Improving useful life of assembled cutting tools by designing a modified flank geometry in indexable cutting inserts

S Mikhailov$^{1,2}$ and N Kovelenov$^{2,3}$

$^1$ Kostroma State University, 17 Dzerzhinskogo st., Kostroma, 156005, Russia
$^2$ Peter the Great Saint-Petersburg Polytechnic University, 29 Polytechnicheskaya st., Saint-Petersburg, 195251, Russia
$^3$ Virial LTD., 27 Engelsa avenue, Saint-Petersburg, 194156, Russia

Abstract. An innovative approach is proposed to increase the useful life of assembled cutting tools by designing a special shape of the flank surface of indexable faceted cutting inserts (IFCIs). Calculation relationships were developed as a way to define the nature and degree of effect of blade geometry on the flank wear rate. The paper describes specifics of designing the optimal flank shape for roughing and finishing operations. Curved (convex) flank geometry is confirmed to effectively increase the tool life before reaching the maximum allowed flank wear land. An important factor for choosing the insert flank geometry and dimensions is the strength of the cutting blade of the insert. To maximize tool life with regard to the insert strength, a CAD method is developed for geometry calculation and optimization of the complex-profile flank surface. IFCI design examples featuring modified flank geometry offer improved tool life. Complex flank shape comprising a series of elementary surfaces with different geometry, is shown to be highly efficient. The results of field tests for new IFCIs in milling operations confirm the great practical value of methods for controlling the tool wear behavior through modified flank geometry.

1. Introduction
The progress in modern metal-cutting tools is pursued along the lines of developing new refractory carbide materials and multilayer wear-resistant coatings, original designs, and processing routes for indexable cutting inserts. Creating the complex-profiled cutting inserts with a modified rake and flank geometry could be a significant factor in maximizing the service life of the tool [1,2,3]. The geometry of the cutting edge depends on the application and cutting conditions of the insert [4]. In high-speed cutting of materials, the tool life is mainly limited by the extent of flank wear, since flank is subject to more intensive wear than the rake surface. The amount of wear after which the tool must be replaced serves as a tool dulling criterion. There are two commonly used dulling criteria: 1) optimal wear criterion; and 2) process wear criterion. Both are based on the linear flank wear of the tool. Optimal wear is understood as the amount of wear corresponding to the maximum tool service life. Process wear criterion means that the tool is considered dull once its flank linear wear reaches a process-defined wear limit, above which cutting must be stopped due to process requirements. The tool is taken off service, since the required accuracy and quality of the machined surface are no longer ensured. Process wear criteria are typically applied for finishing operations. For roughing and semi-finishing tasks it is practical to make maximum use of the service life of the tool. Achieving maximum tool life, with regard to process requirements, largely depends on the geometry of complex-shaped
IFCIs. Moreover, the problem of optimizing the IFCI design involves both selecting the rake surface geometry (which affects the chip shape), and defining the geometry of the flank surface, which directly contacts the workpiece and is subject to the greatest wear.

With the advent of currently available volumetric presses, IFCIs with virtually any degree of complexity of the rake and flank surfaces could be formed with comparative ease. Expanded processing capabilities of tool production lends greater relevance to the task of creating a new tool with modified flank surface and improved efficiency [3,5,6,7]. It should be noted that the theoretical basis to possible improvement of the wear resistance of the tool by deliberate reduction of its flank surface is provided in [8]. Despite its popularity, the method has so far found little application in metalworking either on national or global level. This is likely due to the underestimation of the effectiveness of the method, as well as by relative complexity of its implementation at that time.

2. Predicting the useful life of cutting inserts with various flank geometry

Overall cutting tool life can be divided into three phases with varying flank wear rates. During the running-in phase accelerated tool wear occurs, after which comes the stabilization phase showing decelerating wear intensity. For a prolonged period, the wear rate of the insert $J$ remains constant:

$$ J = \frac{dh_f}{dL} = \text{const}, $$

with $h_f$ being the linear flank wear, and $L$ being the cutting distance.

This period corresponds to the steady-state wear process. Once a certain critical size of the wear land $h_f$ is reached, the tool wear rate accelerates sharply. Accelerated wear rate is caused by higher tool temperature and the temperature-induced structural changes in the peripheral zones of the tool near the tool-workpiece interface. The effect of the contact area of the tool-workpiece interface on the processes that accelerate wear could be reduced by changing the flank geometry of the tool cutting edge.

As postulated by the energy theory of tool wear, the wear resistance of the cutting edge is characterized by the ratio of the friction energy expended to transform the workpiece sliding surface into wear debris, to the mass of tool wear debris under specific tool-workpiece interaction conditions [9]. Removal of the wear particles from the cutting insert requires accumulation of a critical energy in the localized volume of the insert material. The energy flux caused by the dissipation of mechanical frictional energy is stored in the surface layer of the tool cutting edge in the form of structural defects, that cause the removal of wear particles from the friction surface. The volumetric flow rate $Q$ of the removed wear particles can be represented as a function of the cutting power and the strength of the carbide tool material:

$$ Q = C \frac{P_z \cdot v}{HV}, $$

with $P_z$ – tangential component of the cutting force; $v$ – cutting speed; $HV$ – hardness of the tool; $C$ – factor that describes specific cutting conditions, i.e. physical and mechanical parameters of the tool and workpiece materials.

Hertzian hardness of the tool may be calculated using the following equation [10]:

$$ HV = HV_o \exp(-k_0 \theta), $$

with $HV_o$ – the room-temperature hardness, $k_0$ – thermal softening coefficient of the carbide, and $\theta$ – contact temperature.

To quantify the effect of the wear land $h_f$ on the cutting power, one needs to determine the effect of the cutting edge wear on the magnitude of components that comprise the cutting force [11]. We assume that the horizontal (tangential) $R_z$ and vertical $R_{xy}$ components of the chip formation force $R$ act on the rake surface of the tool (see Figure 1). The shear force $R_c$ is the projection of the resultant force $R$ onto the reference shear plane, and the angle between the forces $R_z$ and $R_c$ is equal to the angle of inclination of the reference shear plane $\beta_1$. The chip formation force $R$ during cutting causes compression and fracture of the cut layer along the plane of maximum stresses located at an angle $i_0$ to
its line of action. The angle $i_0$ is determined by the physical and mechanical properties of the workpiece material and usually lies within the range of $45^\circ$ to $50^\circ$.

Figure 1. Cutting scheme for the tool with worn flank

Assuming that the chip-forming force $R$ forms an angle of $i_0$ with the reference shear plane (with the $R_C$ force), then the angle between the forces $R$ and $R_Z$ equals $(i_0 - \beta_1)$.

In this case, the shear force $R_C$ is determined by the following equation:

$$R_C = \frac{\tau_p}{\sin \beta_1} a_1 b_1,$$

whereas the chip-forming force equals:

$$R = \frac{R_C}{\cos i_0} = \frac{\tau_p a_1 b_1}{\sin \beta_1 \cos i_0},$$

with $\tau_p$ being the plastic shear resistance of the workpiece material, $a_1$ – the thickness of the cut layer, $b_1$ – width of the cut layer, $\beta_1$ – inclination angle of the reference shear plane.

Horizontal and vertical components of the chip-forming force on the rake surface may be calculated using the following equations:

$$R_Z = R \cdot \cos(i_0 - \beta_1),$$

$$R_{XY} = R \cdot \sin(i_0 - \beta_1).$$

The flank of the tool is subject to both normal stress and tangential stress. If the law of tangential stress change is assumed to be triangular, then the average tangential stress is $\tau_{av} = 0.5 \cdot \tau_p$. Then the friction force $F_f$ acting on the flank surface of the tool can be calculated using the following equation:

$$F_f = 0.5 \cdot \tau_p \cdot b_1 \cdot h_f,$$

with $h_f$ – the contact length between the tool and workpiece on the flank surface.

Considering the forces acting on the flank, the tangential component of the cutting force equals:

$$P_z = R_z + F_f.$$

Substituting the functions (6) and (8) in equation (9), the resulting equation shall be:

$$P_z = \tau_p \cdot b_1 \left( a_1 \cdot \cos(i_0 - \beta_1) + 0.5 h_f \right).$$

Calculations based on equation (10) show that the tangential component of the cutting force $P_z$ increases monotonically as a result of flank wear. With a 2-fold increase in wear, the tangential component of the cutting force $P_z$ increases by 8%. Considering the proportional nature of the effect
of the width of the wear land \( h_f \) on the tangential component of the cutting force \( P_z \) and a negligible change in the tool hardness \( H_V \) until the onset of catastrophic wear, the volumetric flow rate \( Q \) (m\(^3\)/s) of the worn material can be considered constant over time for specific tribological situation and operating conditions. The possibility of this simplification confirms the linear change in the normal wear of the insert with cutting time, and the constant wear growth rate along this section of the wear curve [9,12].

The relationship between the amount of flank wear and the cutting time of the tool is established from the ratio of the volume of the worn part of the cutting edge, \( V \) (m\(^3\)), to the volumetric flow rate \( Q \) (m\(^3\)/s). In a standard free-cutting tool, the wear volume of the tool material is a geometrical object with the shape of triangular prism (see Figure 2).

![Figure 2. A scheme for calculating the volume of the worn part of the cutting insert with flat work surfaces](image)

The volume of the said prism is equal to the product of the cross-sectional area of wear, \( S_{ABC} \), with the width of the cut layer, \( b_1 \):

\[
V = S_{ABC} \cdot b_1, \quad (11)
\]

with \( b_1 = t / \sin \varphi \), \( t \) – depth of cut, \( \varphi \) – major cutting edge angle.

The area of the triangle, \( S_{ABC} \), can be calculated using the angles \( \alpha \), \( \gamma \) and wear parameters \( h_f \) and \( h_r \):

\[
S_{ABC} = \frac{h_f^2 \sin \alpha \cos \gamma}{2 \cos(\alpha + \gamma)} = \frac{h_r \cdot h_f}{2}. \quad (12)
\]

Equation (12) describes the relationship between the linear flank wear \( h_f \) and dimensional wear \( h_r \):

\[
h_f = \frac{h_r \cos(\alpha + \gamma)}{\sin \alpha \cos \gamma}. \quad (13)
\]

The overall wear volume of the worn part of the cutting insert equals:

\[
V = \frac{b_1 h_f^2 \sin \alpha \cos \gamma}{2 \cos(\alpha + \gamma)} = \frac{b_1 h_r^2 \cos(\alpha + \gamma)}{2 \sin \alpha \cos \gamma}, \quad (14)
\]

where \( b_1 \) is the thickness of the cut layer; \( h_f \) is linear flank wear of the tool; \( h_r \) is dimensional wear of the tool; \( \alpha \) and \( \gamma \) are relief angle and rake angle of the tool, respectively.

The service life of the tool \( T \) up to the value \( h_f \) can be found from the ratio of the volume of the worn part of the cutting insert \( V \) to the volumetric flow rate \( Q \) of the material removed from the tool:

\[
T = \frac{V}{Q} = \frac{b_1 h_f^2 \sin \alpha \cos \gamma}{2Q \cos(\alpha + \gamma)}. \quad (15)
\]
According to model (15), during cutting both the wear land $h_f$ and the dimensional wear $h_r$, change in accordance with the following relationships:

$$h_f = \left( \frac{T2Q \cos(\alpha + \gamma)}{b_f \sin \alpha \cos \gamma} \right)^{1/2};$$  \hspace{1cm} (16)

$$h_r = \left( \frac{T2Q \sin \alpha \cos \gamma}{b_r \cos(\alpha + \gamma)} \right)^{1/2}. \hspace{1cm} (17)$$

Considering that until the onset of catastrophic wear of the tool, the width of the wear land $h_f$ has relatively minor effect of on the wear rate $J$ and therefore, on the volumetric flow rate of the worn material $Q$, the equations (16,17) can be presented as:

$$h_f = C_h \cdot \left( \frac{T \cdot \cos(\alpha + \gamma)}{\sin \alpha \cos \gamma} \right)^{1/2},$$  \hspace{1cm} (18)

$$h_r = C_h \cdot \left( \frac{T \cdot \sin \alpha \cos \gamma}{\cos(\alpha + \gamma)} \right)^{1/2}, \hspace{1cm} (19)$$

with $C_h = \left( \frac{2Q}{b_h} \right)^{1/2}$ being the factor dependent on the cutting conditions and the properties of the tool and workpiece material. This factor may be determined using one of the points on the experimental wear curve, e.g., for milling cutting of the difficult-to-cut material at the speed of $v = 180 \text{ m/min}$, depth of cut $t = 0.6 \text{ mm}$ and feed rate $s = 6 \text{ m/min}$, the factor $C_h$ equals $0.027 \text{ m/s}^{0.5}$.

Relationships (18,19) make it possible to determine the nature and degree of effect of the geometric parameters of the tool cutting edge on the flank wear rate. Calculations show that the effect of the clearance angle $\alpha$ on the wear of the cutting insert $h_f$ is most pronounced for the lower values of the clearance angle (see Figure 3).

![Figure 3. Calculated tool wear curves $h_f$ for the flat flank surface geometry: $C_h = 0.027 \text{ m/s}^{0.5}$, $\gamma = -8^\circ$, $\alpha = 3^\circ$ to $15^\circ$.](image)

With an increase in the clearance angle from $5^\circ$ to $9^\circ$, the dulling time of the insert before reaching optimal wear criterion increases twofold. Additionally, the decrease in the growth rate of $h_f$ is
accompanied by an increase in the dimensional wear rate of the insert, $h_r$, which must be considered during finishing operations (see Figure 4).

![Figure 4](image1)

**Figure 4.** Calculated tool wear curves $h_r$ for the flat flank surface geometry: $C_h = 0.027 \text{ m/s}^{0.5}$, $\gamma = -8^\circ$, $\alpha = 3^\circ$ to $15^\circ$

The strong effect of the clearance angle on the tool wear resistance confirms the relevance and practical importance of methods for controlling the tool wear behavior by changing the geometry of insert flank surface.

We consider a tool cutting edge with a convex flank with a radius $R$ (see Figure 5). The volume of the worn part for this insert up to reaching wear land $h_f$ is equal to the product of the cross-sectional area of wear $S_w$ with the length of the engaged section of the cutting edge $b_1$:

$$V = S_w \cdot b_1.$$  \hspace{1cm} (20)

The cross-sectional area of wear can be defined as the sum of the areas of the ABC triangle and the AB segment:

$$S_w = S_{ABC} + S_{\text{segm}}.$$  \hspace{1cm} (21)

![Figure 5](image2)

**Figure 5.** A scheme for calculating the volume of the worn part of the cutting insert with a convex flank geometry
The area of the triangle $S_{ABC}$ is expressed via the geometric parameters of wear $h_f$, $h_r$ and the angles of the ABC triangle:

$$S_{ABC} = \frac{h_f \sin \left( \alpha + \frac{\theta}{2} \right) \cos(\gamma)}{2 \cos \left( \alpha + \frac{\theta}{2} + \gamma \right)} = \frac{h_f \cdot h_r}{2}. \quad (22)$$

The area of segment AB of a circle with radius $R$ equals:

$$S_{segm}^{AB} = \frac{R^2}{2} \left( \frac{\pi}{180} - \sin \theta \right), \quad (23)$$

with $\theta$ being the angle (in degrees).

To establish the dependence of the angle $\theta$ on the value of $h_f$, we consider the ABC triangle. According to the sine theorem:

$$\frac{h_f}{\sin \left( 90 - \left( \alpha + \frac{\theta}{2} + \gamma \right) \right)} = \frac{AB}{\sin(90 + \gamma)},$$

$$AB = \frac{h_f \cos \gamma}{\cos \left( \alpha + \frac{\theta}{2} + \gamma \right)}. \quad (24)$$

On the other hand, the length of the AB chord of a circle with radius $R$ equals:

$$AB = 2R \sin \frac{\theta}{2}. \quad (25)$$

Equating the expressions (24) and (25) yields:

$$\frac{h_f \cos \gamma}{\cos \left( \alpha + \frac{\theta}{2} + \gamma \right)} = 2R \sin \frac{\theta}{2}. \quad (26)$$

Whence it follows that the wear land $h_f$ equals:

$$h_f = \frac{2R \sin \frac{\theta}{2} \cos \left( \alpha + \frac{\theta}{2} + \gamma \right)}{\cos \gamma}. \quad (27)$$

Substituting relationship (22) into the equation (27) produces the model to calculate the dimensional wear $h_f$:

$$h_f = \frac{h_r \sin \left( \alpha + \frac{\theta}{2} \right) \cos \gamma}{\cos \left( \alpha + \frac{\theta}{2} + \gamma \right)}. \quad (28)$$

Equations (20-28) were used to plot wear curves $h_f = f(T)$, $h_r = f(T)$ for inserts with convex flank surfaces. The calculations were performed according to the following algorithm: 1) the value of $\theta$ was given; 2) the wear values $h_f$, $h_r$ were calculated; 3) the amount of tool wear $V$ was calculated; 4) the volumetric flow rate of the tool was determined $Q = C_n \cdot b/2$; 5) tool life $T = V/Q$ was calculated, based on $h_f$ and $h_r$. Figure 6 shows the calculated wear curves $h_f=f(T)$ for the inserts.
Figure 6. Calculated wear curves for cutting inserts $h_f$ with different flank surface geometry: 1 - flat, 2 - convex; $\alpha = 8^\circ$, $\gamma = -8^\circ$, $R = 3\text{mm}$

The analysis of the wear curves shows that the convex shape of the flank surface can significantly increase the tool life prior to reaching the maximum permissible wear land on the flank surface $h_f$. The life of an insert with a radius of $R = 3\text{mm}$ and an initial clearance angle $\alpha = 8^\circ$ increases by factor of 2, as compared to the insert with standard geometry. However, it should be noted that for such inserts a decrease in the growth rate $h_f$ is accompanied by an increase in the dimensional wear rate $h_r$ of the insert (see Figure 7).

Figure 7. Calculated wear curves $h_r$ for cutting inserts with different flank geometry: 1 - flat, 2 - convex; $\alpha = 8^\circ$, $\gamma = -8^\circ$, $R = 3\text{mm}$

Inserts with a flat flank and small clearance angles are preferred for finishing operations, as these can maintain their process stability for a longer time.

The described procedure was used to predict flank wear of an arbitrarily shaped cutting insert. Theoretical analysis showed that in a number of cases more effective flank shape is the one that comprises a set of elementary surfaces with different geometries. For example, for assembled milling cutters equipped with negative tangential inserts, it is recommended to use flank geometry comprising a straight section with length $l$, a convex surface with $R_1$ and a concave surface with $R_2$ (see Figure 8). Such flank geometry in an insert may be termed “hybrid”. The wear rate $dh/dT$ of a tool with a hybrid flank surface depends on the shape and size of elementary surfaces.
Figure 8. Scheme of cutting with an insert featuring a hybrid flank surface

Figure 9 shows the calculated wear curves for inserts featuring both hybrid and flat flank surfaces when used for milling cutting of rails. In this figure curve 1 corresponds to an insert with a flat flank surface, whereas curve 2 refers to an insert with a hybrid flank geometry comprising adjoining straight sections with the width $l = 0.25$ mm, convex and concave surfaces with radii $R_1 = 1$ mm and $R_2 = 2$ mm. The clearance angle for both inserts was 8 degrees. The curves show that in milling operations using hybrid-flanked inserts the nature of wear is changed. Initial phase of cutting sees all inserts wearing identically. After reaching the wear $h_f = 0.25$ mm, the growth rate of wear in hybrid-flanked insert is dramatically reduced. Reduction of the wear rate $dh/dT$ of the tool depends on the position and curvature of the convex and concave surfaces.

Figure 9. Calculated wear land size on the flank surface vs. cutting time for inserts with (1) flat and (2) hybrid flank geometry: $C = 0.027$, $l = 0.25$ mm, $R_1 = 1$ mm, $R_2 = 2$ mm, $\alpha = 8^\circ$, $\gamma = -8^\circ$
The calculated data are well supported by experimental results. The positive effect of optimizing the flank shape of the SNEX 1207 insert is clearly shown by comparing the wear on standard and modified-flank inserts (see Figure 10).

![Figure 10. Comparison of wear for modified-flank (a, c) and standard (b, d) inserts](image)

Figure 10 shows that on the inserts with a curved flank surface, wear is distributed more evenly along the engaged section of the cutting edge, and the size of the wear land is much smaller than that of standard SNEX 1207 inserts made of the same carbide grade. The average life of new SNEX 1207 inserts is more than by factor of 2 longer, as compared to that of standard inserts.

3. Optimization of the flank geometry for the tool based on criterion of maximizing useful life with regard to the insert strength

When choosing the shape and dimensions of the insert flank geometry, the limiting factor is the strength of the cutting edge of the insert. Therefore, the algorithm for designing the IFCI should include an assessment of the strength of the proposed design. To ensure the maximum tool life with regard to the strength of insert, a Pro/Engineer code was used to develop a procedure for computer-aided design and optimization of the calculation of complex-shaped flank geometry. The procedure includes the following steps: 1) creation of a computational model of the insert; 2) modeling of flank wear; 3) strength analysis of cutting inserts with a complex-shaped flank surface; 4) optimization analysis according to the criterion of maximum useful life, with regard to the strength of the insert (see Figure 11).

![Project goal (output parameters)](image)

Figure 11. The scheme for solving the optimization problem in Pro/EngineerWildfire CAD code, version 4.0

The strength calculation of the insert model is carried out in the ‘Mechanica’ application, activated
directly from the work session on the 3D-model of the insert. The calculation includes splitting the insert model into finite elements, giving contact stresses for the insert rake and flank, determining the stress-strain state of the insert and comparing it to the fracture criterion. Following the iterative changes in the geometry parameters, the optimal design of the insert is selected.

The above design algorithm was used to optimize the shape and to improve the strength of new inserts. As a result, new original complex-shape inserts were proposed with curved rake and flank surfaces that form – in the insert’s reference secant plane – a cutting blade with rake angles decreasing with distance from the cutting edge and increasing clearance angles, whereas the intensity of the increase in the clearance angles is less than or equal to the intensity of the reduction in rake angles [13]. In a particular example, the IFCI can have a concave rake and a convex flank surface, forming a tool blade with a rake angle at the cutting edge \( \gamma_0 \) and a clearance angle at the cutting edge \( \alpha_0 \). In the reference secant plane, perpendicular to the projection of the main cutting edge onto the reference plane of the cutting insert, the surfaces form circular arcs, whereas the curvature radius of the flank surface is greater than or equal to the curvature radius of the rake surface (see Figure 12).

\[ J_{\alpha} = \Delta \alpha / \Delta \rho = (\alpha_0 - \alpha_0) / \rho, \quad (29) \]
\[ J_{\gamma} = \Delta \gamma / \Delta \rho = (\gamma_0 - \gamma_0) / \rho, \quad (30) \]

\[ \gamma_0, \alpha_0 \] being rake angle and flank angle at the cutting edge 4, \( \gamma_0, \alpha_0 \) – rake angle and flank angle at the distance of vector \( \rho \) radius from the cutting edge 4.

Increased strength of the cutting insert is attributable to overall decrease and more favorable
distribution of stresses in the tool edge, as generated by the cutting forces. The effect of increased strength grows more pronounced with the increasing flank curvature radius $R_f$ and diminishing rake curvature radius $R_r$. For example, under effective cutting force of 548 N, the stresses in the tool blade with curved cutting surfaces $R_f = R_r = 10$ mm, $\gamma_0 = 0$ and $\alpha_0 = 10^\circ$ decrease by 30 %, as compared to the stresses in the cutting wedge with flat cutting surfaces. Reduced stresses lead to greater safety margin of the tool, which is beneficial for applications involving higher feed rates and greater depths of cut.

Conclusions
1. A procedure for the optimization design of the IFCIs is proposed, enabling evaluation of effectiveness of various tool flank shapes and substantiation of their rational geometric parameters.
2. The paper enables the designer to control cutting insert wear behavior by changing its flank shape. High efficiency of the new approach was proven.
3. New designs of carbide cutting inserts with a curved flank shape were proposed, offering significant benefits for the tool service life.
4. The results of the cutting tests with new tools show higher efficiency of new inserts with the modified flank shape.

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