>Overall</th>
<th>In between</th>
<th>Smallest &amp; narrowest</th>
<th>Smallest &amp; widest</th>
<th>Gets rougher</th>
<th>Gets smoother</th>
<th>Upper vs Lower disk initially</th>
<th>Upper vs Lower disk after testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>After</td>
<td>after</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L (µm)</td>
<td>Rq (µm)</td>
<td>Ra (µm)</td>
<td>L (µm) (%)</td>
<td>Rq (µm) (%)</td>
<td>Ra (µm) (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brushed</td>
<td>1687</td>
<td>0.262</td>
<td>0.193</td>
<td>2036</td>
<td>21</td>
<td>0.194            -26</td>
<td>0.136               -30</td>
</tr>
<tr>
<td>Phosph.</td>
<td>2036</td>
<td>0.778</td>
<td>0.550</td>
<td>2443</td>
<td>20</td>
<td>0.678            -13</td>
<td>0.421               -24</td>
</tr>
<tr>
<td>MSP</td>
<td>1787</td>
<td>0.398</td>
<td>0.314</td>
<td>3116</td>
<td>74</td>
<td>1.285            223</td>
<td>0.722               130</td>
</tr>
<tr>
<td>Slow disc (Lower)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brushed</td>
<td>1762</td>
<td>0.277</td>
<td>0.220</td>
<td>2039</td>
<td>16</td>
<td>0.198            -29</td>
<td>0.146               -33</td>
</tr>
<tr>
<td>Phosph.</td>
<td>2125</td>
<td>0.798</td>
<td>0.539</td>
<td>2788</td>
<td>31</td>
<td>0.472            -40</td>
<td>0.252               -53</td>
</tr>
<tr>
<td>MSP</td>
<td>1692</td>
<td>0.395</td>
<td>0.318</td>
<td>3525</td>
<td>108</td>
<td>1.118            183</td>
<td>0.611               92</td>
</tr>
<tr>
<td>Faster disc (Upper)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brushed</td>
<td>1860</td>
<td>0.487</td>
<td>0.359</td>
<td>2784</td>
<td>50</td>
<td>0.596            22</td>
<td>0.336               -6</td>
</tr>
<tr>
<td>Phosph.</td>
<td>1892</td>
<td>0.557</td>
<td>0.486</td>
<td>3032</td>
<td>60</td>
<td>0.729            31</td>
<td>0.400               -2</td>
</tr>
<tr>
<td>MSP</td>
<td>1814</td>
<td>0.480</td>
<td>0.361</td>
<td>3114</td>
<td>72</td>
<td>0.814            70</td>
<td>0.449               24</td>
</tr>
</tbody>
</table>

The in-line profilometry technique works well to monitor form and 2D roughness, but is dependent on the accuracy of repositioning between measurements – 100% relocation is impossible and suggests a use of 3D measurements instead.
3.2. CSI on replica

Figure 5 shows the evolution of Pitting area, Svk and Sa. Those parameters described in Table 3 are identified using MountainsMap [17]: Fill in non-measured points, invert surface data (symmetry in Z), removal of form using 2nd order polynomial, Robust Gaussian filter with \( \lambda = 0.25 \) mm (gives Sa, Svk), threshold at 96% and binarize, sort grains with area \( \geq 500 \, \mu m^2 \) and form factor \( \geq 0.3 \) (gives Pitting area).
As can be seen in figure 5 a trend for each combination can be seen – increasing pitting area is followed by increasing roughness parameters. Once again the high wear rate on MSP combination gives large impact to the results – wear rate is faster than the development of (depth) in damages.

The CSI measurements on replicas is an efficient way of documenting and analyzing the evolution of the surface as a measurement technology. However – the analysis of surface damages is dependant on a clear definition between initial morphology and damages, that is to distinguish when a pit is from manufacturing or from fatigue, i.e. micropitting. This implies to also use the USB microscope as a help to identify properties of interest.

3.3. USB microscope

Figure 6 illustrates the evolution for the three combinations as visible to the eye, early (initial) state surface, “halfway” status and final appearance.

![Fig. 6. Example of visual surface evolution](image)

The USB microscope gives a good visual experience of the surface to understand the progression. Technically it is possible to use image analysis to evaluate the damages – but the residues on the surface appear at different color scales at each stop aggravating the actual use. The CSI technology is more beneficial for this task.
4. Discussion

Considering the results presented in table 4, figure 4 and figure 5, the in-line measurements in this kind of tests benefits from a combination of two or all three measurement techniques. For the 2D profiles the accuracy is hardware dependent (positioning) and for the grain analysis and roughness analysis performed from CSI 3D data the accuracy is highly dependent on filtering and sorting in the software – to have a correct separation between initial dimples and so on (both the phosphated and the MSP surface has a initial structure that might fool the analysis) and damages / fatigue that occurs from running the test procedure.

Anyhow the large part of the study was the evaluation of the different performance from the three different manufacturing techniques represented. The MSP had a wear rate high enough to more or less remanufacture the surface, continuously removing traces of fatigue or damages. Important to remember is that the tests were run with a additive free base-oil simulating a gear contact - but it seems that the smoother the initial surfaces are the better wear and fatigue performance will be.

5. Conclusions

The use of In-Line measurements provides useful information about the evolution of roughness, form and surface damage evolution. The three used techniques have their different properties but the results from them follows the same trend and provides information needed to follow wear and fatigue development of gear pairs.

From the three evaluated surface combinations in this study the following conclusions can be drawn:

- Smoother is better, the brushed (comparable to fine ground surface) “won” in this study.
- The form change – contact length – \( L_{\text{brush}} < L_{\text{phosp}} < L_{\text{MSP}} \)
- The MSP couple has a high wear rate, and gets rougher with time.

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6. Future work

The study performed has shown possibilities to use these techniques to evaluate the surface changes over the running time of surface fatigue tests to trace the initiation and growth of different surface fatigue phenomena. But there is work remaining and new future possibilities:

- Implement the procedure in other but similar applications, i.e. real gearbox testing.
- Repeated twin disc test – maybe introducing new oil or other factors affecting results.

References


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