# The Influence of Tool Tolerances on the Gear Quality of a Gear Manufactured by an Indexable Insert Hob

Mattias Svahn, Lars Vedmar and Carin Andersson

Recently, a new type of hob with carbide inserts has been introduced, providing higher cutting speeds, longer tool life and higher feed rates when compared to re-grindable, high-speed steel hobs. But with this kind of hob, new challenges occur due to positional errors of the cutting edges when mounted on the tool. These errors lead to manufacturing errors on the gear teeth which must be controlled. In this paper, the tooth quality of a gear manufactured by hobs with different quality classes is analyzed using a simulation model in combination with Monte Carlo methods.

## Introduction

The most common and economical method to produce involute gears — both spur and helical — is by hobbing. Hobs have been — until now — mainly re-grindable, high-speed steel (HSS) with additional coatings such as TiN, TiCN, etc. Today's new type of hob with carbide inserts is advantageous to HSS hobbing with its ability to increase cutting speed and feed rate while prolonging tool life. However, one obstacle to overcome is to fulfil the requirements for hobbing accurate gears for high-performance applications while using hobs with inserts. The geometry and the positioning of the inserts must be highly accurate for the hob to comply with the tight tolerances of, for example, DIN 3968 (Ref. 1). In the literature (Ref. 2) it is stated that hobbing in industrial applications achieves gear quality according to DIN in the 8-11 range, and grade 7 in less frequent applications. However, there is little experience of the gear quality achieved using the new type of indexable insert hobs, due possibly to errors of the inserts and the higher feed rates that they are capable of operating at. The purpose of this study is to analyze the impact of possible errors of the hob geometry on the manufactured gear tooth.

Previous work in modeling the manufactured gear tooth geometry encompasses, for example, the work of Michalski (Ref. 3) that, by use of CAD environment and logical material removal to determine the manufactured tooth flanks, and Visalis et al (Ref. 4), presents the software module *HOB3D* for CAD systems, where the un-deformed chip geometry and the manufactured tooth surface are modeled. These works do not consider any manufacturing errors due to the tool or machine settings. Chiu et al (Ref. 5) computed the manufactured tooth surface by modeling the hobbing process with introduced eccentricity to the hob axis. Svahn et al (Ref. 6) modeled the manufactured gear tooth hobbed with errors introduced to the manufacturing process.

In this paper a simulation tool is used based on a mathematical, geometric model where the hobbed tooth surface can be determined in three dimensions (Ref. 7). The cutting teeth of the hob can be individually positioned in the axial and in the radial direction, compared to their nominal positions. This is done by using results from measurements of an actual hob or applying continuous probability density functions. Utilizing this simulation model it is possible to compute the gear tooth surface topography manufactured by hobs of different tolerance classes. By applying gear tooth deviation standards, the expected gear tooth quality for the corresponding hob quality class is determined. The input to the simulation software is provided by an analysis of the cutting tooth deviations of a commercial hob with inserts.

Using the Monte Carlo method (Ref. 8), the expected gear tooth quality can be determined by this simulation tool and with hob geometry generated by predetermined statistical functions. The aim of the study is to identify which parameters are influencing gear tooth quality for this new tool concept, and to show that these types of results can be provided without costly, time consuming — and often impossible — experimental testing. The use of simulation tools to analyze the gear hobbing process can be a great benefit to tool developers in finding out which tolerances and other parameters are of importance, and in manufacturing an involute gear within given tolerances. In this study, the focus is on the radial and the axial errors from the nominal position of these inserts. The shape of the inserts, the tool body and generating process will otherwise be considered perfect. The results in this study are based on the numerical values listed in Table 1.

**Table 1 Nomenclature and numerical example**

| Basic Rack | | Gear | |
|---|---|---|---|
| Normal module | $m_n = 4.75$ mm | Number of teeth | $z = 56$ |
| Normal pressure angle | $\alpha_n = 20°$ | Face width | $b = 50$ mm |
| Helical angle | $\beta = 21.5°$ | **Hob** | |
| Tip addendum | $h_t = 7.50$ mm | Number of entrances | $g = 1$ |
| Tip radius | $r_t = 1.63$ mm | Lead angle | $\lambda = 2.37°$ |
| Protuberance | $p = 0.1$ mm | Total number of cutting teeth | $N = 120$ |
| | | Cutting teeth per revolution | $N = 12$ |

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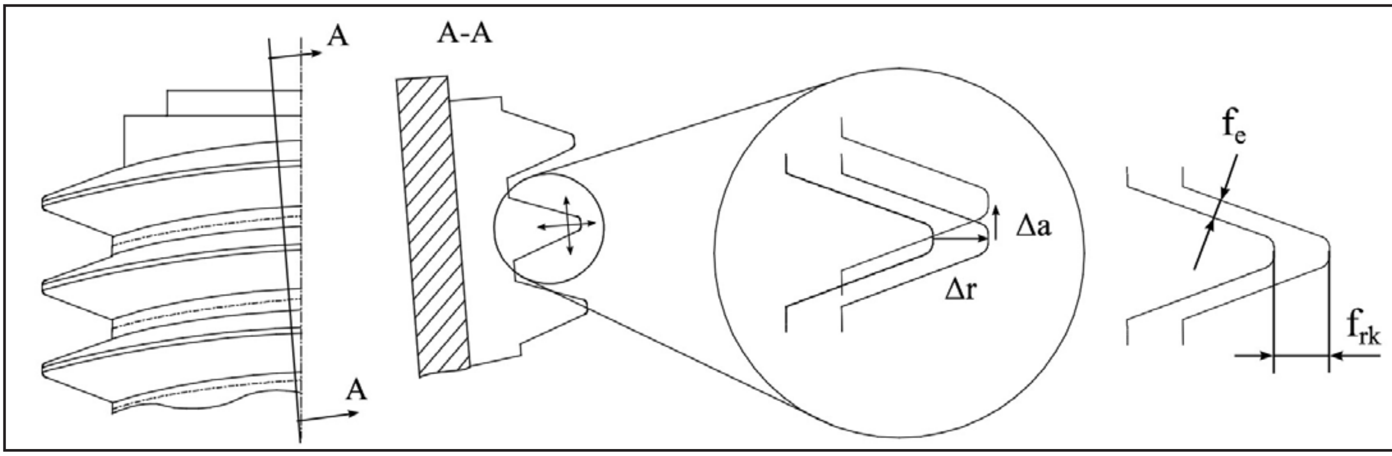


**Figure 1** Deviation of inserts of hob, where Δr is the radial displacement and Δa is the axial displacement. Related measured quantities in DIN 3968 are $f_{rk}$ and $f_e$.

## Generation of Hobs

The hob used in this study is an indexable, insert hob; individual inserts are assembled on the tool body. The position of the cutting edges, which are the boundaries of these inserts, is affected by the geometry of the inserts and their positioning on the tool body. Overly large deviations will directly affect the tooth quality of the hobbed gear tooth negatively. In order to manufacture a gear with satisfactory quality, these deviations must be controlled.

The DIN 3968 standard for single-start hobs (Ref. 1) measures the hob in 17 steps and, depending on normal module $m_n$, classifies the hob in the quality classes AA through to D, with AA being the most accurate hob. The measuring procedure of hobs is well described in VDI/VDO (Ref. 9) and by Goch (Ref. 10). The cutting tooth deviation $\Delta a$ and $\Delta r$ are presented in Figure 1, together with measured quantity $f_e$ and $f_{rk}$ from DIN 3968.

The statistical distribution of the positional error must be known to be able to apply the Monte Carlo method. Knowing the statistical distribution enables generation of new hobs based on this distribution within the same or other tolerance range. These hobs are then to be used as input to the simulation software later described, where the gear tooth topography and the gear quality manufactured by different hob quality classes can be determined.

A commercial hob with carbide inserts is control-measured using a CNC measuring center, Zeiss *CenterMax* with software packages *Calypso* and *Gear Pro Hob*. The distribution of the axial and the radial deviations of the cutting edges of the hob are tested by a null-hypothesis using the Ç$^2$ - test. The measured distribution complies with a normal distribution in both cases at the 5% significance level (Figs. 2, 3). This allows that the inserts follow a normal distribution; it is now assumed that the positional errors of the inserts for all hobs in this study comply with normal distribution.

Considering now only these deviations being present, different hob classes can be generated by positioning the inserts according to a normal density probability function. The position of each individual insert is random, but confirms the given probability functions. For a hob with normal module $m_n = 4.75$ mm, the tolerance levels for different hob classes, according to DIN 3968 (Ref. 1), are defined in Table 2.

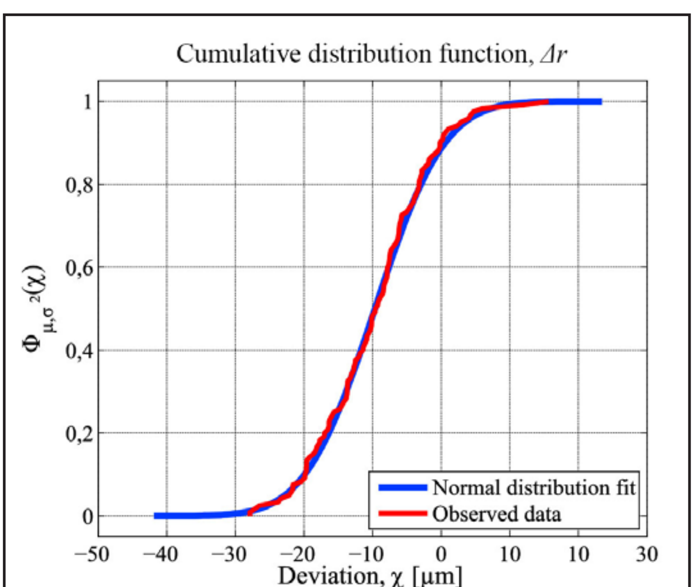


**Figure 2** CDF: plot, radial deviation of inserts.

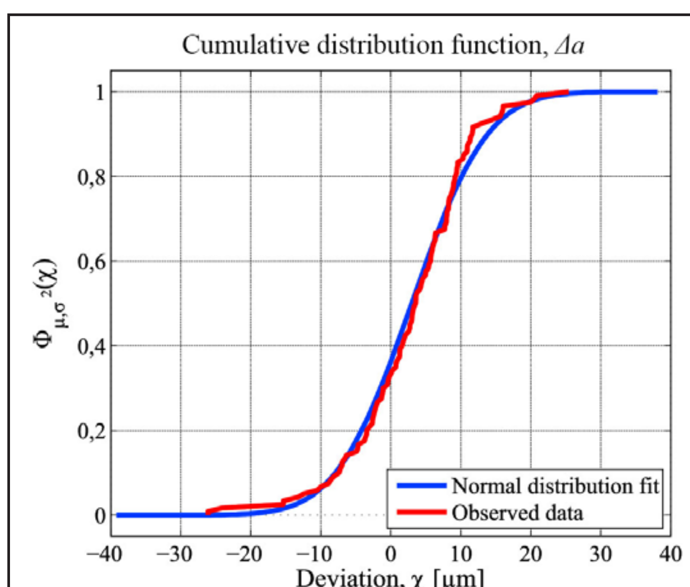


**Figure 3** CDF: plot, axial deviation of inserts.

## Simulation of the Manufacturing Process

To isolate manufacturing errors that arise to only the prescribed positional errors of the tool inserts and to determine the impact of these errors on the manufactured gear tooth, a simulation model is used. With this model, developed by Vedmar (Ref. 7), the hobbed tooth surface topography is determined in three dimensions by using analytical, parametric, differentiable functions. By comparing the hobbed tooth surface with the ideal smooth gear tooth geometry, deviations from the manufacturing process can be analyzed.

To use this simulation tool to determine the manufacturing errors due to imperfections of the hob, hobs are generated by choosing the tolerance levels according to DIN 3698. It is assumed that the positional error of the inserts complies with normal distribution — i.e., $N(\mu,\sigma^2)$. Hobs are now generated using probability density function $N(0, T_i/1.96)$, where $T_i$ is the tolerance for the respective hob quality class. These hobs are then used as input to the simulation model to determine the expected gear tooth topography after manufacturing by these hobs. An example of the results from the simulation model is presented in Figure 4, showing gear teeth manufactured using a perfect hob and a hob of quality class B with grinding stock.

Using a hob allows manufacturing of gears with or without protuberance. In the case of protuberance, the gear tooth is manufactured with grinding stock. The remaining material in the involute region is to be removed in a subsequent refining process, such as grinding or skiving. The gear quality is determined after an eventual refining process, but the same types of measurements are also applied just after hobbing to ensure controlled finished results. If the gear tooth is manufactured with protuberance, the gear tooth quality has no information if the amount of grinding stock accounts for the manufacturing errors. This will then not guarantee that the finished tooth surface is not impaired. In the simulation model this is, however, possible; this could give an indication of the necessary amount of protuberance needed for the specific hob class. The material removal rate is far greater in hobbing than in any refining process, so minimizing the grinding stock would lead to less time-consuming refining steps. As the main

**Table 2 Tolerance levels of a single-start hob with normal module $m_n$ = 4 - 6.3 mm**

| | Hob class | | | |
|---|---|---|---|---|
| | AA | A | B | C |
| $f_{rk}$ [µm] | 20 | 32 | 63 | 125 |
| $f_e$ [µm] | 6 | 10 | 20 | 40 |

**Table 3 Gear tooth quality according to DIN 3962, for a gear with normal module $m_n$ = 3.55 - 6 mm and width b = 40 - 100 mm (- not presented)**

| | | Gear quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Deviation [µm] | $f_{g\alpha}$ | - | - | 10 | 14 | 20 | 32 | 50 | 80 |
| | $f_{f\alpha}$ | 7 | 10 | 14 | 20 | 28 | 45 | 71 | 125 |
| | $f_{H\beta}$ | - | 10 | 14 | 20 | 28 | 45 | 71 | 110 |
| | $f_{f\beta}$ | 7 | 9 | 12 | 18 | 28 | 45 | 63 | 110 |

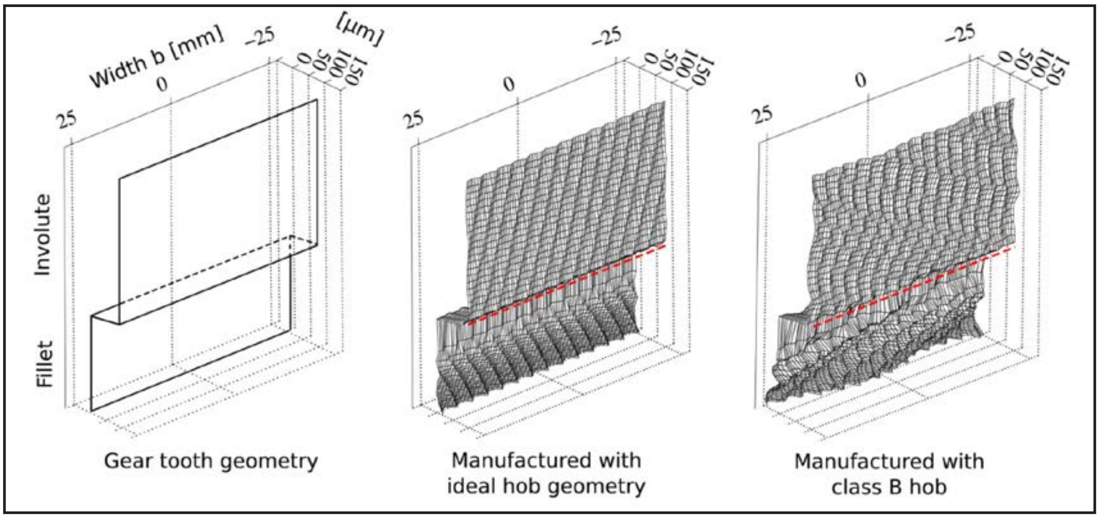


**Figure 4 Hobbed gear tooth from simulation model manufactured by a hob with protuberance = 0.1 mm.**

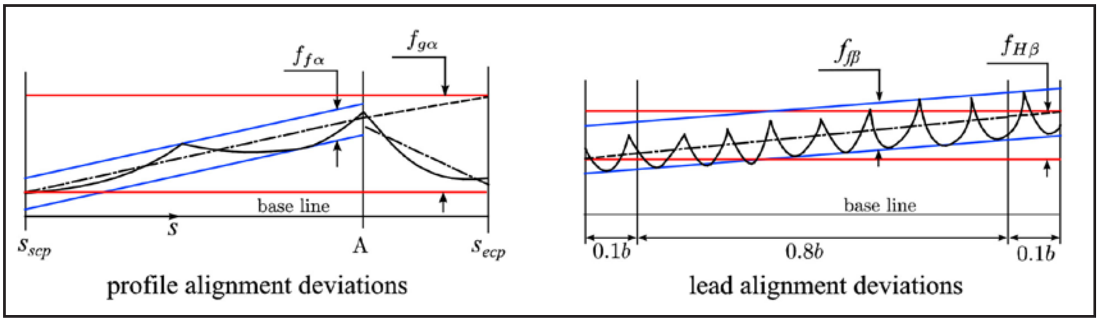


**Figure 5 Inspection charts of manufactured gear tooth for the profile and the lead deviations.**

objective is to find the correlation of the quality class between the hob and the gear tooth, measurements will be restricted to after hobbing and no considerations are taken to any finishing process.

After manufacturing, measurements of the gear tooth are drawn on inspection charts. These charts can be used to determine alignment and form deviations for both the profile and the lead. In the Volvo group standard (Ref. 11), these deviations are defined as $f_{g\alpha}$ for profile alignment and $f_{f\alpha}$ for profile form deviation; $f_{H\beta}$ for lead alignment and $f_{f\beta}$ for lead form deviations.

A stylus tracks the tooth surface at designated lines. For profile deviations the probe starts at $s_{scp}$ (start control point), records tooth deviations and ends at $s_{ecp}$ (end control point), where $s=\sqrt{r^2-r_b^2}$ and $r_b$ is the base circle radius. This is normally performed in the middle of the face width. $f_{g\alpha}$ and $f_{f\alpha}$ are defined in Figure 5, where point $A$ is specified tip relief. The lead deviations are measured of the whole face $b$ at the line $s=(s_{scp}+s_{ecp})/2$. A mean line of first order least square is established within the evaluation area 0.8b. The mean line is then extrapolated over the whole width $b$ and $f_{H\beta}$ and $f_{f\beta}$ are defined (Fig. 5).

The quantitative measure of these tooth deviations quantifies the gear tooth quality by using DIN 3962–Part 1 (Ref. 12) and Part 2 (Ref. 13), depending on the normal module $m_n$ and the face width $b$ of the gear.

## Results

To determine the quality grade of the hob needed to manufacture gears within given tolerance, and what deviation of the inserts impacts the gear quality most, simulations are performed with different hob grades. For each hob class, eight hobs are generated to manufacture one gear each; and for every gear four diametrically positioned gear teeth are control-measured using gear tooth deviation standards. This is performed for two feed rates; the more conventional feed rate $S=3.5$ mm/rev for HSS hobs and the higher feed rate $S=8.0$ mm/rev which hobs with carbide inserts are capable of.

In Figures 6 and 7 the profile and lead deviations are presented. These are separated to only axial deviations of inserts in the left column and only radial deviations of inserts in the right column. The

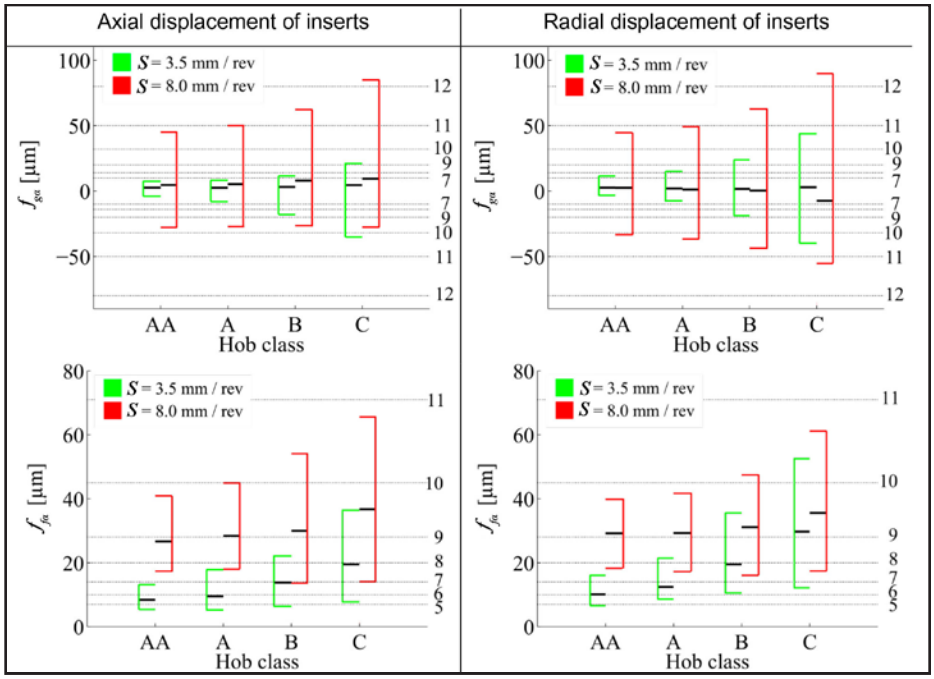


**Figure 6** **Result from simulation where the profile deviations are plotted with varying hob classes. On the left ordinate, the gear tooth deviation, and on the right ordinate, the gear quality, is plotted.**

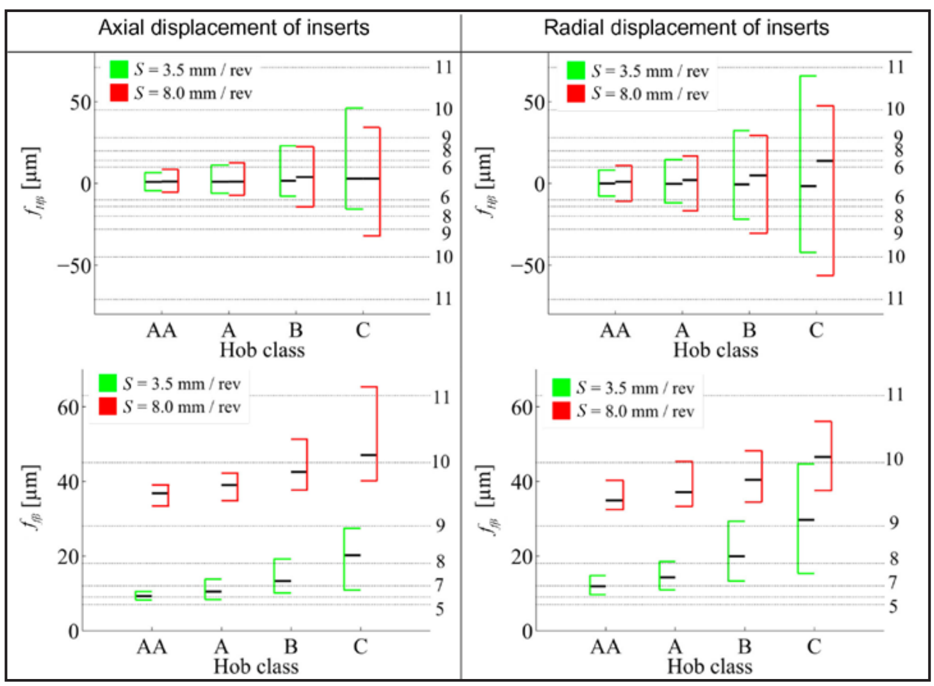


**Figure 7** **Result from simulation where the lead deviations are plotted with varying hob classes. On the left ordinate, the gear tooth deviation, and on the right ordinate, the gear quality, is plotted.**

**Table 4** **Gear tooth quality classes achieved in simulations for different hob classes, presented for two feed rates; mean/maximum quality is considered**

| | Hob class | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | AA | | A | | B | | C | |
| | *Δa* | *Δr* | *Δa* | *Δr* | *Δa* | *Δr* | *Δa* | *Δr* |
| $S=3.5$ mm/rev | <7/**7** | 7/**8** | 7/**8** | 8/**9** | 8/**9** | 9/**10** | 9/**11** | 10/**11** |
| $S=8.0$ mm/rev | 10/**11** | 10/**11** | 10/**11** | 10/**11** | 10/**12** | 10/**12** | 11/**>12** | 11/**>12** |

Table 5 The minimum amount of grinding stock needed for each hob class for the feed rates considered

| | Amount of protuberance, p[μm] | | | |
|---|---|---|---|---|
| | AA | A | B | C |
| $S = 3.5$ mm/rev | 20 | 20 | 30 | 50 |
| $S = 8.0$ mm/rev | 30 | 30 | 45 | 65 |

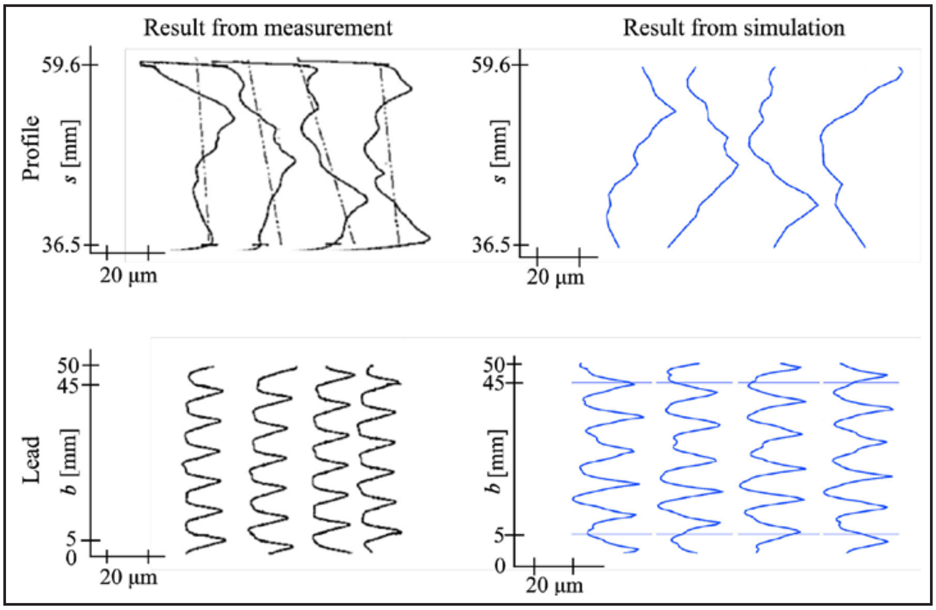


Figure 8 Inspection chart over profile and lead for a gear; hobbed at the feed rate $S = 8.0$ mm/rev. On the left, results from industrial hobbing machine; and right, results from simulation are presented.

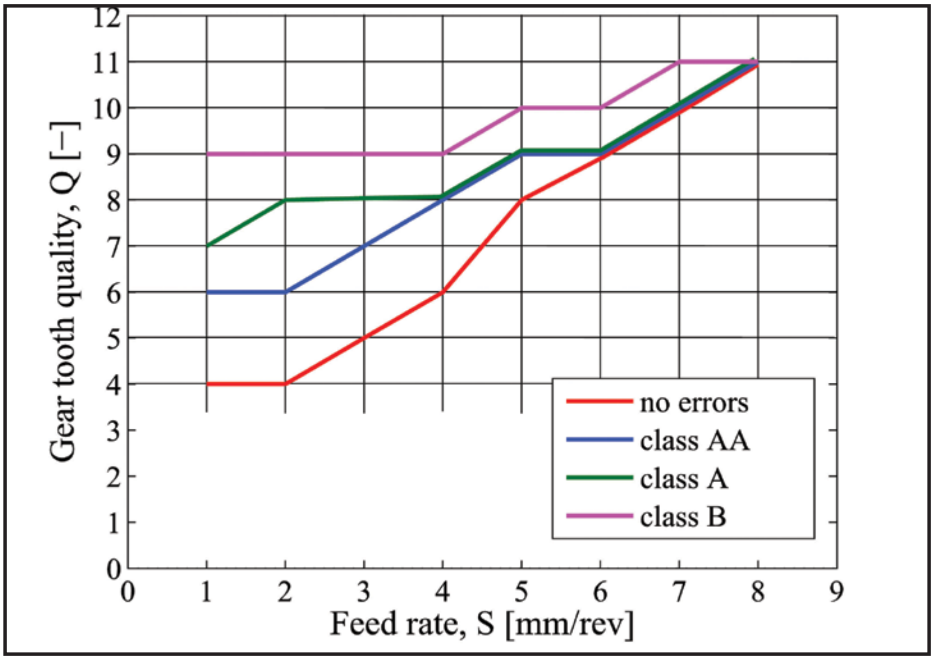


Figure 9 Gear tooth quality vs. axial feed rate of hob for different hob classes.

Table 6 Gear tooth deviations, results from experiments and simulations

| Tooth deviation, mean value of four diametrically positioned teeth. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $f_{g\alpha}$ [μm] | | $f_{f\alpha}$ [μm] | | $f_{H\beta}$ [μm] | | $f_{f\beta}$ [μm] | |
| | manu. | sim. | manu. | sim. | manu. | sim. | manu. | sim. |
| S = 8.0 mm/rev | -15 | 7.3 | 31 | 26.2 | 1 | 2.7 | 21 | 38.3 |

positional error of the cutting edges, giving the different hob classes, complies with given distribution function, here $N(\mu,\sigma^2)$. The outcome from the simulation model will also yield a distribution. In these plots, 95% of the set of the tooth deviation are comprised by the colored bracket, and the mean value is presented by the black line. On the left ordinate in each plot, the measured quantity is presented and on the right ordinate the corresponding gear tooth quality according to DIN 3962 Part 1 and Part 2.

The gear tooth quality is determined by the maximum deviation:

$$Q_{max} = \max(Q(f_{g\alpha,max}), Q(f_{f\alpha,max}), Q(f_{H\beta,max}), Q(f_{f\beta,max})) \quad (1)$$

For the gear geometry in this study (Table 1), the corresponding gear qualities for the resulting tooth deviations from simulations are given in Table 3.

Using the results in Figures 6 and 7, the gear quality according to Equation 1 is given in Table 4.

As earlier mentioned, the presented measurements do not consider if the amount of grinding stock is adequate to ensure that the involute region is not impaired after subsequent refining steps. This is, however, possible in the described simulation model. The amount of protuberance needed for each hob class in this example is given in Table 5. This means the gear in this study will be correct for all hob quality classes using a hob with protuberance $p = 0.1$ mm.

## Experimental Verification

To verify the results from the simulation model, they are compared with a gear manufactured using an industrial hobbing machine, i.e., a Liebherr LC 380. The hob used in this verification was control- measured, and the positional error of the inserts in the axial and in the radial direction was used as input to the simulation model. The gear manufactured — in both experiments and in simulation — was control-measured for alignment and form deviations, according to previous section. The results from these measurements are presented graphically (Fig. 8) and in measured quantity (Table 6).

The shape of the curves corresponds remarkably well for both profile and lead. There is, however, a systematic alignment error present on all gear teeth for the profile. For the lead errors, the form error is overestimated in simulations compared to experiments.

## Conclusions and Discussions

In this paper it is shown that the gear tooth topography and the corresponding quality, manufactured by different hob quality classes, can be determined using a developed simulation model (Ref. 7). Here, errors in the cutting edge position are introduced, so that the cutting teeth deviate in the axial and the radial directions when compared to their nominal positions.

The results show very good agreement with experimental results (Fig 8.; Table 6). Conclusions that can be drawn are that radial deviations impair the gear tooth more than the axial deviation of the inserts. The effect is only slight and most noticeable for the low feed rate, more specific $f_{g\alpha}$, $f_{H\beta}$ and $f_{f\beta}$ in Figures 6 and 7.

For the low feed rate considered in this study, both the mean value and the dispersion of the alignment and the form errors differ significantly between hob classes. But for the higher feed rate, the gear tooth will be manufactured with same quality grade for the hob classes AA and A. The alignment and form errors will differ in small degree but are still classified in the same quality grade. An explanation is due to the higher feed rate. With increasing feed rate the distance between the feed marks will increase, resulting in larger gear tooth deviations and inferior gear tooth quality. However, the positional error of the inserts between the hob classes AA and A impair the gear tooth quality less than the feed rate. Even using a perfect hob, the expected gear tooth quality will not improve significantly. Figure 9 presents the result from the simulation model showing how the gear tooth quality is affected by the feed rate. At the lower feed rate, suitable for HSS hobs, there is a significant difference in gear quality achieved for the different hob classes. However, for the higher feed rate the gear quality converges resulting in the same quality gear tooth for an A, AA and a perfect hob.

The amount of grinding stock needed to account for manufacturing errors, such as tool errors and feed marks, may be minimized if the expected gear tooth deviations can be controlled.

The gear tooth is manufactured with grinding stock by introducing protuberance to the tool. If the protuberance is minimized this will promote the finishing operations.

There are other parameters determining the quality of the gear in addition to those presented in this study. Here, only the form and the alignment deviations of the gear tooth are considered. In DIN 3962, there are also pitch error, concentricity, etc. that are not considered in the quality grading of the gears in this study. The simulations show good agreement with experimental results but additional deviations to the hob cutting teeth may be introduced for even better agreement, such as rotation of the inserts of the hob. This type of error is more probable to insertable hobs than conventional HSS hobs, and is not included in the hob standards.

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**Carin Andersson** is an Associate Professor at the Division of Production and Materials in the Department of Mechanical Engineering, Lund University, Sweden.

**Mattias Svahn** is a Ph. D student at the Division of Machine Elements in the Department of Mechanical Engineering, Lund University, Sweden.

**Lars Vedmar** is an Associate Professor at the Division of Machine Elements in the Department of Mechanical Engineering, Lund University, Sweden.