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Influence of surface finishing on the tribological application behavior using the example of cylindrical gears

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Abstract
Surface finishing has a considerable impact on the application behavior and lifetime of bearings and gears. Using the example of cylindrical gears, it is shown that the tribological behavior in tooth flank contact is influenced through variations in grinding, polishing or milling of the gear pair. For this purpose, three identical tooth flanks with varying surface finishes were measured and digitized using a confocal microscope. Furthermore, these surfaces were used for micro-hydrodynamic simulations conducted with the software Tribo-X from Tribo Technologies to ascertain the solid contact pressure curve and the pressure as well as the shear flow factors in x- and y-direction. Subsequently, these characteristic curves which are necessary for the cylindrical gear simulations. In this analysis, the gear geometry, the interacting surface, the load and the lubricant are taken into account. As a result, e.g. the maximum solid contact pressure, minimum film thickness, coefficient of friction, frictional power and maximum temperature are obtained. In terms of increasing efficiency, resource-efficient production and sustainability, these results are important indicators. For example, the surface finish can be optimized to possess ideal properties with regard to the necessary material processing (costs) and the required tribological properties (efficiency). Another interesting research focus is the comparison of the surface textures of conventional manufacturing technologies such as gear polishing and grinding with those produced by innovative technologies such as the precise electrochemical machining (PECM). The approach enables a direct comparison of these machining processes with their specific surface textures to the tribological application behavior of gears. Our objective is a cross-technology evaluation of machining processes to facilitate optimal selection based on energy, production technology and resource efficiency.

Keywords: surface texture, grinding, polishing, spur gears, micro-hydrodynamic, numerical analysis, FEM

1. Impact of surface finishing

The surface finish of bearings or gears has a significant influence on their application behavior. This influence goes so far that an appropriate surface finish can significantly reduce wear and increase the lifetime or load-bearing. In addition, adapted surfaces can also minimize frictional losses and thus save energy.

In this context, it is interesting to note that each manufacturing process has its own special manufacturing texture. Figure 1 shows a helical spur gear with a detail of the surface texture.

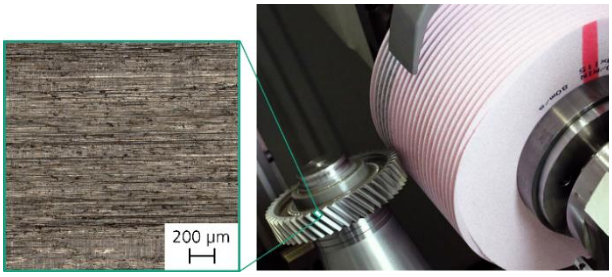

Figure 1. Helical spur gear with an enlargement of the surface texture

In order to gain a better understanding of surface textures in application behavior, a polished gear, a ground gear and a milled gear are compared with each other in this work. This is followed by an evaluation and discussion.

2. Numerical investigation with Tribo-X

The numerical investigations were carried out using the 3D Thermal Elastohydrodynamic (TEHD) simulation software Tribo-X from the company Tribo Technologies [1-2]. This software provides an insight into the frictional contact and supplies specific numerical values of important tribological properties, like lubrication gap height, frictional force, friction coefficient, maximum temperature and many others. Using the tribology software, the influences resulting from the gear geometry, the tooth flank surface, the load and the lubricant can be taken into account. Figure 2 shows a schematic overview.

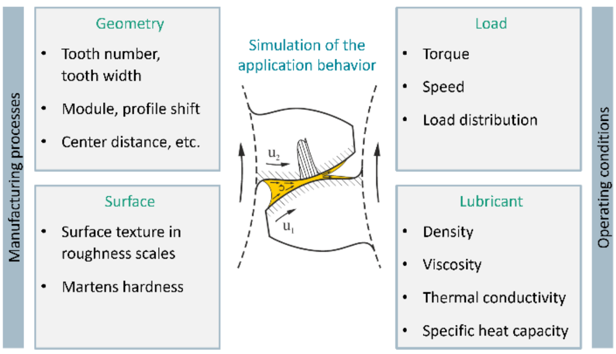

Figure 2. Overview of important properties on the tribological gear contact (picture in the center from Tribo Technologies)

In this paper, the influence of different tooth flanks resulting from the manufacturing process is examined in detail.

The application behavior of the polished, ground and milled gear pair is characterized using a defined gear geometry, a uniform load spectrum and an reference oil. The method is as follows. First, tooth samples are taken from polished, ground and milled gears using wire erosion. The surfaces are measured and important material parameters are determined. In a second step, simulations are carried out with Tribo-X using the MicroSim module for microhydrodynamic simulations. This allows to calculate the solid contact pressure curve and the pressure as well as the shear factors in the x- and y-directions. This micro-hydrodynamic data can then be used in the third and final step to simulate the application behavior in tooth flank contact.

2.1. Surface measurement with confocal mircroscope

In the following, the previously mentioned surfaces are measured using the confocal microscope MarSurf CM mobile from Mahr. Figure 3 shows perspective views of a polished and a ground tooth flank surface.

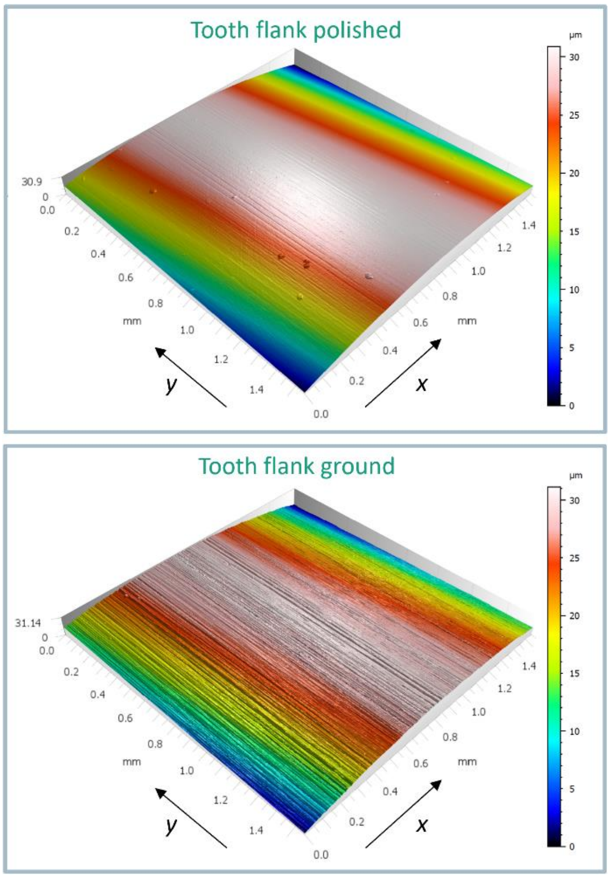

Figure 3. Surface structure for polished and ground tooth flanks

As can be seen, both surfaces have a characteristic manufacturing texture. The roughness values are evaluated according to DIN EN ISO 25178 and DIN EN ISO 21920. For the filter settings, a value of λ_s = 0.8 µm was used for the short-wave filter and a value of λ_L = 0.8 mm for the long-wave filter. The shape of the surface was removed by a 3rd degree polynomial. As a result, the roughness values of the ground surface are on average 10 times greater than those of the polished surface, see table 1.

Table 1 Roughness evaluation according to DIN EN ISO 25178 and DIN EN ISO 21920

DIN EN ISO 25178	**polished**	**ground**	**milled**
S_a [µm]	0.039	0.407	0.478
S_k [µm]	0.108	1.344	1.510
S_{pk} [µm]	0.083	0.314	0.671
S_{vk} [µm]	0.071	0.611	0.564
DIN EN ISO 21920	**polished**	**ground**	**milled**
R_z [µm]	0.444	2.662	3.932
R_a [µm]	0.046	0.397	0.466

2.2. Determination of Martens hardness with nanoindentation

Next, important material parameters are determined by measuring the Martens hardness with the FISCHERSCOPE HM2000. For the simulation with Tribo-X using the MicroSim module, the elastic indention modulus and the plastic flow pressure are required in particular [1]. Note that the plastic flow pressure corresponds to the Martens hardness HM determined from the ultra-microhardness measurements.

$Y_{HU} = E / (1 - v^2)$ elastic indention modulus (1)

$p_{c,lim}$ plastic flow pressure (2)

2.3. Characterization of micro-hydrodynamics

Using MicroSim, the mixed friction maps are calculated. These include solid contact pressure curves, pressure and shear flow as well as shear stress factors in x- and y-direction. The definition of the factors can be found in [1]. All calculations are based on the three-dimensionally measured surface textures. Figure 4 shows the pressure flow factors in x- and y-direction over the deformed gap height.

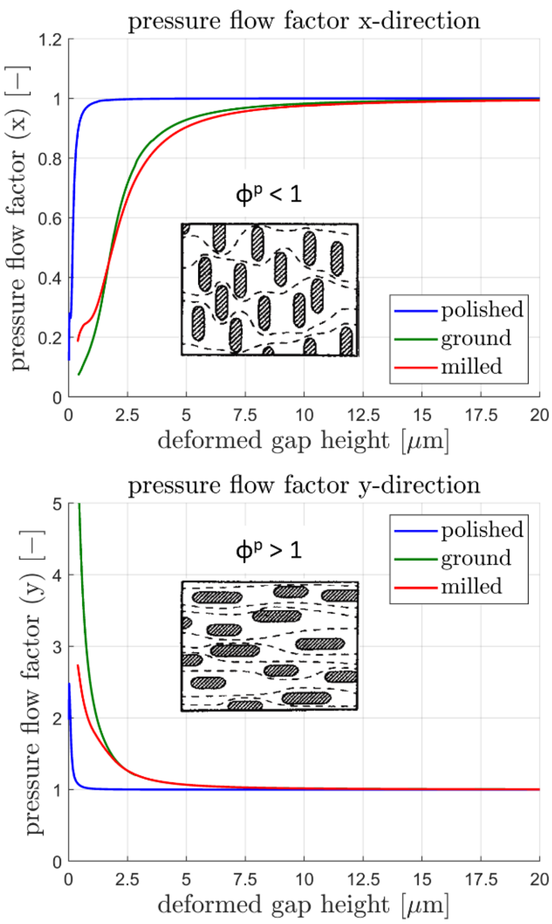

Figure 4. Pressure flow factors in x- and y-direction for different surface textures (small pictures in the center from [1])

The diagrams illustrate a clear difference in the curves. The pressure flow factor is dimensionless and can be interpreted as the ratio of the mass flow in the rough gap to the mass flow in the smooth gap. For example, the pressure flow factors of the polished surface show a much steeper increase than those of the ground surface. In order to better understand the effects of different surface textures, micro-hydrodynamic simulations with milled surfaces were also analyzed (red curves).

3. Simulation of the tribological application behavior

After completion of all surface measurements and determination of mixed friction parameters, the application behavior in tooth flank contact can be calculated with Tribo-X using the Cylindrical Gears module. This involves recording both the gradual tooth engagement and disengagement of the teeth with helical gearing by dynamically adjusting the contact surface. For the TEHD simulation reference oil ISO VG 150 was used as lubricant. For more information regarding the reference oil ISO VG 150 and its physical properties, such as density, viscosity, thermal conductivity and specific heat capacity, see [1,3]. The maximum normal force was 5231.36 N and the rotational speed was 1485 rpm. Observe that the force was gradually increased and reduced over the standardized line of action (Sloa). Table 2 lists the most important geometry parameters of gear 1 and gear 2.

Table 2 Helical gear pair

Normal modulus	m_n	3 mm
Normal pressure angle	α_n	20°
Helix angle	β	20°
Number of teeth gear 1	z_1	24
Number of teeth gear 2	z_2	61
Gear ratio	i	2.542
Center distance	a	137 mm
Addendum modification gear 1	x_1	0.3125
Addendum modification gear 2	x_2	0.1404
Width of gear 1	b_1	27.5 mm
Width of gear 2	b_2	27.5 mm
Crowing gear 1	δ_{sph1}	8 µm
Crowing gear 2	δ_{sph2}	8 µm
Transverse contact ratio	ε_α	1.454
Length of action	g_α (AE)	13.596 mm

Using Cylindrical Gears module a large number of different variables along the tooth engagement path can be calculated. These include, e. g. maximum pressure, maximum solid contact pressure, solid contact load ratio, minimum film thickness, coefficient of friction, frictional force, frictional power and mean as well as maximum temperature.

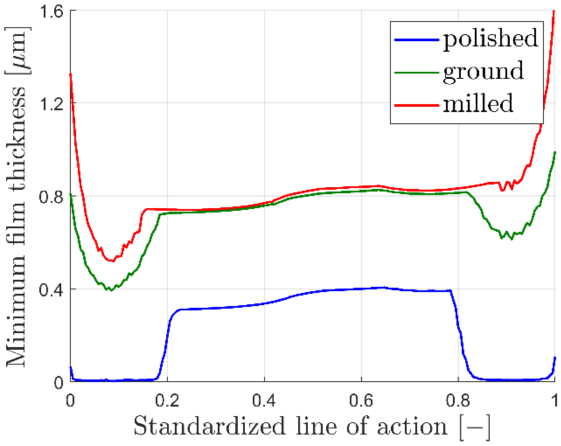

Figure 5. Minimum film thickness over standardized line of action for three different surface textures

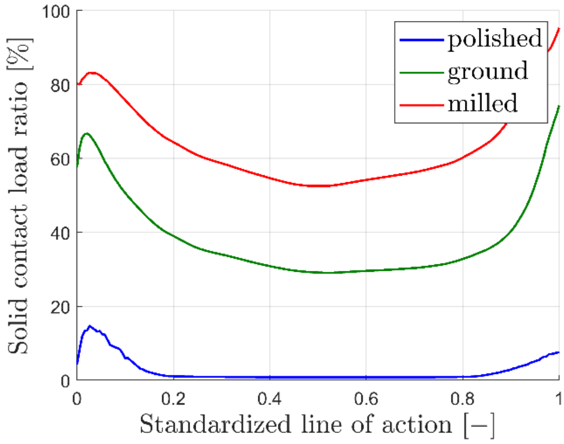

Figure 6. Solid contact load ratio over standardized line of action for three different surface textures

Figures 5 and 6 show the minimum film thickness over the standardized line of action and the solid contact load ratio over the standardized line of action for three diferent surface textures.

The following insights can be obtained from the figures:

- The valleys at the beginning (0 - 0.2) and at the end (0.8 - 1) of the minimum film thickness diagram show the influence of the tooth engagement and disengagement.
- A smaller minimum film thickness does not necessarily lead to a high solid contact load ratio or a maximum solid contact pressure.

Next, the coefficient of friction and the frictional power of the various surface textures are compared, see figure 7.

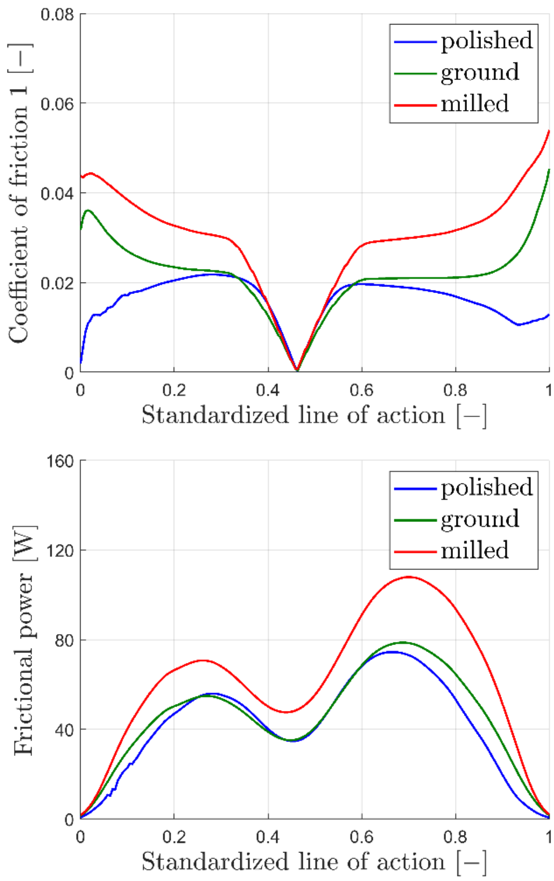

Figure 7. Coefficient of friction and frictional power over standardized line of action for different surface textures

The diagrams illustrate that the polished surface has the lowest and the ground surface texture the highest coefficient of friction and frictional power in direct comparison. The reversal point at approx. 0.5 of the standardized line of action in the friction coefficient diagram can be explained by the change of sign of the frictional force at the rolling point [2]. It is interesting to observe that despite the different coefficient of friction, the frictional power between the polished and ground surface is almost the same. Using these evaluations, surface textures can be selected on the basis of a weighted objective function not only from a tribological but also from an energetic point of view. For example, a surface texture can be optimized in such a way that it has ideal properties in terms of solid contact load ratio Lo_c and frictional power P_f. If these variables are integrated over the standardized line of action g_α, the objective function f to be optimized is obtained. A factor $\alpha \in [0, 1]$ can be used to weight the objective function terms differently.

$$f := \alpha \int Lo_c(g_\alpha)\, dg_\alpha + (1 - \alpha) \int P_f(g_\alpha)\, dg_\alpha \tag{3}$$

Basically, this procedure and the definition of corresponding objective functions can be used to perform a qualitative evaluation of all important influencing variables. However, it should be noted that the results shown here only apply to a fixed gear geometry (see table 2), a fixed load type and the reference oil.

4. Design approaches for future surface finishes

In further studies, models are to be developed which enable the design of new adapted surface textures which can be used instead of the measured and digitized tooth flank surfaces [4]. This approach allows the identification of favorable surface textures at an early stage and the optimal selection of the corresponding manufacturing process parameters. Figure 8 shows an example of a synthetically generated ground surface texture.

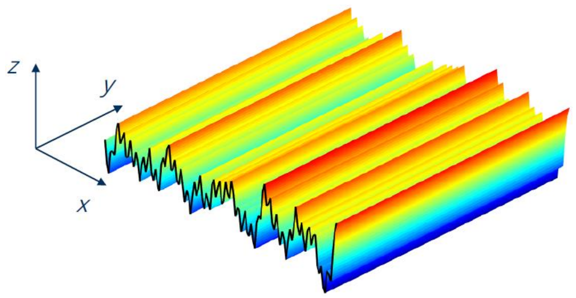

Figure 8. Synthetically generated ground surface texture

The aim is not to obtain the lowest roughness values (see table 1), but the values required for tribological application behavior.

5. Summary and outlook

In this publication, the influence of three different surface textures (polished, ground, milled) on helical gears was investigated. This was carried out using the tribology software Tribo-X, which provides an insight in tooth flank contact taking into account the geometry, the load, the surface texture and the lubricant. The results indicate that the surface textures have a strong influence on the tribological application behavior. In particular, the minimum film thickness and the coefficient of friction are strongly influenced by the surface texture. In addition, a low minimum film thickness does not necessarily lead to a high solid contact load ratio.

The numerical results provide an important insight how manufacturing technologies effect the application behavior. Moreover, efficiency (reduction of coefficient of friction in tooth flank contact and frictional power) can be improved by adapting the surface texture.

In future work, the numerical results described here are to be validated with experimental results on a tribometer. In particular, the friction behavior and friction performance are to be tested. Furthermore, the simulation findings in combination with experimental data enable a targeted choice of manufacturing strategy. As a consequence, it no longer needs to be as smooth as possible, but only as fine as necessary. This enables targeted savings in production costs and resources.

In addition, surface textures from other manufacturing technologies such as EC-machining [5] are to be compared with conventional ones. This enables a cross-technology evaluation of machining processes based on energy, production technology and resource efficiency. Finally, the manufactured surfaces are to be used to evaluate the operating life in order to relate the impact of manufacturing with the operation life.

Acknowledgements

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