*Andrzej Piotrowski*
*Rafał Gołębski*
*Piotr Boral*

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# GEOMETRIC ANALYSIS OF COMPOSITE HOBS

**Summary**

The paper presents the universal mathematical model-based geometric analysis of a composite hob with replaceable sintered carbide cutting inserts. Composite hobs are characterised by lower accuracy compared to monolithic hobs and are generally used in roughing. Based on a computational algorithm developed by the authors of this study a computer program has been created to model the position and the geometry of the cutting insert placed on the rake face. A generalised case of a composite hob with a flat rake face not parallel to the hob axis and with rake angles different from zero has been analysed. Methods for correcting the cutting insert position and geometry to improve the composite hob accuracy are presented.

*Key words:* *composite hobs, geometric analysis, hob accuracy*

## 1. Introduction

Gear wheels can be machined using several methods, among which hobbing is the most accurate and efficient one. In his study, Piotrowski [1] described tools with a rectilinear cutting edge profile (e.g. a rack). During machining, the tool performs rectilinear motion perpendicular to the axis of rotation of the blank and reciprocating motion on the axis which is either parallel with or at an angle to the axis of rotation of the blank, while the round cross-section blank performs rotational motion (Maag, Sunderland). The superposition of these motions produces hobbing, a machining process by which the involute profile of gear wheel teeth is formed. Tools with the gear wheel profile are also used (Fellows).

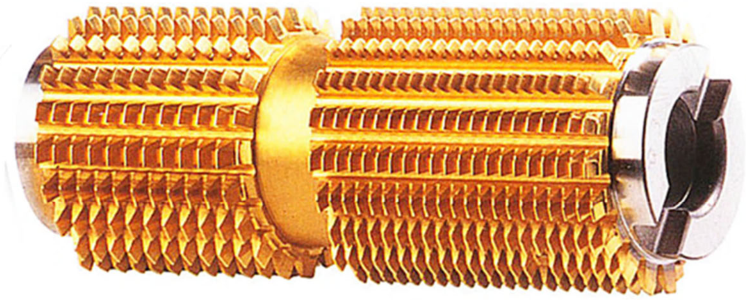

**Fig. 1** A monolithic modular hob with a large number of teeth on its perimeter (leaf-type hob) used for roughing and finishing [2]

A tool that is most commonly used in the modern gear wheel machining industry is the monolithic modular hob with a very large number of teeth on its perimeter (leaf-type hob) (Fig. 1)- During machining, the tool is moved (shifted) relative to the gear wheel being machined. Gear wheel hobs are ranked among the tools of the most complex geometry [3, 4, 5, 6] and are used for cutting spur gears and helical gears within a whole range of modules, from 0.25 to 25 mm [7, 8]. Machining is conducted on specialised hobbing machine tools. The development of technology and materials science has contributed to the emergence of hobs made wholly of sintered carbides (small modules) and of composite hob designs with cutting inserts made of super-hard materials (such as sintered carbides, ceramics, borazon, diamond) embedded in a body made of high-speed or tool steels (Figs. 2, 3), presented in [2, 8, 9-12]. Jaster, [7], investigated the use of state-of-the-art universal multi-purpose multi-axis CNC machine tools in the manufacture of gear wheels. In the case of large modules, the machinable layer is divided into two parts in order to reduce cutting resistance and to improve machining accuracy (Fig. 3) [2].

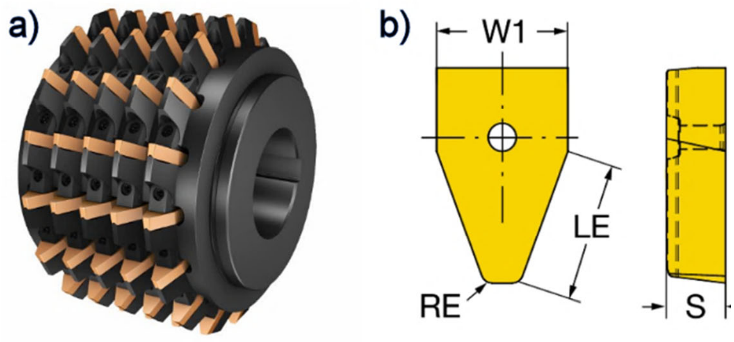


**Fig. 2** A composite hob: a) CoroMill® 176 with replaceable inserts on the rake cutting face b) the geometry of the cutting insert [2]

Initially, composite hobs had toothed bars modelled on the design of Maag or Sunderland cutters, and their rake face was parallel to the hob axis. The next step in the design was a hob furnished with sockets, in which cutting inserts were mounted. In terms of geometry, this design did not differ from the hobs with toothed bars; this means that for a rake angle equal to zero (on the outer diameter), the rake face passed through the axis of the hob and its action surface was an Archimedean helical surface (ZA surface - DIN 3975/87 [15]). A characteristic feature is the difference in profile between the right-hand and the left-hand tooth flank at hob helix angles greater than $3^{\circ}$ [2].

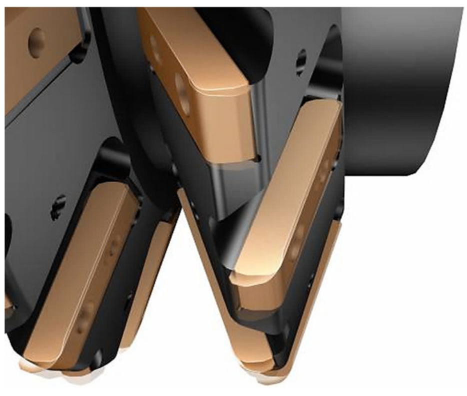

**Fig. 3** A CoroMill 177®. Modern hob with replaceable carbide inserts used for roughing [2]

CoroMill 176 composite hobs, put on the market by company Sandvik, have cutting inserts positioned perpendicular to the hob thread line [2]. By improving the accuracy of insert positioning, the accuracy class of the hobs has been improved so that they are now manufactured in accordance with the requirements for Class B (DIN 3968). The use of special coated sintered carbide cutting inserts increases the tool life by two times and enhances the machining parameters. The result is a machining time shortened by half, compared to classical tools. A drawback of composite tools is their lower accuracy compared to conventional modular solid hobs. This is due to the composite tool design itself – the problems with the correct positioning of the cutting inserts in sockets made in the tool body. In this study, an analysis of the geometry of gear wheel hobs is made based on a mathematical model which includes replaceable sintered carbide inserts. A method for improving the accuracy of composite hobs is presented. Hobs with a rake angle different from zero and insert positioning parallel to the hob axis or perpendicular to the hob thread helix, together with a rake angle correction capability, are considered.

## 2. A mathematical model of the hob

The cutting edge is a key element in the accuracy of a hob. It is the locus of points lying on the rake surface and on the flank faces. The topic was investigated by Piotrowski and Nieszporek [1, 6, 9]. The shapes and position of these surfaces have an immediate effect on the cutting edge. In the case of composite hobs, the position of the insert can be corrected by modifying the socket in the tool body, or the cutting insert profile can be changed.

The tool action surface is a locus of tool blade cutting edges and, in hobs, it is a helical surface. In accordance with ISO standards [16] and DIN 8000 [17], a reference surface in the design of hobs is the involute helical surface (ZE) with a rectilinear profile in the section tangential to the base cylinder. In the case of composite hobs with replaceable sintered carbide inserts, the inserts are most often mounted on the blade rake surface (Fig. 2a). The cutting edges can be positioned either perpendicular to the hob thread helix or parallel to the hob axis. For technological reasons, the inserts have a rectangular cutting edge profile and a fixed profile angle. The cutting edge profile error is understood as a difference between the hob action surface profile and the nominal profile of the involute helical surface in the plane tangential to the base cylinder of the hob.

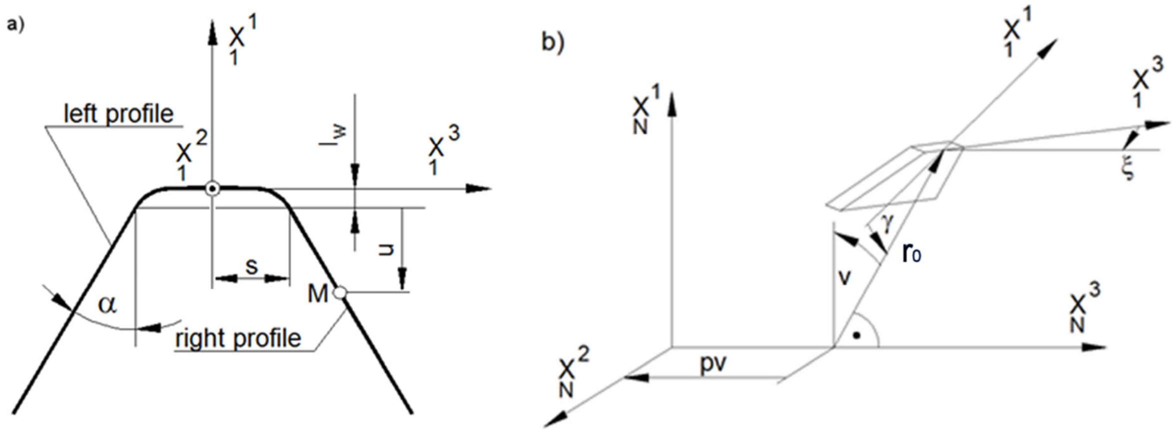


**Fig. 4** The cutting insert profile (a) and its setting in the hob layout (b)

The cutting edge profile of a symmetric and flat insert can be described using the following equation (Fig. 4a).

$$\underset{1}{\mathbf{x}}(u)=\left[-u-l_w,\quad 0,\quad \pm\left(s+u\ \mathrm{tg}\alpha\right)\right]^T \tag{1}$$

where: u –– the insert cutting edge profile parameter, $l_w$ –– the tip clearance, s –– the half-width of the cutting insert at the insert tip (at the height corresponding to the forming of the origin of the active involute of the machined gear tooth profile), α –– the cutting edge profile angle, ± - respectively, for the left-hand and the right-hand cutting insert edge.

For a hob rake angle γ different from zero, the tip clearance and the active insert profile height are determined from equation (2):

$$x = (a+b)\cos\gamma - \sqrt{(a\cos\gamma)^2 - b(2a+b)(\sin\gamma)^2} \tag{2}$$

where the following designation is adopted:

$$x = l_w,\ a = r_p + m_n,\ b = 0{,}25 m_n \tag{3a-c}$$

or

$$x = 0{,}5h,\ a = r_p,\ b = 1{,}25 m_n \tag{4a-c}$$

where: $m_n$ - the normal hob module, $r_p$ - the hob pitch radius, h - the active insert height.

The hob action surface equation is obtained by rotating the insert around the $\underset{1}{X}^1$ axis by the hob thread lead angle ξ, then by rotating the insert around the $\underset{1}{X}^3$ axis by the rake angle γ, and by helical insert motion around the $\underset{N}{X}^3$ hob axis – Fig. 4b:

$$\begin{gathered}\underset{N}{\mathbf{x}}(u,v) = [3, -v]\begin{pmatrix}[1, & -\xi][3, & -\gamma]\underset{1}{\mathbf{x}}+ \\ +[r_0, & 0, & 0]^T\end{pmatrix} \pm \\ \pm[0, \quad 0, \quad pv]^T = \begin{bmatrix}\underset{N}{x}^1, & \underset{N}{x}^2, & \underset{N}{x}^3\end{bmatrix}^T\end{gathered} \tag{5}$$

where: v - the hob action surface parameter, ξ - the angle of insert positioning relative to the hob axis, γ - the apex hob rake angle, $r_0$ - the hob radius, p - the hob helical action surface parameter, ± - respectively, for the right-hand and the left-hand hob; the subscript identifies the coordinate system.

On the other hand, the matrices of rotations are equal to [6]:

$$[3, \quad -v] = \begin{bmatrix}\cos v & -\sin v & 0 \\ \sin v & \cos v & 0 \\ 0 & 0 & 1\end{bmatrix} \tag{6a}$$

$$[1, \quad -\xi] = \begin{bmatrix}1 & 0 & 0 \\ 0 & \cos\xi & -\sin\xi \\ 0 & \sin\xi & \cos\xi\end{bmatrix} \tag{6b}$$

$$[3, \quad -\gamma] = \begin{bmatrix}\cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1\end{bmatrix} \tag{6c}$$

In order to determine the accuracy of the hob, its action surface in the plane tangential to the base cylinder needs to be determined from the condition below:

$$\underset{N}{x}^2 \pm r_z = 0 \tag{7}$$

where: $r_z$ - the radius of the base cylinder of the helical involute hob action surface, $\pm$ - respectively, for the left-hand and the right-hand side of the hob action surface profile. In $\underset{N}{X}^2$ the right-hand superscript identifies the vector coordinate (2).

For declared subsequent values of the parameter of the point location on the outline of the cutting insert edge profile, it is possible to determine the values of the hob action surface parameter v (using the bisection method). The coordinates of the points of the hob action surface profile in the plane tangential to the base cylinder can be determined using equation (2). On the other hand:

$$\sin\beta = \frac{m\,k}{d_p},\ \operatorname{tg}\alpha_c = \frac{\operatorname{tg}\alpha}{\sin\beta},\ r_z = \frac{d_p}{2}\cos\alpha_c \tag{8a-c}$$

$$p = \frac{m\,k}{2\cos\beta},\ \xi = \beta \quad \vee \quad \xi = 0 \tag{9d-e}$$

where: $d_p$ - the hob pitch diameter, $\alpha_c$ - the face angle of the involute helical surface profile, $\beta$ – the hob thread lead angle on the pitch diameter.

The hob action surface profile in the plane tangential to the base cylinder is curvilinear. Therefore, the profile error $f_f$ is divided into a profile angle error $f_\alpha$ and a rectilinearity error $f_p$ – Fig. 5. The profile angle error $f_\alpha$ (in μm) is defined as the error of the angle of the straight line passing through the extreme profile points

$$f_\alpha = 1000\left|\underset{N}{x}^1[n] - \underset{N}{x}^1[1]\right|\left(\operatorname{tg}\alpha_f - \operatorname{tg}\alpha\right)\cos\alpha_f \tag{10}$$

where: n - the number of profile points, i - the successive profile point number, $[\bullet]$ - the profile point identification index, $\alpha_f$ - the angle of the hob action surface profile in the plane tangential to the base cylinder.

The profile angle and the profile angle error of the hob action surface in the plane tangential to the base cylinder are equal to (in deg):

$$\alpha_f = \operatorname{arctg}\left|\frac{\underset{N}{x}^3[n] - \underset{N}{x}^3[1]}{\underset{N}{x}^1[n] - \underset{N}{x}^1[1]}\right|,\ \delta_\alpha = \alpha_f - \alpha \tag{11a-b}$$

The error $\Delta$ (in μm) of the hob profile rectilinearity is defined by the distance of the profile points from the straight line passing through the extreme profile points:

$$\Delta[i] = 1000\left(\underset{N}{x}^3[i] - \underset{N}{x}^3[1] - \left(\underset{N}{x}^1[1] - \underset{N}{x}^1[i]\right)\operatorname{tg}\alpha_f\right)\cos\alpha_f \tag{12}$$

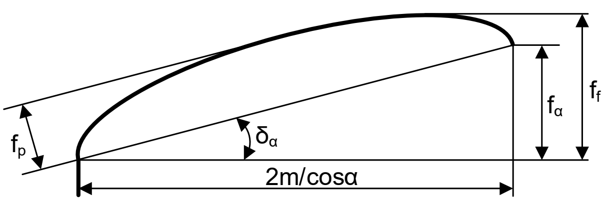

**Fig. 5** Hob action surface profile deviations [1,6]

The rectilinearity deviation will be equal to the maximum deviation Δ[i]. It is assumed in the case where n = 7 that the maximum deviation $f_p$ from the straight line occurs on the hob pitch diameter

$$f_p = \Delta[4] \tag{13}$$

In equations (9) and (11), the points for the right-hand and the left-hand hob profile side, respectively, should be taken into account.

## 3. The computer program

Based on the derived relationships, a mathematical hob model has been developed and, subsequently, a computer program (Fig. 6) which enables one to take into account a hob rake angle different from zero and insert positioning either at the hob thread lead angle on the reference cylinder or parallel to the hob axis. The hob action surface profile is determined in the plane tangential to the base cylinder and in the hob axial plane.

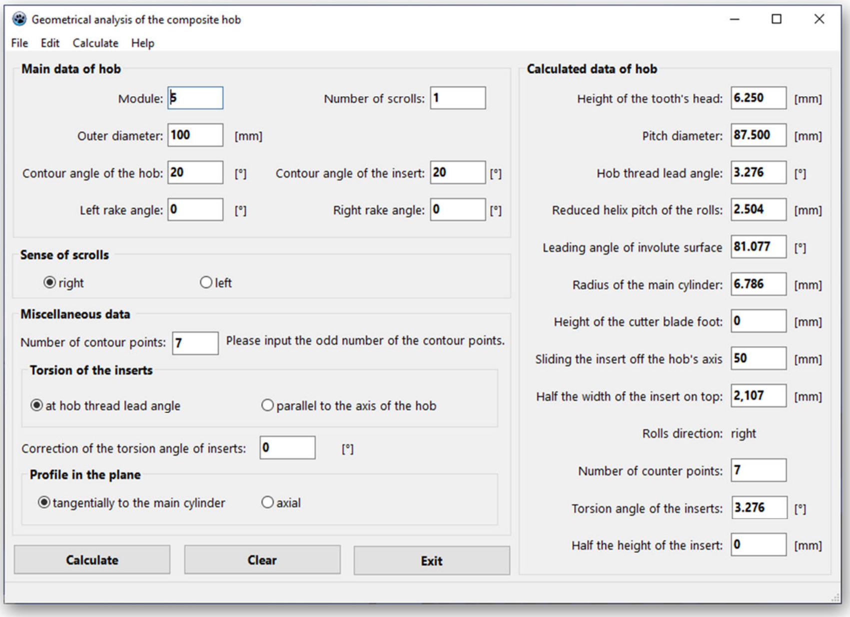


**Fig. 6** The program „Geometrical analysis of the composite hobs" – the main screen

The computation determines the values of the hob action surface parameters, the profile point coordinates, the profile deviations from the straight line, the profile angle error and the total profile error for successive profile points and for the left-hand and the right-hand hob thread side – Fig. 7. The program is created in the Lazarus 2.0 programming environment using the Object Pascal language and elements of the User Interface available in the software. The program developed in this study (Fig. 6) enables one to record and retrieve the hob data; computation results are presented in a tabular form in Fig. 7, legible graphs of deviations broken down into the nominal hob in Fig. 8, and the corrected hob in Fig. 9. By using the mathematical model and the computer program developed in this study, it is possible to improve the accuracy of composite hobs.

Based on the written program, we analysed the geometry of a hob with the following parameters (Fig. 6): module, m=5 mm; number of convolutions, k=1; profile angle, α=20 deg; outer diameter, D=100 mm; insert setting angle, ξ=0; rake angle, γ=0; that is, with an action surface ZA [15]. The rectilinearity deviations of the left-hand and the right-hand profile are equal, amounting to $f_p$=-3.6 μm. The minus sign indicates that the hob action surface in the plane tangential to the base cylinder is concave (Fig. 8). The profile angle deviation is

$\delta_\alpha$=17.7055 min., or $f_\alpha$= 55.628 μm when expressed in length units; thus, it is classified as Class C - DIN 3968 and Class D - ISO [16].

| | Profile of the cutter's working surface in the plane tangent to the main cylinder [mm] | | | | | |
|---|---|---|---|---|---|---|
| | Left | | | Right | | |
| i | x1N | x2N | x3N | x1N | x2N | x3N |
| 1 | 47.013050 | -6.786 | -2.924583 | 47.013050 | 6.786 | 2.924583 |
| 2 | 45.328605 | -6.786 | -3.545531 | 45.328605 | 6.786 | 3.545531 |
| 3 | 43.642834 | -6.786 | -4.167642 | 43.642834 | 6.786 | 4.167642 |
| 4 | 41.955549 | -6.786 | -4.791065 | 41.955549 | 6.786 | 4.791065 |
| 5 | 40.266597 | -6.786 | -5.415951 | 40.266597 | 6.786 | 5.415951 |
| 6 | 38.575722 | -6.786 | -6.042501 | 38.575722 | 6.786 | 6.042501 |
| 7 | 36.882665 | -6.786 | -6.670939 | 36.882665 | 6.786 | 6.670939 |

| | Deviations from the stright line [mm] | |
|---|---|---|
| i | Left profile | Right profile |
| 1 | 0.000000 | 0.000000 |
| 2 | -0.001860 | -0.001860 |
| 3 | -0.003089 | -0.003089 |
| 4 | -0.003612 | -0.003612 |
| 5 | -0.003342 | -0.003342 |
| 6 | -0.002179 | -0.002179 |
| 7 | 0.000000 | 0.000000 |

**Profile angle error**

Left: 17.7055 [min] Right: 17.7055 [min]

Left: 55.628 [μm] Right: 55.628 [μm]

**Total error of the profile angle**

Left: **55.628** [μm] Right: **55.628** [μm]

**Fig. 7** The results of the calculation of a composite hob with m=5, k=1, α=20 deg, D=100 mm, ξ=0°, γ=0°

The profile angle errors are much larger than the profile rectilinearity errors (in the given example, by one order of magnitude, while the profile rectilinearity errors are negligibly small – Figs. 7, 8). Therefore, the accuracy of replaceable sintered carbide-insert composite hobs can be improved by correcting the insert profile angle by the error of the hob action surface profile angle in the plane tangential to the base cylinder. Further calculations were made using the modified angle α= 19.7049 [deg] automatically computed by the program (Fig. 9).

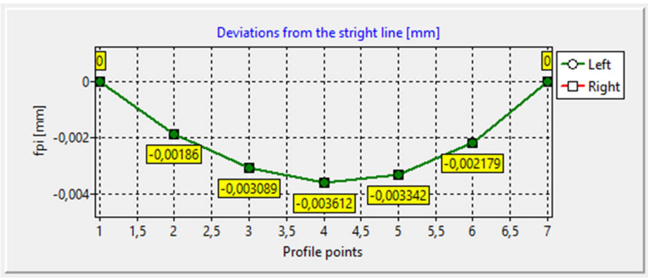


**Fig. 8** Diagram of nominal insert deviations from the straight line

| | Deviations from the stright line [mm] | |
|---|---|---|
| i | Left profile | Right profile |
| 1 | 0.000000 | 0.000000 |
| 2 | -0.001877 | -0.001877 |
| 3 | -0.003118 | -0.003118 |
| 4 | -0.003646 | -0.003646 |
| 5 | -0.003374 | -0.003374 |
| 6 | -0.002199 | -0.002199 |
| 7 | 0.000000 | 0.000000 |

**Profile angle error**

Left: 0.2504 [min] Right: 0.2504 [min]

Left: 0.785 [μm] Right: 0.785 [μm]

**Total error of the profile angle**

Left: **-3.646** [μm] Right: **-3.646** [μm]

**Fig. 9** The results of the calculation of a composite hob with m=5, k=1, α=19.7049 deg, D=100 mm, ξ= 0, γ= 0

As a result of the angle α modification, a hob with a total error of $f_\alpha$=-3.646 μm was obtained with practically identical profile straight line deviations. If a hob action surface profile angle in the plane tangential to the base cylinder is greater than the nominal one, then the insert profile angle should be decreased by that difference (and vice versa). The profile angle of the insert after correction will be:

$$\alpha' = 2\alpha - \alpha_f \tag{14}$$

The next analysis concerns a hob with the following parameters: module, m=5 mm; number of convolutions, k=1; profile angle, α=20 deg; outer diameter, D=100 mm; insert setting angle, ξ= 0°; rake angle, γ=15°. The result of changing the rake angle is a change in the left-hand and right-hand profiles. For the nominal hob (with no correction) (Fig. 10), the maximum profile error is 184.644 μm for the left-hand side and 270.917 μm for the right-hand side, which means that the hob is classified as Class D – ISO [16]. It is proposed to optimise the profile by changing the profile angle of 19.0251 deg for the left-hand side and of 18.5651 deg for the right-hand side (Fig.10).

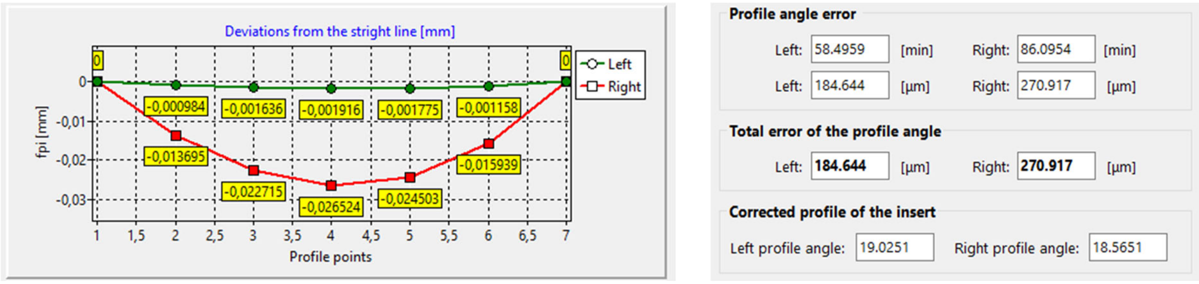


**Fig. 10** The results of the calculation of a composite hob with m=5, k=1, γ= 15°, D=100 mm, ξ= 0

Recalculation of the hob parameters following the proposed optimisation leads to an increase in the tool accuracy. The maximum profile error for the left-hand side is -3.978 μm and -7.042 μm for the right-hand side, which means that the accuracy of the hob corresponds to Class 2A – ISO [16]. The profile angle change resulted in a dramatic improvement in the tool quality; as a result, the hob price has significantly increased but the user is able to machine gear wheels of higher functional parameters.

Using the program, one can determine the hob action surface profiles in the plane tangential to the base cylinder (Fig. 5) for the nominal insert profile angle and the corrected insert profile angle. Then, the hob action surface profile angle in the plane tangential to the base cylinder is determined again for the corrected insert profile angle (Fig.11). After the correction of the cutting insert profile angle, the total profile angle error, $f_f$, in the given example is classified as Class 4A in accordance with ISO [16].

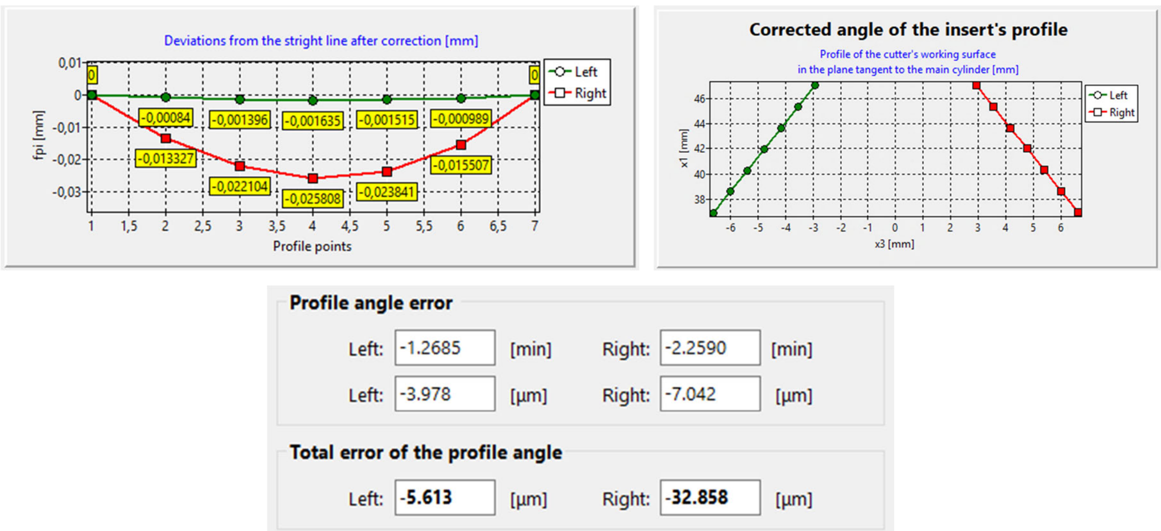


**Fig. 11** The results of the calculation of a corrected composite hob with m=5, k=1, γ=15°, D=100 mm, ξ=0°, $\alpha_l$= 19.0251 deg (left), $\alpha_p$= 18.5651 deg (right)

Table 1 shows the data for five examples of hobs. The results of hob accuracy calculations, using the initial data shown in Table 1 but in different insert setting cases, are given in Tables 2, 3, and 4. Table 2 shows the cases when the rake surface of the hob coincides with its axial plane ($\xi$=$\gamma$=0), that is the cases of hobs with the action surface ZA [8]. Hob profile errors arise from:

1) differences between the action surface (ZA) and the nominal surface (ZE) of the hob;
2) errors in setting the inserts in the hob body; and
3) profile errors caused by a change in the hob rake angle.

Rectilinearity and profile angle errors are transferred to the hob on a 1:1 scale. Small changes in the rake angle have little influence on the hob profile errors. The example of hob 1 in Table 1 shows that changing the rake angle by 0.2 deg changes the hob profile angle by 0.7 min., or 2.6 μm. An error in twisting the inserts at an angle of 0.2 deg relative to the hob axis results in a hob profile angle change of 0.27 min., or 1 μm. Rectilinearity errors are negligibly small. The example of hob 3 in Table 1 shows that changing the rake angle by 0.2 deg changes the hob profile angle by 0.8 min., or 3.1 μm. An error in twisting the inserts at an angle of 0.2 deg relative to the hob axis results in the hob profile angle change of 0.31 min., or 1.2 μm. Clearly, the rectilinearity deviations are negligibly small in this case.

**Table 1** The main data for five examples of composite hobs

| Example | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| m, mm | 6 | 6 | 6 | 12 | 24 |
| D, mm | 120 | 180 | 180 | 180 | 360 |
| K | 1 | 1 | 2 | 1 | 1 |
| B, deg | 3.276 | 2.084 | 4.171 | 4.589 | 4.589 |

**Table 2** Profile accuracy of hobs with the action surface ZA ($\gamma$= 0): * - not specified in the standard, ** - does not conform to the standard [15, 16]

| Example | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| $\alpha$, deg | | 20 | | | | |
| $\xi$, deg | | 0 | | | | |
| $f_p$, μm | | -3 | -1 | -3 | -17 | -34 |
| $f_\alpha$, μm | | 52 | 21 | 84 | 207 | 415 |
| Class | DIN | C | B | * | ** | ** |
| | ISO | D | B | ** | ** | * |
| | AGMA | * | C | ** | ** | ** |
| $\alpha'$, deg | | 19.771 | 19.908 | 19.633 | 19.547 | 19.547 |
| $f_p$, μm | | -3 | -1 | -3 | -17 | -34 |
| $f_\alpha$, μm | | 0.7 | 0.1 | 2 | 6 | 12 |
| Class | DIN | 2A | 2A | * | 2A | A |
| | ISO | 4A | 4A | 4A | 2A | A |
| | AGMA | 3A | 3A | 3A | A | B |

In the analysis of the calculation results it was found that the errors in the action surface profile of hobs with the inserts set parallel to the hob axis (Table 2) were smaller than in the case when the inserts were set perpendicular to the hob thread helix (Table 3); the differences between the two cases were small. This is due to the fact that in the former case the hob action surface is an Archimedean helical surface ZA, while in the latter case, it is a convolute helical surface ZN. Regardless of the hob type, profile errors depend on the hob thread helix angle, which is a function of the module, the diameter, and the number of threads. Therefore, many companies manufacture hobs with increased diameters, while single-thread hobs (k=1) with a zero rake angle (γ=0) are used for finishing machining. With an increasing number of hob threads, the hob thread lead angle increases (it is assumed that this angle should be within the 2-6 deg range) and the load of the blade cutting edges is increasingly non-uniform, which increases the wear of the blades.

**Table 3** Profile accuracy of hobs with the action surface ZN (γ= 0): * - not specified in the standard, ** - does not conform to the standard [15, 16, 18]

| Example | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| α, deg | | 20 | | | | |
| ξ, deg | | ξ=β | | | | |
| $f_p$, μm | | -4 | -1 | -4 | -23 | -45 |
| $f_\alpha$, μm | | 62 | 24 | 99 | 257 | 513 |
| Class | DIN | C | B | * | ** | ** |
| | ISO | D | C | ** | ** | ** |
| | AGMA | ** | C | ** | ** | ** |
| α', deg | | 19.723 | 19.891 | 19.568 | 19.440 | 19.440 |
| $f_p$, μm | | -4 | -1 | -4 | -23 | -46 |
| $f_\alpha$, μm | | 0.8 | 0.1 | 2 | 7 | 13 |
| Class | DIN | 2A | 2A | * | A | B |
| | ISO | 4A | 4A | 4A | B | B |
| | AGMA | 3A | 3A | 3A | B | B |

A good method of improving the hob accuracy, as indicated by Tables 2 and 3, is the correction of the cutting insert profile angle. However, the profile angle improvement of hobs with a flat rake surface, as shown in Tables 1 and 2, cannot be achieved by changing the rake angle. It is true that changes in the rake angle do result in changes in the right-hand and the left-hand side profile angles, but with the opposite sign. For example, an increase in the rake angle causes an increase in the left-hand profile angle, but also a decrease in the right-hand profile angle at the same time. In that case, it is not possible to improve the hob profile angle by changing the rake angle [19].

**Table 4** Hob profile accuracy – a general case: * - not specified in the standard, ** - does not conform to the standard [15, 17, 18]

| Example | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| ξ, deg | | ξ=β | | | | |
| γ, deg | | ±7.8 | ±5.3 | ±5.3 | ±10.3 | ±10.3 |
| α', deg | | 19.583 | 19.819 | 19.518 | 19.231 | 19.231 |
| $f_p$, μm | | 0 | 0 | -1 | -1 | -1 |
| $f_\alpha$, μm | | 0.4 | 0.1 | * | 3.2 | 6.4 |
| Class | DIN | 2A | 2A | 2A | 2A | 2A |
| | ISO | 4A | 4A | 4A | 4A | 4A |
| | AGMA | 3A | 3A | 3A | 3A | 3A |

When using inserts with corrected profile angles, hob profile errors are very small. In that case, the total hob profile error is determined chiefly by the hob profile rectilinearity error; for example, hobs no. 1 from Tables 1 and 2 will be classified as Class 4A according to the ISO standard [16].

In large-module hobs, inserts can be mounted on the blade flanks (Fig. 3). Hob blade cutting edges (Fig. 2) are formed then by two different inserts; it should be noted that the rake angles may be different on the left-hand and the right-hand hob blade. The blade cutting edges do not lie in one plane, which creates a possibility of reducing hob profile errors by using different rake angles for inserts mounted on both blade surfaces. For the insert setting angle of $\xi=0$ and for a rake angle (15), the hob profile errors are equal to zero (the rake surfaces of the cutting inserts lie in the plane tangential to the base cylinder of the hob).

$$\gamma = \pm \arcsin \frac{2r_z}{D} \tag{15}$$

where ± refers to the left-hand and the right-hand hob blade flank, respectively.

In a general case, for $\xi=\beta$, when taking into consideration the rake angles for the inserts on both hob blade flanks according to relationship (14), the change in the profile angle should additionally be accounted for according to relationship (13) – Table 4. In practice, the profile of the blade flanks to which the inserts are fixed should be changed in this case (that is, the hob body needs to be changed accordingly).

## 4. Conclusions

The mathematical model of the composite hob developed here enables the analysis of the tool profile and the improvement in its accuracy to be made. The computer program created on the basis of the model automates the process of improving the accuracy of the tool by analysing the effect of initial parameters (Fig. 6) on the hob accuracy. To sum up, composite hobs with replaceable cutting inserts of the nominal cutting edge profile angle are inaccurate, especially when compared to monolithic hobs in which we can modify the profile of surfaces forming the cutting edge. The hob action surface profile in the plane tangential to the base cylinder is curvilinear and it is different for the left-hand and the right-hand profile side. The error of the hob action surface profile can be divided into a rectilinearity error and a profile angle error.

Profile rectilinearity errors are usually negligibly small (Figs. 7-11). By correcting the cutting insert profile angle, the hob accuracy can be significantly improved. Inserts mounted on the blade rake face parallel to the hob thread helix, or those mounted parallel to the hob axis, have almost identical profile errors. In the case of hobs with replaceable roughing and high-speed machining inserts mounted separately on the hob blade flanks for the left-hand and the right-hand cutting edge) (Fig. 3), the rectilinearity error can be reduced by using a different rake angle for either of the inserts. In that case, however, in order to reduce the total hob profile angle error, the profile angles of the hob blade flanks, on which the cutting inserts are mounted, must also be changed.

In conclusion, due to the huge cost of composite hobs and their high performance, the improvement in the accuracy of these tools will enable their wider use on multi-purpose universal CNC machine tools. This is cost-effective especially for large-lot and high-speed machining. One of the ways is to use the composite hob model developed and presented here.

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Andrzej Piotrowski
Rafał Gołębski
Piotr Boral
Czestochowa University of Technology,
Faculty of Mechanical Engineering and
Computer Science
Al. Armii Krajowej 21,
42-201 Czestochowa, Poland