VIRTUAL HOBBING

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SUMMARY

Hobbing is a widely used machining process to generate high precision external spur and helical gears. The life of the hob is determined by wear and other surface damage. In this report, a CAD approach is used to simulate the machining process of a gear tooth slot. Incremental removal of material is achieved by identifying contact lines. The paper presents an example of spur gear generation by means of an unworn and a worn hob. The two CAD-generated gear surfaces are compared and showed form deviations.
Keywords: gear machining, CAD, simulation

1 INTRODUCTION

The quality and cost of high precision gears are aspects which are constantly of interest. Demands stemming from increasing environmental awareness, such as lower noise and improved gear efficiency, are added to traditional demands to create (MackAldener [1]) a challenging task for both manufacturers and designers. To be able to adjust to these demands, a design must be robust; that is, it must deliver the target performance regardless of any uncontrollable variations, for example manufacturing variations.

Manufacturing variations can include geometrical variations caused by imperfections in the manufacturing process, for example, wear of tools. The geometrical deviations of each part must be limited by tolerances in order to ensure that the functional requirements are met. According to Bruyere et al. [2], tolerance decisions are of great importance for the quality and cost of gears. Szczepanski et al. [3] state that gear tolerances must be closely adhered to during the early soft working processes, such as hobbing, to ensure proper mesh operation. In order to allow analysis of the tolerances applied to gears, each step in the manufacturing process must be optimized. Better understanding of the geometrical variations would facilitate tolerance decisions, and make it easier to meet new demands.

Gear manufacturing consists of several operations; table 1 shows an example of a gear manufacturing sequence for high precision external spur or helical gears.

Table 1. Example of a gear manufacturing sequence for high precision external spur or helical gears, adapted from Amini [4]. Soft working operations are shaded.

Casting
Turning
Hobbing
Hardening
Grinding
Honing
Assembly

In gear hobbing, the surface is obtained as the envelope of a series of cutter surfaces formed during a continuous motion between workpiece and cutter. A recent literature study showed a number of different possible ways to generate gear surfaces. One example employs analytical methods, using coordinate transformation and differential geometry to determine the tool surface [5]. These methods give precise solutions, but it is necessary to specify the tool with a mathematical model. A worn hob, for example, would require complex new analytical models.

Another approach is to use CAD software. According to Mohan el al. [6], the literature describes only a few attempts at using the CAD approach to simulate the generation machining process and identify the contact lines of conjugate action. Mohan et al. demonstrated the capability of the CAD approach by taking simple cases of helical groove machining with disc-type and pencil-type cutters and a complex case of worm gear machining. Michalski et al. [7] presented a computer simulation method for modeling the tooth flanks of hobbed gears; the hob was modeled as a worm.

The present study describes a CAD approach to studying the geometrical deviations caused by a worn hob. Ideal conditions were simulated, and hence surface effects resulting from moving or removing material, such as elastic deformations and machine settings, were not considered.

2 MANUFACTURING OF GEARS

2.1 Generation of involute curves by hob

Hobbing is a widely used machining process to generate involute gear profiles. It is based on rack-cutter generation [5]. The rack-cutter profile is a cutting edge whose straight sides and fillets machine the flanks and the gear fillet respectively. A hob (figure 1) is comparable with a non continuous screw thread, where grooves for chip transfer are made at an angle along the axis to form a series of cutting edges.

Figure 1. Picture of a hob.

The involute gear profile is generated in a continuous rounding process in which wheel and hob rotate in fixed ratios. The angles φ_o and φ of hob and workpiece rotations are related as follows [5]:

$$\frac{\varphi}{\varphi_o} = \frac{N}{N_o} \quad (1)$$

where N is the number of gear teeth and N_o is the number of hob threads. The lead angle of the hob is determined as [8]

$$\gamma_o = \arcsin\left(\frac{m_{no} \cdot N_o}{d_o}\right) \quad (2)$$

where m_{no} is the normal module and d_o the hob pitch diameter. The pitch value p specifies the distance traveled by the helix in one turn:

$$p = \pi \cdot m_{no} \qquad (3)$$

The angle through which the hob is swiveled is known as the swivel angle. The swivel angle is determined by the lead direction of the hob and the workpiece. The equation for the swivel angle reads as follows [9]:

$$\eta = \beta \pm \gamma_o \qquad (4)$$

The swivel angle for spur gears is equal to the lead angle of the hob [10].

It is possible to change the straight sided rack form to generate a modified gear tooth form. This is achieved by means of a protuberance; a modification of the hob reference profile near the top of the hob tooth which generates undercut at the bottom of the tooth of the workpiece [11]. The hob reference profile is the normal section of the teeth of the basic rack tooth profile [9]. The dimensions of the reference profile for a protuberance hob are given in figure 2.

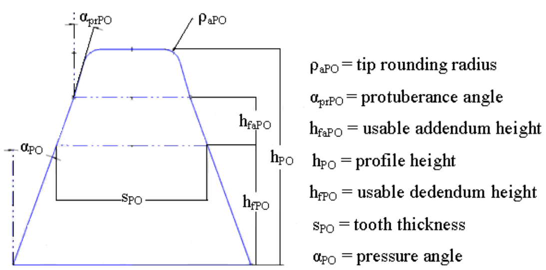

Figure 2. Hob reference profile in the normal section.

Nomenclature

φ_o	angle of rotation for hob
φ	angle of rotation for workpiece
N_o	number of hob threads
N	number of gear teeth
γ_o	lead angle
m_{no}	normal module for hob
m_n	normal module for workpiece
d_o	pitch diameter for hob
d	pitch diameter for workpiece
p	pitch value
η	swivel angle
β	helix angle
a	distance between workpiece and hob
l	distance the hob will move
s	feed
b	workpiece face width
α_n	standard normal pressure angle
n	number of chip grooves

3 THEORY

3.1 Simulation of generation machining

The simulation was carried out in Solid Edge [12], which is a 3D CAD parametric feature solid modeling software. In this CAD approach, the hob was first modeled as a cylinder. From the reference profile, a *helical protrusion* created the hob teeth with or without modified teeth failures and a *lofted cut out* created the grooves. The grooves were at an angle γ_o along the axis. The number of chip grooves n was set to 16. The workpiece was modeled as a cylinder, initially blank. For reasons of computer capacity and time saving, a piece just big enough to generate a gear tooth slot was used (figure 3). The simulation differed from the real hobbing machining process in that the workpiece was stationary and the hob was transferred around the workpiece. However, the same relative motions were modeled as in the real machining process.

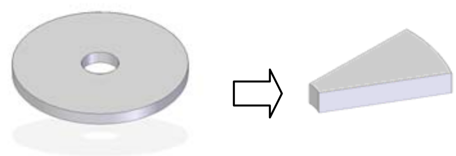

Figure 3. The modeled workpiece.

The hob and workpiece were moved to an assembly environment where an animation program was used to set the joints and relative motions. After the simulations of the hobbing process, the interferences were converted into solid models and then subtracted from the workpiece by Boolean operations.

Figure 4 shows the coordinate systems used in the simulation. Coordinate system S_w corresponds to the workpiece, which was stationary and was set as a reference. The initial coordinate system S_h corresponds to the hob. The constant distance a between hob and workpiece was determined as

$$a = \frac{d_o}{2} + \frac{d}{2} \qquad (5)$$

where d_o and d are the pitch diameters for hob and workpiece respectively, calculated using SS 1863 [13]. The swivel angle was set to γ_o, and so according to equation (4) the helix angle β_o was zero. The swivel angle was obtained by rotating the coordinate system for the workpiece about the z_w axis by an angle of γ_o. The hob will translate a distance l in the negative direction of y_w, half the distance $l/2$ is marked out in figure 4.

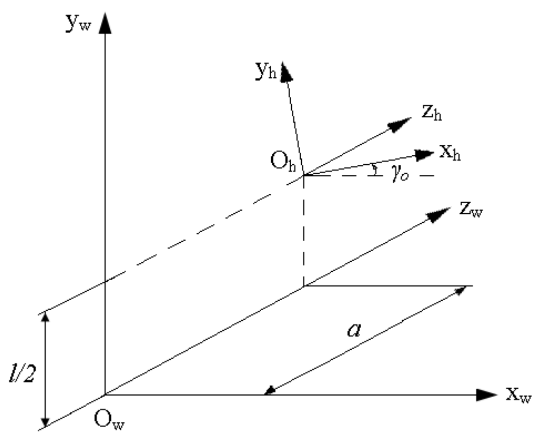

Figure 4. Coordinate system for the workpiece, which was also set as a reference system and as the initial coordinate system for the hob. The constant distance a, the axial feed length l/2, and the swivel angle γ_o are shown.

The kinematics of the simulation process are shown in figure 5. There was no interference between hob and workpiece in the start and stop positions. The hob was rotated in the opposite direction to the feed of the hob relative to the workpiece.

The rotary feed was set so that the workpiece rotated one circular pitch while the single thread hob rotated one revolution. The axial feed was determined from the feed s, the axial distance the hob would move for one revolution of the workpiece. The cutting speed was determined from the axial feed and the time taken for the hob to rotate one revolution. Given knowledge of the feed length l and the axial feed, the time for running the simulation was then set.

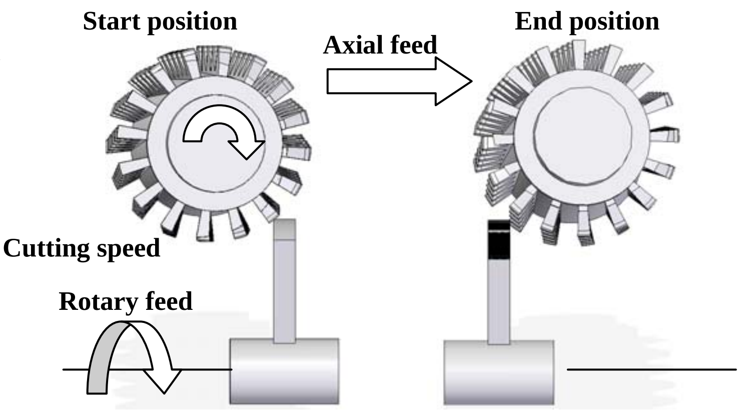

Figure 5. The kinematic motions; axial feed, cutting speed, and rotary feed are marked. The hob rotates around the workpiece and creates the same relative motion as if the workpiece were rotating.

The virtual gear generating simulation was carried out as follows:

1. The hob performed the relative motions and the interferences were identified.
2. The interferences were converted into solid models.
3. The solid models were subtracted from the workpiece by Boolean operations.

4 RESULTS

An unworn hob and a reconstructed hob with surface damage near the top of the tooth were used in the simulations to generate a spur gear tooth slot. The reconstructed hob was motivated by a real hob with surface damage; see figure 6, taken from Gerth [14]. In order to allow comparison with previously reported results [6, 7], the simulation of the generating process was performed again using a hob without grooves along the axis (figure 7).

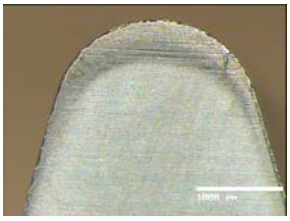

Figure 6. Characteristic wear is shown on the rake face of the hob [14].

Figure 7. The hob without chip grooves.

The surface damage was defined on the hob tooth reference profile in the form of cylindrical cuts; see figure 8. The diameters of the cylinders ranged from 10 to 100 µm.

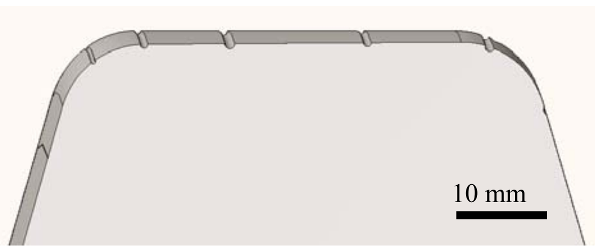

Figure 8. A reconstructed hob for imitating a worn hob. The picture shows the top of the tooth (the protuberance).

The workpiece terms, the machining data, and the hob data are presented in tables 2, 3, and 4, respectively. All data were motivated by real gear manufacturing and adapted for the simulation environment.

Table 2. The workpiece terms.

Pitch diameter	d	130	mm
Face width	b	10	mm
Number of teeth	N	26	
Standard normal pressure angle	α_n	20	deg
Normal module	m_n	5	mm
Helix angle	β	0	deg

Table 3. Machining data.

Feed length	l	70	Mm
Feed	s	3.5	mm/gear revolution

Table 4. The protuberance and hob data.

Tip rounding radius	ρ_{aPO}	20	deg
Protuberance angle	α_{prPO}	16	deg
Usable addendum height	h_{faPO}	2.5	mm
Profile height	h_{PO}	11.25	mm
Usable dedendum height	h_{fPO}	6.25	mm
Tooth thickness	s_{PO}	7.85	mm
Pressure angle	α_{PO}	20	deg
Normal module	m_{no}	5	mm
Pitch diameter	d_o	80	mm
Lead angle	γ_o	3.58	deg
Number of threads	N_o	1	
Number of grooves	n	16	

The two generated gear surfaces are presented in figure 9. It is possible to see regular surfaces resulting from the subtracted parts. Sharp edges can be seen on the surface. The distance between two sharp edges near the top of the generated gear tooth, for example, is the same as the distance the hob would move for one revolution of the workpiece.

The gear surface generated by the unworn and worn hob had equal surface structures, apart from the leftover material produced by the cylindrical cuts on the reconstructed worn hob. The gear flanks were not influenced by the surface damage on the hob.

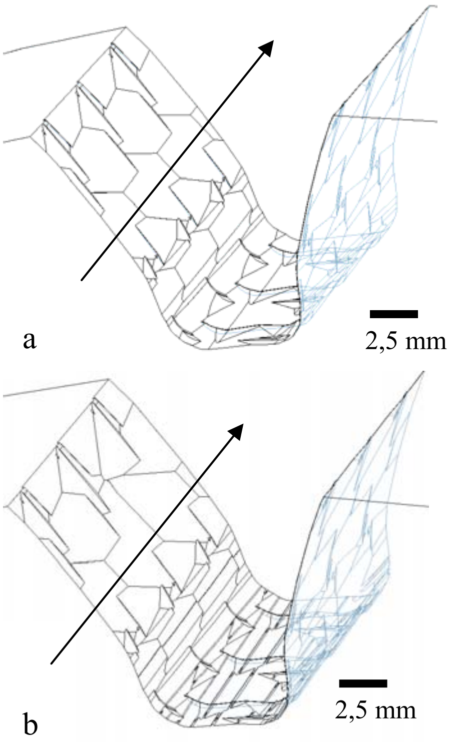

Figure 9. The generated surfaces using (a) a hob without surface damage and (b) a hob with surface damage. The hob translates in the direction indicated by the arrow.

From the different view presented in figure 10 it is possible to see form deviations on the gear surface generated by the hob with surface damage. These form deviations are similar, but the other way around, to the ones found on the worn hob. In figure 10, an irregular removal of material is visible in the bottom land of the gear tooth slot.

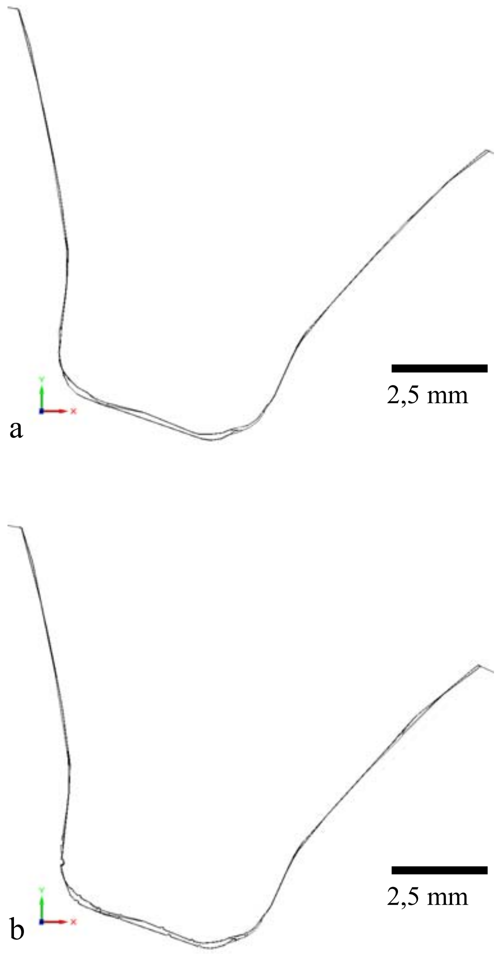

Figure 10. The generated surfaces using (a) a hob without surface damage and (b) a hob with surface damage.

Figure 11 presents the generated surface using a hob without chip grooves. The regular surfaces are more continuous compared to the generated surfaces in figure 9.

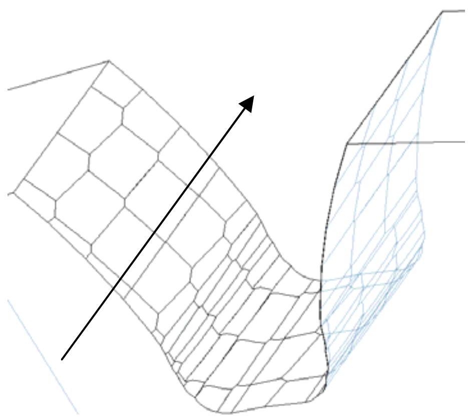

Figure 11. The generated surface using a hob without chip grooves. The hob translates in the direction indicated by the arrow.

From the view in figure 12 it can be seen that there is less leftover material on the surface generated by a hob without chip grooves compared to the generated surfaces in figure 10.

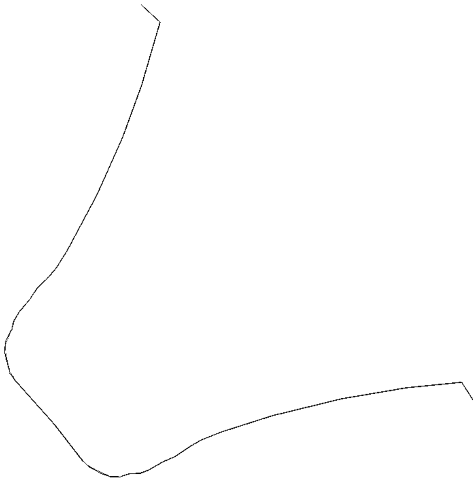

Figure 12. The generated surfaces using a hob without chip grooves.

5 DISCUSSION

Analytical methods require complex mathematical models to describe a tool with surface damage. The CAD approach simplifies the modeling of surface damage on a tool. Irregular machine parameters and different sources of machine error, such as oscillation coming from the machine settings, can also be simulated with CAD.

The hob tooth in this study could have been given any surface damage, but due to computer limitations only a few simple surface alterations were made.

Using the *motion* program in the Solid Edge software package, the discrete number of frames per time set strongly influenced the accuracy of the surface. The sharp edges on the surface can be explained by the use of a discrete number of frames, meaning that the material removal was not continuous. This CAD approach would need a complement in the form of a wear simulation to ensure proper material removal.

The sharp edges on the gear surface may be due to the feed *s*; see figure 9. The distances between the sharp edges in the direction of the axial feed are the same as the distance moved by the hob during one revolution of the workpiece. The two CAD-generated gear surfaces are compared and showed form deviations. These form deviations are similar to, but mirror images of, the ones found on the worn hob. The gear flanks were not affected by the surface damage on the hob tooth.

In order to allow comparison with previously reported results [6, 7], the same simulation generating process was performed using a hob without grooves along the axis. A tool without grooves is a tool with no cutting edges, which will give a more continuous material removal and be less influenced by the set of frames. Hence, no sharp edges were found on the generated gear surface using a hob without chip grooves. This is more comparable with a grinding process, which does not occur in hobbing.

In this study, ideal conditions were simulated; and so real surface effects caused by, for example, elastic deformations and machine settings when moving/removing material, were not considered. If an ideal generated surface can be identified, it can be used in studies of real manufactured surface structures, since it can be removed from the real surface structure to leave only the errors introduced by elastic deformations and the machine settings.

This CAD approach could also provide a simple tool to understand the gear generation process and the importance of accurate machine parameters such as axial feed, rotary feed, machine settings, and so on.

Future work might include comparison of a real manufactured gear surface with a surface generated using a CAD approach. It would also be possible to reverse the generating process, to generate cutter geometry.

6 CONCLUSIONS

1. It is possible to simulate the gear generation process in CAD. Complete gear surfaces can be generated using a CAD approach.

2. The CAD approach needs a complement in the form of a wear simulation, to ensure proper material removal.

3. Ideal conditions for gear generation can be obtained and compared with real surface effects when removing material.

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