Optimisation of metal-cutting tool geometry based on chip formation requirement

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Abstract. This study of the process of chip formation and curling when cutting ductile materials supplements the work of well-known authors in this field. The relevance of theoretical and experimental research stems from determination of the design parameters of chip formation by the flat spiral shape. The study used tools and materials that closely resemble those used in machine repair shops. A distinctive feature of this study is the use of theoretical and experimental data to determine the conditions of chip breaking and to design chip-forming elements on the cutting face of a metal-cutting tool. The obtained results allowed theoretical calculation of the geometrical parameters of a metal-cutting tool in constrained cutting and determination of the areas of chip formation with a high bulk density.

1. Introduction

Modern machine-building industry has a fairly wide range of metal-cutting tools at its disposal. This is especially true for lathe tools. Tools with replaceable indexable inserts are considered to be the most cost-effective. The main structural elements on the cutting face of a metal-cutting tool designed to form and remove chips from the cutting zone are the width of the chip-breaking step, its height, and cutting edge inclination angle $\lambda$, indicated in Fig. 1 as the angle between the Y axis and the inclined cutting edge. The latter angle determines the chip flow direction. The geometrical parameters of these elements are mainly assigned on the basis of empirical studies after conducting the relevant experiments, which is indicated by the relationship observed between the centres of the areas of the recommended cutting conditions in the S/t coordinates, which is equal to 0.1 [2]. The presence of various geometries of the cutting face in replaceable indexable inserts and the constraint $S/t = 0.1$ may be considered unreasonable. The use of expensive tools in agricultural repair shops is economically impractical. Therefore, there is a need for a simplified pattern of chip formation and curling, which could provide adequate information about the processes occurring during the transformation of the cut layer into chips. These phenomena should be examined in the plane of deformation that passes through the direction of the movement vectors of the cut layer and the chips [1].

The objective of this study is to develop a simplified pattern of chip formation and curling, which could provide adequate information about the processes occurring during the transformation of the cut layer into chips when workpieces are machined during the repair and reconditioning of machine components. Chip formation should be examined in the plane of deformation that passes through the direction of the movement vectors of the cut layer and the chips.
2. Theoretical section

Chip formation in constrained cutting has certain particular features. Here, several straight and curved cutting blades are involved in the cutting process. This results in a variable thickness of the cut layer, sometimes a variable cutting speed, and, as a consequence, a variable rate of deformation of metal particles. Studies of the features of the constrained cutting process largely deal with finding the shape of the conditional shear surface and determining the angle of chip deviation from the plane perpendicular to the main cutting edge [6, 10 - 12].

In constrained cutting patterns, it's not the length that plays a vital role, but the contact spot, which can be obtained as follows [3, 8]: the contact length calculated for the specific cutting layer thickness $a_i$ is marked from the cutting edge in the chip flow direction $\eta$. The geometry of this contact for constrained cutting of brittle materials is based on the experimentally observed symmetry of the contact spot shape [11, 12].

It follows from the examined chip formation pattern that the chip flow direction defined by the angle $\eta$ is very important for studying the mechanics of constrained metal cutting. It has been found that the initial angle of the chip flow is determined by the ratio of the projected areas of the conditional shear surface to the coordinate planes $F_x$ and $F_y$ [2]:

$$\tan \eta = \frac{F_x}{F_y}.$$ (1)

Using CAD/CAM/CAE software eliminates the need for numerical and approximate calculations of the projected areas and the positions of the centres of gravity of projections and cross-sections. We used the KOMPAS-3D software in our calculations. Figure 1 shows a version of simulation of the chip element flow over the cutting face of a metal-cutting tool built in the above-mentioned software. KOMPAS-3D can calculate not only the coordinates of the centres of gravity of projections of conditional shear surfaces, but also the values of moments of inertia, which affect the shape of the chips being formed [3, 7].

Chip formation patterns in constrained metal cutting can help determine the direction of chip movement at the beginning of chip formation and explain the complex shape of the cross-section of chips; however, the above patterns cannot help predict the shape and dimensions of the chips being formed along its length. Chip curling patterns solve this problem.

Certain chip formation parameters during oblique constrained cutting are described fairly well [7, 8, 9, 11, 12]. The main disadvantage of the existing models is that they examine the deformation of chips in the plane perpendicular to the supporting surface. We suggest examining a model of chip formation in space. A distinguishing feature of the proposed model is the interconnection between the chip formation and curling zones. The layer of metal being cut is deformed into chips, passing the regions of elastic, plastic flow, elastic recovery, and a rigid one. During continuous chip formation, the chips, moving on the cutting face of the tool at a constant speed, are in a state of dynamic equilibrium. The chip flow direction is in the plane of action of the resultant of forces and the cutting speed. Applying weak external forces to the chips at the time of their formation changes their shape, because the region of plastic flow exists constantly, while the rigid portion of the chips, which becomes free from the external cutting forces, remains connected thereto. In general, chip curling occurs in two planes: the plane of the cutting face of the tool and the plane of the chip flow perpendicular to the cutting face.

In terms of cutting process stability, safety of machining, transport and recycling conditions, the most convenient chips are chips curled in a flat spiral, which have the lowest weight factor for flow chips [3]. This shape comes from chip curling in the cutting plane of their flow.

Figure 1, a shows the cutting portion of the tool with an element of the flowing chips. Let us assume that the normal and tangential loads on the force contact spot between the chips and the cutting face are distributed according to a certain law. As a first approximation, it can be assumed that the stresses on the conditional shear surface and the tangential loads on the contact spot are evenly distributed. If the chips encounter no obstacles along the way, assuming the chip movement speed on
the cutting face of the tool to be constant, we find that the forces acting on the chips from the conditional shear plane $ABD$ and the cutting face $AA'B'B$ are balanced. This will fulfil the condition of circular curling shown in Figure 1, b.

![Diagram for determining the centres of gravity of the cross-section of chips, the force contact spot, and the chip flow angle](image)

**Figure 1.** Diagram for determining the centres of gravity of the cross-section of chips, the force contact spot, and the chip flow angle, a – diagram of a chip element on the cutting face of a metal-cutting tool; b – diagram of projections of the conditional shear surface.

In general, the points of application of the chip pressure to the tool at the centre of gravity of the conditional shear surface $ABD$ and the centre of the contact spot $AA'B'B$ do not coincide. This results in a bending moment that defines the so-called “natural” curling of chips of general form. In this case, the arm between the centres of forces, specifically the centres of gravity of the conditional shear surface and the chip contact spot, determines the bend of chips in the vertical plane towards the cutting face [7]. Circular chip curling occurs when the forces of chip formation and friction on the cutting face are in the same vertical plane. This condition is fulfilled when the horizontal coordinate of the centre of gravity of the cross-section of chips coincides with an equivalent coordinate of the centre of gravity of the force contact area between the chips and the cutting face of the tool.

To design the cutting face of a metal-cutting tool that fulfils the conditions for circular chip curling in the cutting plane of chip flow, it is necessary to know the chip flow direction and the contact spot dimensions. Generally, the cutting edge $AB$ can be described by the sequence of points $(x_i, y_i, z_i)$, and its previous position $A'B'$ can be described by the sequence of points $(x_i-s, y_i, z_i)$, where $s$ is the feed rate, mm/rev. Let us examine the cut layer cross-section, which is formed by two consecutive positions of the cutting blade (Fig. 1). In the case of a curved blade of arbitrary shape, for certain cutting depths $t$ and feed rates $s$, it is always possible to determine the coordinates of the nodal points of the cut layer cross-section: $AA'B$. Let us assume that the shear angle $\beta_i$ in the chip flow direction for any point of the working section is constant and apply the pattern with a single conditional shear surface. The ratio
of the projected areas of the conditional shear surface to the coordinate planes $F_x$ and $F_y$ sets the initial chip flow angle $\eta_0$, and the actual chip flow angle $\eta_d$ depends only on the cutting depth and the feed rate, which determine the nodal points of the cut layer cross-section and the cutting edge geometry in plan view.

Knowing the chip flow angle will help predict the chip movement on the cutting face of a metal-cutting tool and design the geometry of replaceable indexable inserts with predetermined properties with greater precision. The proposed methodology can be used to calculate the simplified geometry of replaceable indexable inserts for mechanical sharpening in shops for repair and reconditioning of machine components.

3. Experiment

The main factor that complicates the study of the chip movement pattern on the cutting face is its sensitivity to external forces, which causes changes in the chip flow direction while the machining conditions remain unchanged. In addition, there are no reliable methods for measuring the chip flow angle [3].

The analysis of literature sources has shown that most definitions of the term “chip flow angle” or “chip deviation angle” refer to machining with a straight cutting edge. These angles are measured from the perpendicular to the cutting edge [11, 12].

In machining with a curved cutting edge, the concept of the perpendicular to the main cutting edge becomes irrelevant for chips in general. In our studies, we assumed that the chip flow angle is measured as the angle in the cutting face plane of the insert between the perpendicular in the line defining the chip cross-section $AB$ and the workpiece rotation axis.

Various means and methods are used to measure the chip flow direction. One of the simplest and most effective methods is coating the tool with paint or some other material (the most common being a layer of copper) and observing the trace left by the chips on the cutting face after the cutting process is stopped. In this case, even minor oscillations in the chip movement will distort the trace pattern. In addition, it is believed that during the curvilinear motion of chips the trace left on the cutting face defines only a certain average direction of the chip flow within the contact patch between the chips and the cutter. Another method is based on the immediate stop of the cutting process and the direct measurement of the chip flow direction along the chip root. In this case, it is the immediate stop that is very difficult to carry out. A more reliable method of direct observation is taking photographs of the chips when they move on the cutting face [3]. The series of photographs of the instantaneous positions of the moving chips allow examining the process kinematics. However, this method is labour-intensive.

If we replace the taking of photographs of the chip flow with video recording with further digital representation, the process of data processing becomes faster and allows performing a detailed analysis of the image. Figure 2 shows the digital photographs of the chip flow taken within 10 seconds with one-second intervals. These measurements have shown that the chip flow angle varies from $43^\circ$ to $57^\circ$ within 10 seconds, with its arithmetic mean value being $50.4^\circ$. The calculated value of $50^\circ$ was obtained using the same machining conditions. The minimum value of the absolute error of the calculated chip flow angle on the cutting face was 2%, the maximum value was 14%, and the average value was 9.2%. Therefore, later in the study, the chip flow angle was measured using the video recording of the chip flow on the cutting face of replaceable indexable inserts.

In the experiments on measuring the chip flow angle, the cutting conditions were chosen such that “flat” or “cylindrical” spiral chips were formed in most cases.

Figure 3 shows the experimental measurement results for the chip flow angle on a flat cutting face. A cemented carbide tool with replaceable indexable inserts with a flat cutting face was used. The 20G steel was chosen as the material to be machined. A very wide range was adopted for the cutting conditions, with the cutting depth varying in the range of $t = 0.3–3$ mm and the feed rate $S = 0.17–1.2$ mm/rev.
Figure 2. Sequence of images showing the change in the chip flow angle over a 10-second period during formation of helical spiral chips.
The cutting speed varied from 120 m/min to 200 m/min. An analysis of the results obtained showed that with an increase in the feed rate, the chip flow angle also increased, while the cutting depth and speed within the specified intervals did not have a significant effect on the chip flow angle. In this respect, we consider the presentation of experimental data depending on the S/t relationship to be the most convenient, especially because this coordinate reflects the chip-breaking areas in the manufacturers’ catalogues [4, 5]. It follows from this relationship that with an increase in the feed rate the chip flow angle increases, and that this effect is the greatest with comparable values.

A correlation relationship between the chip flow angle and the S/t ratio may be constructed (Figure 3). In the case of a linear relationship, the correlation coefficient is 0.93. The analysis of the linear regression equation demonstrated the significance of the coefficients and the equation as a whole.

The theoretical calculations of the chip flow angle and the circular curling conditions and their experimental verification allowed designing replaceable indexable inserts with the required cutting face shape. The complex reticulate surface [2] was replaced with a plane; deviations from the calculated values of the cutting edge inclination angle did not exceed 1.5°.

Figure 3. Dependence of the chip flow angle on the cut layer cross-section S/t:
• – calculated from the ratio of the projected areas of the conditional shear surface;
x – measured for the conditions: t = 0.3–3 mm and feed rate S = 0.17–1.2 mm/rev, the tip radius was 0.5 mm.

Figure 4. Drawing for sharpening and insert designed from the conditions of circular curling for the following conditions: t = 0.5–2 mm and S = 0.05–0.6 mm/rev
Figure 5. Effect of the S/t value on the bulk density of chips when machining at a cutting depth: x – using an insert with the designed cutting face shape; • – using an insert with a flat cutting face

Experiments were performed to determine the chip-breaking properties of inserts with a flat cutting face and with a radius groove using a CNC lathe, which ensured the required rigidity of the manufacturing system. A cutting tool with the following geometrical parameters was used: \( \varphi = 45^\circ \), \( \varphi_1 = 45^\circ \), \( \alpha = 7^\circ \), \( \gamma = 4^\circ \), \( \lambda = 3^\circ \). A 20G steel shaft with a diameter of 70 mm was machined.

Two types of inserts were tested in the course of the study: an insert with a flat cutting face, taken as the standard, and an insert with a chip-forming groove. The material used for the insert was T15K6, according to GOST 3882-74. The experimental inserts were produced by modifying the standard insert for the calculated conditions of circular curling.

During the experiments the formed chips were collected and weighed using a precision balance to determine the bulk density. The bulk density \( \rho \) was determined by dividing the chip weight by their volume.

During the first stage, the chip-breaking properties of inserts were tested for the design conditions. The tests showed that the standard insert produced flow chips in the form of a helical spiral, whereas the insert with the proposed shape produced finely broken chips with highly stable pieces.

For an exhaustive comparison of the chip-breaking properties of replaceable indexable inserts with the designed shape and those with a flat cutting face, experiments were performed within the cutting depth range \( t = 0.5 \)–\( 2 \) mm and the feed rate \( S = 0.05 \)–\( 0.6 \) mm/rev \( (V = 1.67 \) m/s); the results were used to obtain the chip-breaking diagrams shown in Figure 5.

The results of the study of the chip-breaking properties of replaceable indexable inserts with a flat cutting face showed that in fine-finish and semi-finish cutting conditions, in the depth range \( t = 0.5 \)–\( 1 \) mm and \( S = 0.05 \)–\( 0.6 \) mm/rev, both flat and helical spiral chips are formed by external longitudinal cutting. The bulk density in this case varies from 1.78 g/cm\(^3\) to 2.5 g/cm\(^3\). When the cutting depth is increased to \( t = 1.5 \)–\( 2 \) mm and in the feed rate range \( S = 0.2 \)–\( 0.6 \) mm/rev, the shape of the formed chips changes from multi-turn to single-turn and half-turn spirals, which leads to a sharp decrease in the bulk density. Thus, when \( t = 1 \) mm and \( S = 0.2 \) mm/rev, \( \rho = 2 \) g/cm\(^3\), and when \( t = 2 \) mm and the feed rate is the same, \( \rho = 0.97 \) g/cm\(^3\).
The analysis of the chip shapes produced by cutting with the standard and experimental inserts clearly demonstrates that the proposed shape of a square indexable insert with a chip-forming groove has high chip-breaking properties not only for the design conditions, but also in the expanded range of t and S. This is confirmed by an average 4- to 6-fold reduction in the bulk density of chips.

The economic efficiency achieved as a result of introduction of replaceable indexable inserts with improved chip-breaking properties has several aspects: in the case of mass production, the chip recycling time will be reduced, and for one-off production associated with shops for repair and reconditioning of machine components, the proposed methodology will reduce the expenses for metal-cutting tools and support of the machining process in general.

4. Conclusions
1. The importance of the cutting face shape in chip formation was determined, the shape elements of replaceable indexable inserts that are directly involved in cutting and chip formation processes were identified.
2. The use of the Kompas-3D CAD/CAM/CAE software enabled us to change the method of calculating the circular curling conditions and to simplify the calculation procedure.
3. Based on the theoretical and experimental studies performed, we established that the chip flow angle on a flat cutting face depends only on the cutting edge shape and the cut layer cross-section and, consequently, on (S, t, r, φ, φ1), but not on the cutting speed. The comparison of the experimental and calculated values of the chip flow angle and the contact length allows using calculated data in the design of the chip-forming elements on the cutting face of replaceable indexable inserts.
4. A methodology was proposed for designing chip-forming elements to form circular chips, the latter being the optimum choice for subsequent recycling.

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