Modelling and controlling the process of cutting with complex-geometry tools to improve efficiency of mining machines and plants

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Abstract. Constant quality improvement through automation of production processes is an important prerequisite for increased viability of mining machines and plants. Factors that limit the automation of the cutting machining operations include the problem of controlling the chip formation and chip crushing. Solution of this problem necessitates theoretical description of the material cutting conditions for tools with curvilinear surfaces. The paper describes basic principles of modeling the cutting process using complex-geometry tools with curvilinear rake. The theory is based on the concept of chip formation as a process of inhomogeneous strain in the plastic zone where the chip originates. Based on the analysis of the stress-strain state in the cutting zone, criterial relationships were derived that correlate the geometric parameters of the chip shape and machining conditions of the curvilinear-rake tool. Prerequisites for chip breaking are stability of the chip shape during cutting, stable chip-to-obstacle contact, high chip stiffness and low flexibility. The machining conditions leading to chip fragmentation could be found by solving the strength problem. Through establishing the cause-and-effect relationships of the processes of chip formation, curling and breaking, new approaches to achieving favorable chip shape may be found by exerting deliberate impact on the plastic zone of the chip formation through optimizing the conditions for the chip flow off the tool. The established relationships between the output parameters of the cutting process and process conditions of cutting with a complex-geometry tool offer the way to control the chip flow parameters in various machining operations. The research is aimed at creating scientifically informed design codes and optimization of cutting parameters for tools with curvilinear chip-curling and chip-breaking rake surfaces.

1 Introduction

Efficiency gains in mining machinery and plants' engineering are directly related to the automation of technological processes, the use of CNC machines, automated machine tool lines, and flexible processing systems. Among most pressing problems in setting up the cutting process under automated production is the problem of controlling the chip formation and crushing. Formation of an unfavorable chip shape during cutting may drastically reduce machining reliability, and in some cases also endanger the feasibility of processing automation and robotization. The simplest and reasonably effective approach involves controlling the chip shape through adaptation of cutting conditions, as well as tool rake geometry and shape. The proposed guidelines for design and application of cutting inserts with complex-geometry rake are mainly founded in author's processing experience and experimental research.

2 Materials and methods

The process of cutting with tools featuring flat rake surface has been thoroughly researched by now. Significant efforts have been dedicated to gaining insights into the mechanisms controlling the formation of rectilinear continuous chips. In contrast, there are few systematic studies aimed at modeling the cutting process with a tool that features a complex-geometry curvilinear rake surface. The obvious advantages offered by the complex-geometry designs of cutting inserts impart high relevance to the problem of predicting the process of cutting with such tools.

The established classical theory of cutting treats chip formation as a process of uniform deformation of the cut layer [1,2]. This approach cannot be used to effectively predict the performance of a complex-geometry tool, nor to design improved tools with curvilinear rake surfaces. As a result, the selection of rational cutting parameters and tool geometry is achieved through labor-intensive experimental approach.

3 Results and discussion

The important advantages of the curvilinear rake of the tool are stabilization and control of the processes of chip curling and chip breaking [3,4]. Unfavorable chip

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formation shortens tool life and lowers the quality of the machined surface of the workpiece, causes machining problems and tool failure, prevents automatization of chip removal and transportation, and reduces the efficiency of chip recycling. This problem is relevant for most metalworking companies.

Much attention is paid globally to the problems of predicting and controlling chip shape. The controllability of the chip formation process is of par importance with the quality of machining, durability of the tool, and cutting power. This area is actively discussed by the engineering community and experts. Despite extensive research, the problem is yet to be solved. Theoretical papers mainly offer kinematic analysis of the chip curling mechanism [5,6,7]. Practical solutions are mostly based on processing experience [8,9]. Empirically developed guidelines for the design and use of cutting inserts to achieve a favorable chip shape (FCS) have only limited applicability. Lack of adequate models to simulate chip formation, describing chip geometry and methods of breaking the chip into fragments is a major factor that limits development of automated systems for designing machining processes and tools.

The main reason complicating the research is the inherently unstable nature of the chip formation process. The instability of chip formation is manifested outwardly in the fact that under identical cutting conditions different types of chips could be observed to form. The shape of the chip depends on multiple factors, including apparently minor effects on the zone where the chip originates. Even limited forces can be sufficient for redistribution of the stress-strain state in this plastic zone.

When cutting tool has a chip curler feature, initial chip curvature radius is limited by a ledge placed in the chip flow path. Creation of chip curler elements on the rake surface stabilizes the contact conditions of chip deformation, reducing the range of variation of all parameters of the cutting zone. The chip curler elements act - through the elastic part of the chip - on the plastic deformation zone of the cut layer, changing parameters in the cutting zone and altering the chip shape as it forms.

The natural cause of chip curling is inhomogeneous plastic deformation of the cut layer, which leads to variable shrinkage over the thickness and width of the cut layer. As a result of inhomogeneous plastic deformation in the primary shear plane, conditions are created for the curling of chip in three orthogonal planes [3, 10]. The most sensitive parameter of the inhomogeneous stress-strain state in the cutting zone is the chip curvature radius in the chip flow plane, R_n. Fig. 1 shows the diagram of chip curling process in this plane, based on experimental data.

The diagram on Fig.1 shows the source of primary plastic deformation as a single curved shear surface A-M-B. The area of secondary plastic deformation is limited by the slide lines A-M and M-C. As a result of nonuniform deformations along the thickness of the cut layer, the main part of the chip assumes curved shape already when it exits the primary plastic deformation zone, and - due to the secondary deformation of the contact layers- chip flows not parallel to the cutter rake surface, but at an angle to it. This leads to a decrease in the actual cutting angle and an increase in the angle of inclination of the conditional shear surface. By creating optimal conditions for chip curling, it is possible to achieve reduction of the cutting forces. According to both calculated and experimental data, the cutting forces and cutting power could be reduced by up to 20%. The apparent paradox of a decrease in cutting forces when chip breaker is present on the tool rake is explained by reduction of plastic deformation zone caused by more inhomogeneous stress-strain state in the cutting zone. Conversely, any attempts to curl the already formed chip shall require significant additional efforts. The insights into the physical nature of chip curling found in the course of research provide the basis for development of a mathematical model of chip formation, linking processing conditions with the output characteristics of the cutting process, including the shape and direction of chip flow.

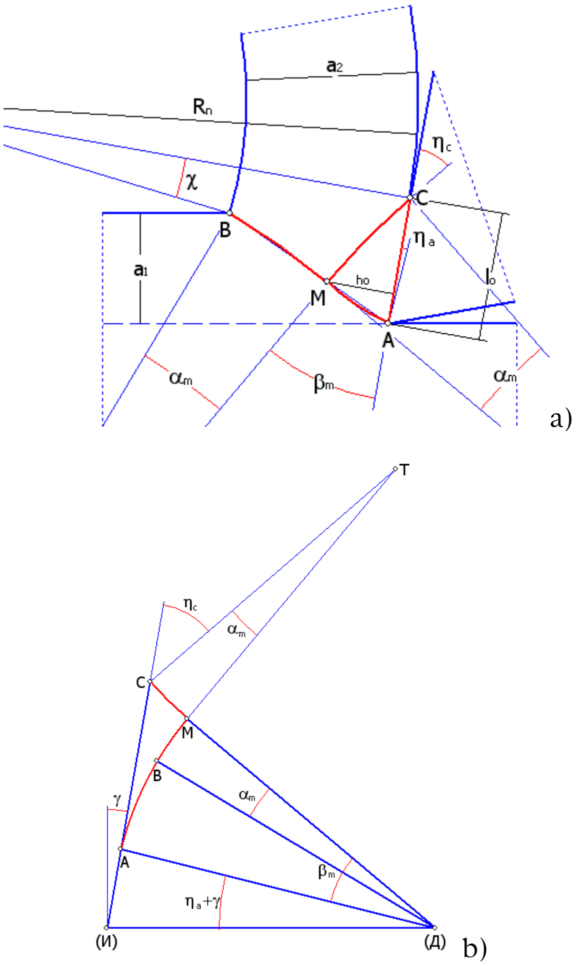

Fig. 1. (a) The boundaries of slide lines in the cutting zone. (b) velocity hodograph. a_l=0.5mm, β_1=35°, γ=10°, η_A=4°, η_C= 39°, R_n =2.6mm, α_m=9.2°, β_m =26°.

The analysis of the inhomogeneous stress-strain state of the cutting zone by similarity theory techniques yielded the criterial functions to describe average shrinkage and chip-tool contact length, depending on the cutting conditions [11] and chip curvature radius R_n:

$$B = c \cdot A^{x} D^{z} E^{y} \left(1 - \sin \gamma_{\phi}\right)^{n} k_{\text{И}} k_{C} \qquad (1)$$

$$\frac{l}{a_1} = \frac{2{,}4\left(1 + B^2\right)\left(1 - \left(a_1 / R_n\right)^{0{,}912} \cdot exp\left(-3{,}958 \cdot a_1 / R_n\right)\right)}{B\left[cos\,\gamma\left(1 + B\right) - sin\,\gamma\left(1 - B\right)\right]} \qquad (2)$$

where $B = tg\beta_1;\ A = v \cdot a_1 / a;\ D = a_1 / b_1;\ E = \lambda_p \cdot \beta \cdot \varepsilon / \lambda$ are dimensionless similarity criteria that characterize the conditions for the process of edge cutting of materials; *c, x, y, z, n* are dimensionless coefficients that depend on the properties of the workpiece and tool materials; $k_{\text{И}}, k_C$ are dimensionless coefficients depending on tool wear and applied cutting fluid;β, ε– wedge angle and nose angle of the cutter; v - cutting speed; a_1, b_1 – thickness and width of the cut layer; α– thermal diffusivity of the workpiece material;λ, λ_p,– thermal conductivity of the workpiece and tool materials.

With known tool-chip contact length and geometry of the chip curler, the chip curvature radius R_n can be found through geometry approach. For example, for the diagram shown in Fig. 2, the chip curvature radius is:

$$R_n = (L - l) / tg(\psi / 2) \qquad (3)$$

In equation (3), the parameters L and ψ describe the geometry of the tool chip curler, the contact length *l* is a function of cutting conditions and can be calculated using equation (2). The joint solution of equations (1–3) will yield main parameters of the cutting zone of the workpiece machined with a tool featuring chip curler surface, with regard to chip curling. The calculated dependencies of the radius on cutting conditions and rake geometry of the cutting insert are shown in Figs. 2 and 3.

The study of the chip formation process using the above model shows, that under mechanical impact of the chip, equilibrium in the "shear zone - contact zone" system can be achieved via redistribution of stresses and deformations within the cutting zone.

Through finding the actual relationship between the stress-strain state in the cutting zone and the chip curvature, the conditions for favorable chip curling can be defined and new possibilities open for controlling spatial chip formation.

Controlling the process of breaking the continuous chip into fragments that are easily removable from the cutting zone and from the machine, is a separate problem though closely related to the problem of controlling the chip curling. Chip breaking occurs during when chip impacts the cutting surface, machined workpiece surface, and tool flank. Crucial for chip breaking are the stability of the chip geometry during cutting, stable chip-to-obstacle contact, high stiffness and low flexibility of the chip.

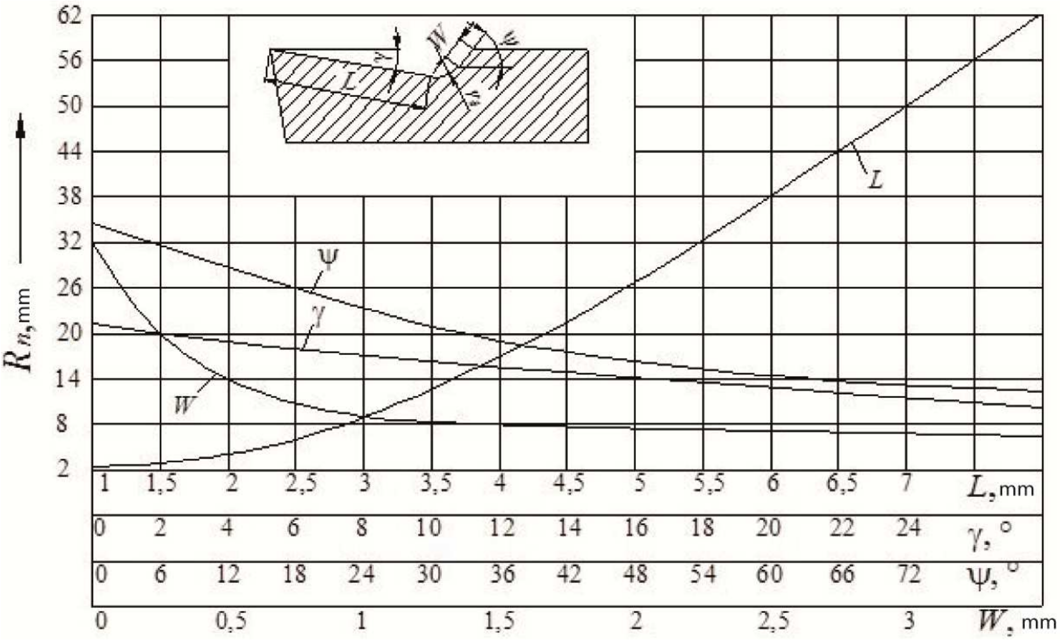

Fig. 2. Dependencies of the chip curvature radius R_n on the geometry of the chip curler surface of the tool (workpiece: steel EN 1.4541); tool: WC-6Co), *v*=1 m/s, *s*=0.3 mm/rev, *t*=1.5mm, φ=90°, γ=10°, λ=0, φ_1=10°, r=0.2mm, ω=0.4mm, L=4mm, ψ=45 deg., r_K=0.2mm.

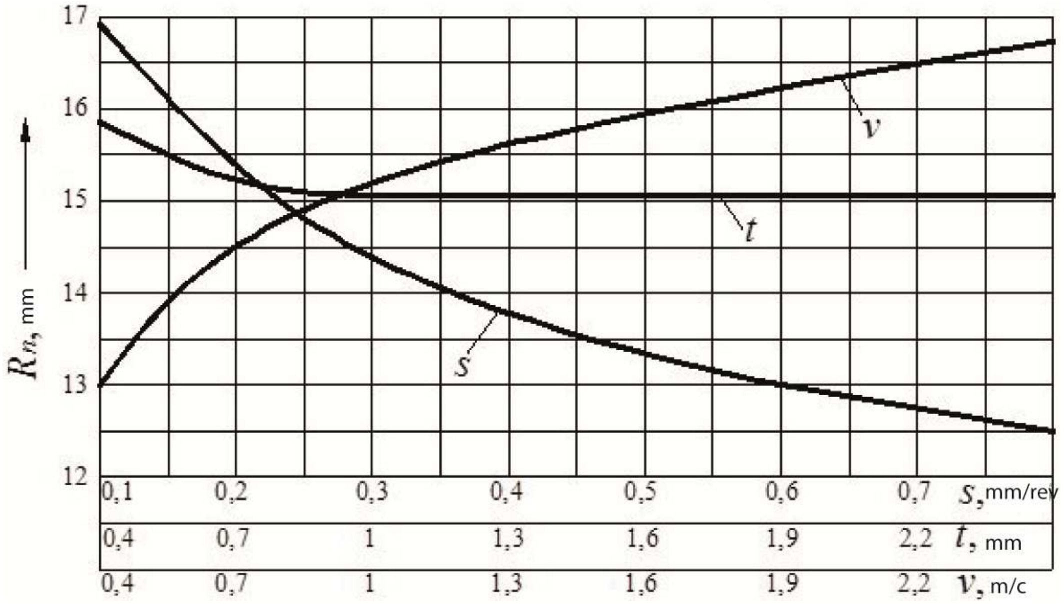

Fig. 3. Dependencies of the chip curvature radius R_n on cutting conditions (workpiece: steel DIN EN 1.4541; tool: WC-6Co), v=1 m/s, s=0.3mm/rev, t =1.5mm, φ =90°, γ=10°, λ=0, φ_1=10°, r=0.2mm, w=0.4mm, L=4mm, ψ=45 grad, $r_к$=0.2mm.

Fig. 4 shows the diagram describing deformation of the single curl in spiral continuous chip for the case of 'chip-tool flank' contact. The chip impacts the insert and uncurls under the forces acting in the plane that is perpendicular to the axis of the chip helix. As the impact plane of the 'uncurling' moment M is different from any of the main planes of the chip cross-section, the deformation follows the oblique flexure pattern.

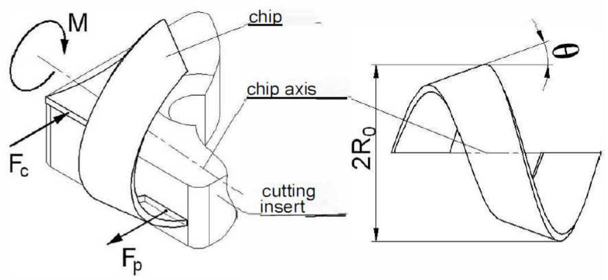

Fig. 4. Diagram describing the action of 'uncurling' forces acting on the chip curl: F_c – chip-forming component of the force; F_p is response force of the cutting insert.

The conditions for breaking of spiral chip may be found by solving the strength problem [12]:

$$R_{кр} = l + \left(\frac{1+\sigma_T / E}{R_0 - l} - \frac{\sigma_T}{E \cdot y_{\max} \cdot (0{,}086 - 0{,}11\delta)} \right)^{-1} \quad (4)$$

where

$$y_{\max} = 0{,}5 \cdot \left(a_2 \cdot \cos\left(\operatorname{arctg}\left(\left(\frac{a_2}{b_2} \right)^2 \cdot \operatorname{tg}\theta \right) \right) + b_2 \cdot \sin\left(\operatorname{arctg}\left(\left(\frac{a_2}{b_2} \right)^2 \cdot \operatorname{tg}\theta \right) \right) \right);$$

$l = 0{,}5(a_2 \cdot \cos\theta + b_2 \cdot \sin\theta)$; *R0* – outer curvature radius of the spiral chip; □, □□ – Young' modulus and yield stress of the chip material; □ – elongation at rupture; □*2*, *b2* – chip thickness and width, respectively.

An important result of modeling is the demonstration of manifold increase in chipbreaking efficiency caused by modification of the parameters of the spatial chip curling [12].

From the constitutive equation (4) specific equations could be derived to describe the cases of chip deformation when stress plane coincides with the longitudinal or transverse symmetry planes of the chip. When cylindrical chip is formed with □ = 0 □*max* = □*2* ⁄*2*, the equation to determine the critical chip curvature radius will be:

$$R_{кр} = 0{,}5 \cdot a_2 + \left(\frac{1+\frac{\sigma_T}{E}}{R_0 - 0{,}5 \cdot a_2} - \frac{\sigma_T}{0{,}5 \cdot a_2 \cdot E \cdot (0{,}086 - 0{,}11\delta)} \right)^{-1} \quad (5)$$

For most cases, the outside chip curvature radius is approximately equal to the chip curvature radius in the orthogonal secant plane, $R_0 = R_n$.

The models developed for processes of curling and breaking of continuous chips provide guidelines for informed selection of the optimal tool geometry and conditions for turning machining of ductile materials. The general solution for a tool with an arbitrary rake profile is obtained by computer-aided design of the cutter and by predicting the shape of the chip produced thereby.

Computer analysis shows that the chip-breaking efficiency within described schemes can be increased by additional rotation of the chip in its cross-sectional plane. To this end, it is necessary to create variable conditions for chip flow off the cutter that will fluctuate along the cutting edge in such a way, so that the chip rotates in the plane transverse to machined workpiece

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surface. A distinctive feature of the cutter rake is the presence of a helical chip-curler groove with spiral profile and a curvature radius variable along the cutting edge of the tool, to rotate the chip transversally towards the machined workpiece surface. By controlling the gradient of change in the tool geometry along its cutting edge, it is possible to influence the length of the chip fragments.

Simulation of cutting process using complex-geometry tool was instrumental in identifying the ways to effectively control the chip flow parameters in various machining operations. A new direction was thus established for development of natural ways to control the chip geometry by intensified curling in the cross-sectional plane of the chip. Through close cooperation with the Saint-Petersburg-based tool manufacturer company Virial LTD, the range of new tool designs was launched, set to increase efficiency and improve chip removal from the cutting zone.

4 Conclusions

This paper describes the model developed for the process of cutting using a complex-geometry tool, based on the concept of chip formation as a process of inhomogeneous deformations in the plastic region of chip origin. The performed research provides necessary theoretical foundation informing strategies of design and optimization of the operating conditions for tools featuring curvilinear chip-curling and chip-breaking rake features. New designs of complex-shaped cutting inserts have improved performance, offering efficiency gains and better build quality for mining machines under automated manufacturing.

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