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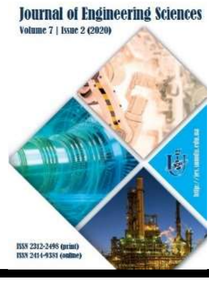


# Effect of Insert Angles on Cutting Tool Geometry

Shvets S. V.[1*], Astakhov V. P.[2]

[1] Sumy State University, 2 Rymskogo-Korsakova St., 40007 Sumy, Ukraine;
[2] Production Service Management Inc, 1255 Beach Court, Saline, Michigan 48176, USA

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***Corresponding email:**
s.shvets@tmvi.sumdu.edu.ua

**Abstract.** An analysis of publications has shown that mechanically clamped indexable inserts are predominantly used in modern tool manufacturing. Each insert has its shape and geometry in the tool coordinate system. The static system's required geometry is achieved by the tilting of the insert pocket in the radial and axial directions. Therefore, it is of great importance in the tool design to know the relationships between the insert's geometry parameters in the tool coordinate system where the geometry paraments of the insert are defined and working geometry parameters of the tool defined in the static coordinate system. The paper presents the developed methodology for determining the insert pocket base surface position to ensure the required values of the tool geometry parameters of the selected indexable insert in the static coordinate system. The graphs of the dependence of each of the angles of the insert geometry on the angles of rotation of this insert in the front and profile planes are presented as the level lines for practical use. Using these graphs, one can optimize all geometric insertion parameters in the static coordinate system. The model of the calculations of the mechanism of the insert clamping by a screw is developed. The basic size and tolerance of the output link determine the distance from the intersection line of the base surfaces to the thread axis on the pocket and the minimum amount of the screw stroke on the insert clamping in the pocket.

**Keywords:** indexable insert, cutting tool, coordinate system, base surfaces, geometric parameters.

## 1 Introduction

Reducing direct manufacturing costs associated with machining operations is a never-ending challenge for manufacturing plants that have this problem more pressing in recent years because of two prime reasons. The first one is the increased use of special alloys with advanced properties and significant tightening of machined parts' quality requirements. The second one is increasing global competition, which is changing most companies' environment today [1].

At the same time, the market needs more varieties of products, and therefore equipment and processes need to be more flexible to meet the needs and reduce the cost of manufacturing. A considerable amount of time is spent on designing and manufacturing the cutting tool as an essential component of technological equipment.

In modern tool production, mechanically clamped indexable inserts are preferably used [2, 3]. The shape and geometry of an insert and its correct placement in the tool body affect the quality and productivity of machining and the stability of the tool [4, 5]. The use of inserts allows one to develop various cutting tools of special geometries while reducing the time to restore the tool after tool life.

Simultaneously, the design of insert holders for such tools is complex as related to the necessity of developing their 3D models, CNC programs for their machining and inspection procedures.

Work on developing the common types of cutting tools with indexable inserts is carried out in the research laboratories of many companies. In such endeavors, the already developed shapes of inserts are mostly used while new shapes of inserts are developed to meet practice needs. Clamping mechanisms for indexable inserts are also in the focus of attention in the tool design.

However, flexibility is also required in cutting tool designs to ensure production flexibility. Despite the widespread use of modern CAD/CAM systems, many intellectual resources are still being spent on adapting standard solutions to a specific cutting tool design. Unfortunately, practically no research aimed at developing CAD/CAM systems of the tool geometry for special cutting tools with indexable inserts.

Therefore, in terms of increasing modern production flexibility, the current work aimed to feel this gap is extremely relevant.

## 2 Literature Review

The required quality of machined parts and the maximum efficiency of their machining depend on the correct selection of cutting operations parameters. Among many, the most important is the cutting tool's geometry with indexable inserts [6]. In practice and analytically by finite element method [5] it is established that the geometry of the indexable insert in a static coordinate system influences the temperature in the cutting zone and the wear of the insert itself.

The geometry in the static coordinate system is formed on the basis of a pre-selected indexed insert. The insert rotates around the local axes to achieve the desired position in the global coordinate system associated with the tool body [7]. Formulas for discrete geometric analysis of indexed insert tools have been proposed [8]. Their use makes it possible to determine the geometry of indexable inserts in a static coordinate system and thus improve the design of tools because the blades' geometrical parameters affect the quality of processing and stability of the tool [9], chip curling and shredding [10].

As far as the author is aware, there are still no clear algorithms for determining the positions in the base surfaces' space on the tool body with which the indexable insert contacts when fixed. Neither standards nor manufacturers of inserts make such recommendations [11]. This can be explained by the presence of many requirements when implementing a specific cutting process. Therefore, determining the insert's position and its geometry during cutting remains an important task [12]. Known schemes of action of forces at the fastening of inserts: C, S, P, M – are realized by various mechanisms. When designing an axial tool, a screw is a fairly common and reliable [13] mounting mechanism that implements Scheme S. However, there are no instructions for constructive implementation, such as the thread axis position to secure the insert securely.

The peculiarity of using indexable inserts to equip composite tools is that the geometric insertion parameters are tightly coupled. Optimization of one of the geometric insertion parameters in a static coordinate system may lead to the others' invalid values.

This work aims to develop an algorithm for determining the base surfaces' positions on the tool body to provide the required geometry of the selected indexable insert in a static coordinate system.

To achieve this goal, it is necessary to solve the following tasks: to determine the basic forms of the working part of the axial tools (the original tool surface), to propose a methodology for calculating the mechanism of fixing the insert, to develop a methodology for calculating the position of the base surfaces in a static coordinate system.

## 3 Research Methodology

There are a significant number of indexable inserts available in the market. To equip the tool to be designed with an indexable insert, it is necessary to select the insert from the manufacturer's catalog. The shape and geometry of the selected inserts should be as close as possible to the cutting edge's required geometry in the static coordinate system. Multiple recommendations on the insert shape selection are widely available in the catalogs of the leading cutting tool manufacturers and literature [6].

Each insert has its own shape and geometry in the tool coordinate system (according to the national standard DSTU 2249–93 "Machining. Terms, Definitions, and Symbols"). The static system's required geometry is achieved by the tilting of the insert pocket in the radial and axial directions, as shown in Figure 1. Therefore, it is of great importance in the tool design to know the relationships between the insert's geometry parameters in the tool coordinate system where the geometry paraments of the insert are defined and working geometry parameters of the tool defined in the static coordinate system. Note that the latter parameters define tool performance. To establish these relationships, a model of the tool geometry should be developed.

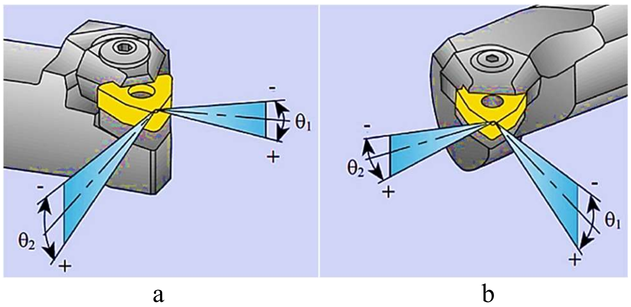


Figure 1 – The meaning of the radial $\theta_1$ and axial $\theta_2$ tilting angles for the external (a) and internal (b) turning tools

The first step in the development of the above-discussed model is to set the tool coordinate system at a point of the insert and position of the indexed insert in this system (Figure 2).

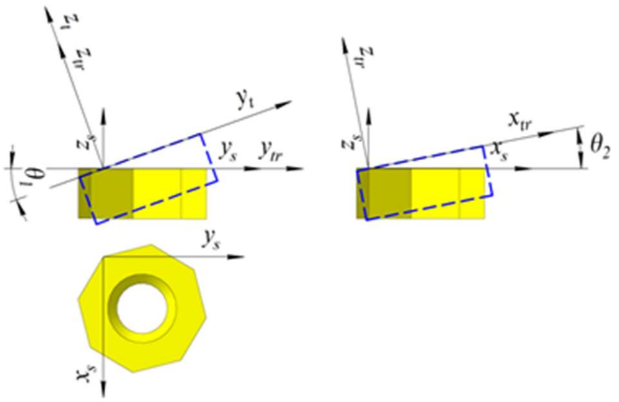


Figure 2 – Coordinate systems for determining angles $\theta_1$ and $\theta_2$

The cutting tool geometry parameters are considered in three coordinate systems: static (or global) – $x_s y_s z_s$, transitional – $x_{tr} y_{tr} z_{tr}$, tool – $x_t y_t z_t$. In the second step of the model development, the insert is rotated in the front and profile planes by the angles $\theta_1$ and $\theta_2$ to obtain the necessary angles in a static coordinate system.

The system $x_t y_t z_t$ specifies the original insert geometry and the transition from this system through $x_{tr} y_{tr} z_{tr}$ to $x_s y_s z_s$ allows determining the position of the indexed insert after rotating by the angles $\theta_1$ and $\theta_2$ to obtain the required geometry of the cutting edge in the static coordinate system. When rotating the insert by the angle $\theta_1$ (Figure 2), the $x_t y_t x_t$ the system rotates and the $x_{tr} y_{tr} z_{tr}$ and $x_s y_s z_s$ systems are stationary (all the systems coincide before the rotation) [14].

After turning in the front plane by the angle $\theta_1$, the coordinates in the transition system are as follows [15]:

$$\begin{cases} x_{tr} = x_t; \\ y_{tr} = y_t \cos\theta_1 - z_t \sin\theta_1\,; \\ z_{tr} = z_t \cos\theta_1 + y_t \sin\theta_1\,. \end{cases} \tag{1}$$

After rotating the insert in the profile plane by the angle $\theta_2$, the transition from $x_{tr} y_{tr} z_{tr}$ to $x_s y_s z_s$ is represented by the equations:

$$\begin{cases} x_s = x_{tr} \cos\theta_2 - z_{tr} \sin\theta_2\,; \\ y_s = y_{tr}; \\ z_s = z_{tr} \cos\theta_2 + y_{tr} \sin\theta_2\,. \end{cases} \tag{2}$$

Finally, after both rotations, the coordinates of the points of the indexable insertion in the static coordinate system are determined by the substitution equation (1) into the system (2):

$$\begin{cases} x_s = x_t \cos\theta_2 - (z_t \cos\theta_1 + y_t \sin\theta_1)\sin\theta_2\,; \\ y_s = y_t \cos\theta_1 - z_t \sin\theta_1\,; \\ z_s = (z_t \cos\theta_1 + y_t \sin\theta_1)\cos\theta_2 + x_t \sin\theta_2\,. \end{cases} \tag{3}$$

To determine the working orthogonal clearance angle of the indexable insert, a vector $\bar{e}$ is introduced in the coordinate frame. The vector $\bar{e}$ is directed along the flank plane's intersection line and the tool orthogonal plane $P_{\tau t}$ (Figure 3). The modulus of this vector $|-\bar{e}| = 1$. Therefore, $-\bar{q} = -\bar{e}\cos\alpha_t$, $\bar{e} = \bar{d} + (-\bar{q})$.

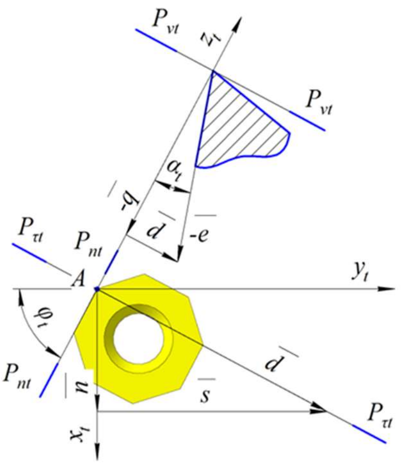

Figure 3 – Determination of the coordinates of the vector $\bar{e}$ in the tool coordinate system

On the plane $x_t y_t$, vector $\bar{d} = -\bar{e}\sin\alpha_t$ has projections; $\bar{n} = \bar{e}\sin\alpha_t\cos\varphi_t = \bar{\imath}\sin\alpha_t\cos\varphi_t$; $\bar{s} = -\bar{e}\sin\alpha_t\sin\varphi_t = -\bar{\jmath}\sin\alpha_t\sin\varphi_t$. Consequently, $\bar{d} = (-\bar{\imath}\sin\alpha_t\cos\varphi_t) + (-\bar{\jmath}\sin\alpha_t\sin\varphi_t)$. Therefore, $\bar{e} = -\bar{\imath}\sin\alpha_t\cos\varphi_t - \bar{\jmath}\sin\alpha_t\sin\varphi_t + \bar{k}\cos\alpha_t$.

Denoting the coordinates of the vector $\bar{e}$ in the system coordinate $x_t y_t x_t$ as $x_1$, $y_1$, $z_1$, $x_1 = -\sin\alpha_t\cos\varphi_t$, $y_1 = -\sin\alpha_t\sin\varphi_t$, $z_1 = \cos\alpha_t$, one can obtain

$$\bar{e} = \bar{\imath}x_1 + \bar{\jmath}y_1 + \bar{k}z_1. \tag{4}$$

In the static coordinate system, the same vector has other coordinates (Figure 4):

$$\bar{e_s} = \bar{\imath}x_{1s} + \bar{\jmath}y_{1s} + \bar{k}z_{1s}. \tag{5}$$

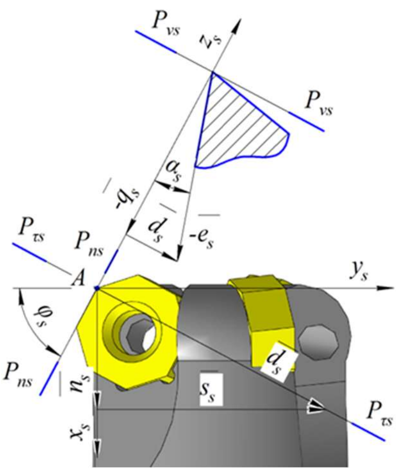

Figure 4 – Scheme for determining working orthogonal clearance

Having developed system (3), one can make the transition from the system $x_t y_t x_t$ to the static coordinate system as follows:

$$\begin{cases} x_{1s} = x_1 \cos\theta_2 - (z_1 \cos\theta_1 + y_1 \sin\theta_1)\sin\theta_2\,; \\ y_{1s} = y_1 \cos\theta_1 - z_1 \sin\theta_1\,; \\ z_{1s} = (z_1 \cos\theta_1 + y_1 \sin\theta_1)\cos\theta_2 + x_1 \sin\theta_2\,, \end{cases} \tag{6}$$

Working orthogonal clearance is the angle between the vector $\bar{e}$ directed along the intersection line of the flank face and the intersecting plane $P_{\tau s}$, and the $z_s$ axis.

Consequently, the following formula can be applied:

$$\alpha_s = \mathrm{arctg}\frac{\sqrt{x_{1s}^2 + y_{1s}^2}}{z_{1s}}. \tag{7}$$

## 4 Results

A plot of the dependence of the working orthogonal clearance angle on the angles of rotation, $\theta_1$ and $\theta_2$ (Figure 5 a) is constructed using equation (7) while considering the coordinates of the vector $\bar{e_s}$ (equation (6)). This graph's level lines (Figure 5 b) facilitate the proper selection of angles $\theta_1$ and $\theta_2$ depending upon the required working orthogonal clearance angle.

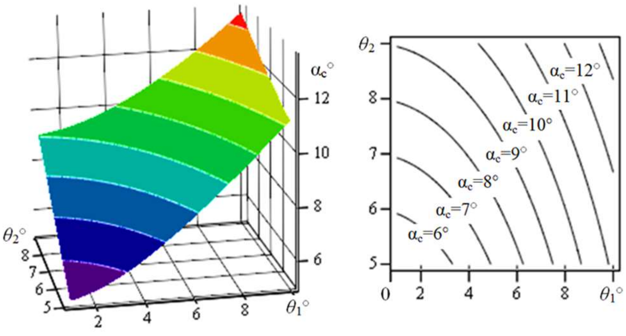


Figure 5 – Graph of the dependence of working orthogonal clearance on the angles of rotation of the base surfaces (a) and its line of level (b)

Similarly, the formulas for determining the rake angle, tool cutting edge angle, and tool cutting edge inclination angle in the static coordinate system are obtained. The rake angle is equal to

$$\gamma_s = arctg \frac{z_{2s}}{\sqrt{x_{2s}^2+y_{2s}^2}}. \tag{8}$$

The coordinates of a vector along the intersection line of the rake surface and the cutting edge normal plane in the static coordinate system are as follows:

$$\begin{cases} x_{2s} = -\cos\gamma_t \cos\varphi_t \cos\theta_2 - \\ -\sin\theta_2(\sin\gamma_t \cos\theta_1 - \cos\gamma_t \sin\varphi_t \sin\theta_1)\,; \\ y_{2s} = -\cos\gamma_t \sin\varphi_t \cos\theta_1 - \sin\gamma_t \sin\theta_1\,; \\ z_{2s} = cos\theta_2(\sin\gamma_t \cos\theta_1 - \cos\gamma_t \sin\varphi_t \sin\theta_1) - \\ -\cos\gamma_t \cos\varphi_t \sin\theta_2\,. \end{cases} \tag{9}$$

The tool cutting edge and tool cutting edge inclination angles are:

$$\varphi_s = \mathrm{arctg}\frac{x_{3s}}{y_{3s}};\ \lambda_s = arctg\frac{z_{3s}}{\sqrt{x_{3s}^2+y_{3s}^2}}. \tag{10}$$

The coordinates of a vector tangent to the cutting edge in the static coordinate system are as follows:

$$\begin{cases} x_{3s} = \cos\gamma_t \sin\varphi_t \cos\theta_2 - \\ -\sin\theta_2(\sin\gamma_t \cos\theta_1 + \cos\gamma_t \cos\varphi_t \sin\theta_1)\,; \\ y_{3s} = \cos\gamma_t \cos\varphi_t \cos\theta_1 - \sin\gamma_t \sin\theta_1\,; \\ z_{3s} = cos\theta_2(\sin\gamma_t \cos\theta_1 + \cos\gamma_t \cos\varphi_t \sin\theta_1) + \\ +\cos\gamma_t \sin\varphi_t \sin\theta_2\,. \end{cases} \tag{11}$$

Therefore, the influence of each of the angles of rotation on the final value of the static angles of the selected indexed insert (with known geometry in the instrument coordinate system) can be determined using formulas (7)–(10).

Depending on the contact conditions of the workpiece surface of the cut and the tool intended surface (a point or a line), the tool body and insert pocket are designed to place the insert accordingly (Figure 6).

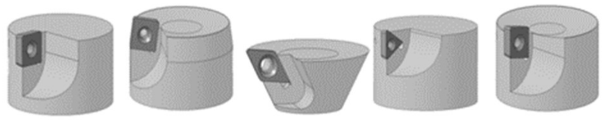

Figure 6 – Correspondence of insert forms and basic tool surface

The pocket shape and size resemble those of the selected insert. At the same time, the base surface of the pocked is inclined with the above-determined angles $\theta_1$ and $\theta_2$ to achieve the required tool geometry, namely its clearance, tool cutting edge, and inclination angles.

Due to the fact that the insert is positioned in the pocket are only on its outer surface, the locating surface of the pocket resembles the insert shape.

The geometric and kinematic relationships between the insert sizes, the base surfaces on the tool body, and the mounting screw can be determined using the dimensional chain theory. The nominal size and tolerance of the output link determine the distance from the line of intersection of the insert pocket's locating surfaces to the axis of the thread and the minimum amount of the screw travel when clamping the insert.

Figure 7 shows the mounting model of insert 2 on the tool pocket 3 using a screw with a conical head 1.

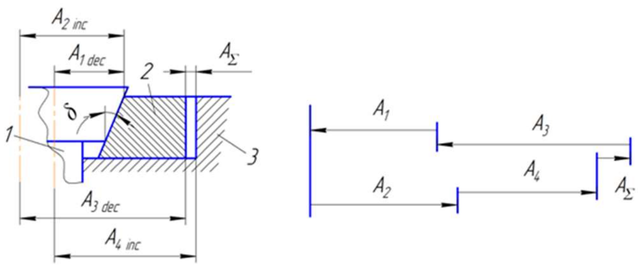


Figure 7 – The node of the mechanical retention of the indexable insert

This figure also shows the corresponding dimension chain. The initial link is $A_\Sigma$, the nominal size of which is equal to zero. The dimension chain equation is as follows:

$$A_\Sigma = \Sigma A_{inc} - \Sigma A_{dec} = A_2 + A_4 - A_1 - A_3. \tag{12}$$

The nominal dimensions of the $A_2$ and $A_3$ units of this equation are determined by the dimensions of the insert (Figure 8): link $A_2 = d/2$, link $A_3 = n$ (or $A_3 = m$, depending on the placement of the insert on the pocket).

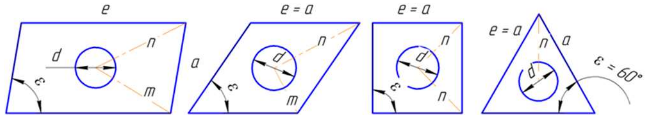


Figure 8 – Common forms of indexable inserts

Link $A_1$ also depends on $A_2$: $A_1 < A_2$. Hence, $A_4 = A_1 + A_3 - A_2$.

For the most common forms of indexable inset (Figure 7), the parameters $n$ and $m$ are determined as:

$$n = \frac{1}{6}(k-1)\sqrt{e^2 + 2ae\cos\varepsilon + a^2};$$
$$m = \frac{1}{6}(k-1)\sqrt{e^2 - 2ae\cos\varepsilon + a^2}, \quad (13)$$

where $k$ is the number of corners.

Tolerances for sizes $A_2$ and $A_3$ are determined using the international standard ISO 1832: 2004/2005, according to which the third letter in the inser designation code defines these tolerances (C, H, E, G, M, U).

Tolerance for size $A_1$ is selected with 12th IT grade of tolerance, tolerance for size $A_4$ is selected with 8th IT grade of tolerance. The tolerance for the size of the source link is equal $T_\Sigma = T_{A_2} + T_{A_3} + T_{A_4} + T_{A_1}$. As the function of the tool cutting edge angle, $\kappa_r$ for various standard $\Delta p$ and $\Delta f$ ($-4^\circ$, $-4^\circ$; $-5^\circ$, $-5^\circ$; $-6^\circ$, $-6^\circ$) commonly used for tool holders. As seen, the normal flank angle is sub-optimal, i.e., it is $4^\circ$–$5^\circ$, while the optimal flank angle for machining of many steel grades is $7^\circ$ – $9^\circ$ and $10^\circ$ – $12^\circ$ for finishing operations. These causes burn marks on the flank surfaces of many standard inserts. Although such marks are common, tool manufacturers did not correct the flank angle. That is $A_{\Sigma \mathrm{mi}} = 0$, $A_{\Sigma \max} = T_\Sigma$, so that the magnitude of the stroke of the screw $h$ when securing the insert can be determined as $h = A_{\Sigma \max} \operatorname{ctg} \delta$.

## 5 Conclusions

The results obtained in this paper allow determining the position of the face of the insert pocket for placement of an indexable insert to achieve the required geometry of the cutting tool. In other words, it provides optimization of its geometric parameters in a static coordinate system. Using the graphs of the dependence of each of the cutting tool geometry angles on the angles of rotation of an indexable insert in the front and profile planes, respectively, $\theta_1$ and $\theta_2$, one can find the level lines of these graphs. Then angles $\theta_1$ and $\theta_2$ can be determined to required tool geometry parameters and thus to optimize the value of all geometric insertion parameters in the static coordinate system.

The model for calculations of the mechanism of clamping of the indexable insert with the screw is developed. The geometric and kinematic relationships between the insert sizes, the insert pocket base surfaces, and the mounting screw are identified. The basic size and tolerance of the output link determine the distance from the intersection line of the base surfaces to the thread axis on the pocket and the minimum amount of the screw stroke on the insert clamping in the pocket.

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