Virtual Evaluation of Gear Manufacture –
To Use 3D Surface Data to Predict Performance

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Abstract

The manufacturing and finishing of gears include several processes such as grinding, hobbing, shaving, honing, shot peening and phosphating. For the automotive industry it is a constant challenge to improve the durability and reduce the fuel consumption in a cost effective way by using robust processes for mass manufacturing. A better knowledge of the properties of the manufactured surfaces in gears, and especially how they interact in different combinations is an important knowledge when designing gearboxes for the future. The following paper proposes an efficient way for choosing the better manufacturing and predicting the behavior of new combinations of process parameters in the early stage of the design process based on simulations of 3D surface measurements. The simulation model uses two rough surfaces of counterpart gear teeth contacting and deforming elastically under a typically critical load during operation. Outputs from the simulations are the pressure distribution and real contact area later used for ranking the differently manufactured surfaces. Four different types of surfaces were taken from manufacturing; samples were extracted and measured on a coherence scanning interferometer. Two surface types were ground differently and two were shot-peened with different process parameters. The results show the shot-peened surfaces, especially the double shot-peened type B1, performed better than the ground ones manifested in larger real contact areas and lower/fewer pressure spikes. Based on the correlations of the 3D roughness parameters with the simulation outputs, some roughness parameters are suggested for more robust quality control.

Keywords: rough surfaces, white light interferometer, elastic contact.

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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 two 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 surface modification processes like phosphating to coat the surface and create oil pits, or shot peening to induce compressive residual stresses for improved performance [7,8,9,10]. Not to be forgotten is that those modification processes is 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, but the manufacturing costs increase with the finer surface finishes. It is of interest to investigate how different surface finishes manufactured by commonly used processes affect the performance.

The main idea of this paper is to simulate the contact of the different surface finishes for prediction of the performance. The simulation model uses two rough surfaces of counterpart gear teeth contacting and deforming elastically [11] under a typical critical load during operation. Outputs from the simulations are the pressure distribution and real contact area, to be used for ranking. Another objective is to find what roughness parameters correlate with the ranking and to be recommended for more robust quality control.

What is not taken into account, more than from stochastic appearance, are the effects of manufacturing errors in the surface [12] e.g. unwanted physical peaks in the gear remaining after grinding.

2. MATERIALS AND METHODS

The samples for the simulation were chosen to be representative for some of the most common manufacturing methods, grinding – without any surface modification, and surfaces modified with double shot peening (DSP).

2.1. Surface samples

In total four different surface samples were used in this study, representing four different standard manufacturing processes in commercial gear production, all with significantly differences in topography hill-area and -volume, see Table 3. Table 1 defines the sample type, and Figure 1 visualizes the structure for the four sample types.

- A ground surface (Type A1 and Type A2 in Table 1 and Figure 1 below) on a gear has a linear pattern with a texture direction connected to the manufacturing process, usually parallel to gear tooth width. This pattern, consisting of (sharp) peaks and microvalleys, is linked to the formation of micropitting, either through the plastically strained surface or stress concentrations [10].
- A shot-peened surface (Type B1 and Type B2 in Table 1 and Figure 1 below) in this study, DSP [13]- has a directionless, continuous pattern. The shot peening process induces compressive residual stresses, increasing fatigue life. The level of induced stresses, and the pattern – or roughness – is depending on process parameters like media size and pressure [9,13,14].

<table>
<thead>
<tr>
<th>Surface sample</th>
<th>Manufacturing method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A1</td>
<td>Grinding type 1</td>
</tr>
<tr>
<td>Type A2</td>
<td>Grinding type 2</td>
</tr>
<tr>
<td>Type B1</td>
<td>Double shot peening type 1</td>
</tr>
<tr>
<td>Type B2</td>
<td>Double shot peening type 2</td>
</tr>
</tbody>
</table>

Figure 1: Visual characteristics of the four types of surface samples. A1 and A2 are ground while B1 and B2 are shot peened.

2.2. Surface characterization

Surface measurements were performed on a coherence scanning interferometer [15] (MicroXam, ADE Phase Shift Technologies). The measurements used in this study was performed using a 5x objective, giving a measured area of 1,6x1,2 mm and a resolution of 2,2x2,6 µm. The software used to condition the measurements is MountainsMap v.7 from Digitalsurf [16], and the measurements were processed in three steps:

- 4th order polynomial form removal
- Gaussian filter, 800 µm cut-off
- Outliers with slopes greater than 12 degrees removed

Outlier removal is a new function in MountainsMap v.7 to remove optical effects (spikes) in the measurements, which would result in unrealistic pressure spikes in simulations. This is also a suitable way for resembling surfaces that would have topographies close to those after run-in.
In table 3 some of the surface roughness parameters for the samples are presented (average of 10 measurements). The surface parameters used are in accordance to ISO 25178-2:2011 [17], shortly presented in table 2 below.

Table 2: Surface roughness parameters used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>Arithmetic mean deviation</td>
</tr>
<tr>
<td>Sz</td>
<td>Ten point height of the surface</td>
</tr>
<tr>
<td>Sds</td>
<td>Density of peaks</td>
</tr>
<tr>
<td>Ssc</td>
<td>Arithmetic mean summit curvature of the surface</td>
</tr>
<tr>
<td>Sha</td>
<td>Mean hill area</td>
</tr>
<tr>
<td>Shv</td>
<td>Mean hill volume</td>
</tr>
<tr>
<td>Sk</td>
<td>Kernel roughness depth (roughness depth of the core)</td>
</tr>
</tbody>
</table>

Table 3: Surface sample properties

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Sa</th>
<th>Sz</th>
<th>Sds</th>
<th>Ssc</th>
<th>Sha</th>
<th>Shv</th>
<th>Sk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A1</td>
<td>0.42</td>
<td>6.20</td>
<td>0.0044</td>
<td>0.0317</td>
<td>2642</td>
<td>106</td>
<td>1.2</td>
</tr>
<tr>
<td>Type A2</td>
<td>0.47</td>
<td>4.94</td>
<td>0.0035</td>
<td>0.0194</td>
<td>5038</td>
<td>126</td>
<td>1.34</td>
</tr>
<tr>
<td>Type B1</td>
<td>0.58</td>
<td>8.07</td>
<td>0.0026</td>
<td>0.0192</td>
<td>11709</td>
<td>834</td>
<td>1.84</td>
</tr>
<tr>
<td>Type B2</td>
<td>0.56</td>
<td>7.25</td>
<td>0.0029</td>
<td>0.0220</td>
<td>8099</td>
<td>481</td>
<td>1.78</td>
</tr>
</tbody>
</table>

2.3. Contact mechanics

As mentioned in the introduction there are several models to calculate surface durability, e.g. ISO 6336-2 [6]. The purpose of the model used in this study does not apply to do this work, instead the purpose is to have a simplified way to rank different combinations of gear surfaces – coming from different manufacturing methods. In Table 4 below, the inputs and outputs of the simulations for the surfaces (see Table 1) are presented.

Table 4: Inputs and outputs

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load: 1400 N/mm</td>
<td>Pressure distributions</td>
</tr>
<tr>
<td>Gear radii: 14 &amp; 11 mm</td>
<td>Peak pressures (1-8% percentiles)</td>
</tr>
<tr>
<td>Elastic modulus of 210 GPa (Steel)</td>
<td>Real contact area (%)</td>
</tr>
</tbody>
</table>

2.4. Simulation strategy

In this study, the simulations have been performed on surface type combinations from the same kind of surface, i.e. Type A1 in contact with Type A1, but on different discrete positions on gear tooth sample.

Despite that in reality there is an almost infinite number of surface, load and macro geometry combinations available throughout a real continuous contact, here only 10 combinations were simulated.

In Figure 2 the strategy for taking measurements on the gear flank – surface samples – and simulation combinations is presented.

Note that the form (local radius) on the gear flank is removed from the measurement data, and default radii is used for all combinations, see Table 4.

Figure 2: Illustration of measured area on gear flank and pairing strategy used in this study.

3. RESULTS

The simulations of the four surface types gives two outputs usable for ranking of surface combinations, Real contact area and Peak pressures. The Real contact area is considered the most useful measurement to predict performance.

3.1. Real contact area

Figure 3 shows the average real contact area (for ten simulations), and spread (± 1s), for the four surface combinations used in this evaluation. As a comparison, a virtual smooth surface is added as a reference. It can be easily seen that the surface type B1 has the largest contact area and points out on the most durable surface.
3.2. Pressure spikes

Figure 4 shows the average (maximum pressures) and spread at 1-8th percentile for the four surface combinations used in this evaluation. It is interesting to see that curve representing the surface type B1 is the lowest one (lowest maximum pressure spikes), confirming that it has more even contact distribution than the other surface types. It has also the lowest spread (± 1s) in the diagram.

3.3. Surface parameters

In Table 3, seven surface parameters are presented to put a number on the properties of the surface types. When correlating those parameters with the results in Figure 3 and Figure 4, four of them (Sk, Sds, Sha & Shv) follow the ranking, and one (Ssc) does not.

4. DISCUSSION

Considering the results presented in Figure 3 and Figure 4, it is worth noting that the best surface (Type B1) is not the smoothest one if the Sa (see Table 3) is considered as a general roughness parameter. This implies that “the smoother, the better” is not always true as the surfaces have more complex 3D nature and function. However, the parameters Sk, Sds, Sha and Shv follow the ranking i.e. show functional correlation. The Ssc parameters which was found [18] to be correlated with the function of the cam-roller contacts shows no correlation for the gear surfaces used in this study.

5. CONCLUSIONS

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

- The double shot-peened TypeB1 surface was the best combination.
- Surface parameters Sk, Sds, Sha & Shv are following the ranking and should be used for quality control.
- The simulation method in this paper shows potential to rank differently manufactured gear surfaces from a durability perspective.

Acknowledgements

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6. Future work

The study performed has shown possibilities to use this model for ranking, but there is work remaining in different aspects:

- Increased number of simulated and evaluated surface combinations from different manufacturing methods.
- Verify this simplified ranking method both experimentally and with expected performance for familiar combinations of manufactured surfaces.

7. REFERENCES


