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Theoretical research of the chip removal process in milling of the closed profile slots

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ABSTRACT

Purpose: The chip removal from the cutting zone of closed slots (T-shaped, "dovetail", etc.) is relevant since the repeated cutting of the chip with the blades of the tool teeth leads to a decrease in the resource of the cutting tool and processing accuracy. However, theoretical studies of the processes of filling, accumulation, and movement of the chip have not been considered. The purpose of the research is to develop the theoretical foundations of the chip filling and removing processes from profile slots using pneumatic hydrodynamic action of pressure jets of cooling liquid.

Design/methodology/approach: Several stages of the analysed process are considered, namely the separation and filling of the space between the cutter teeth with the chip, filling the machined slot with the chip, removing the chip element from the space between the cutter teeth, moving the chip element along the machined slot, moving the chip array along the machined slot, pneumatic hydrodynamic impact.

Findings: The complex of mathematical models have been developed to describe the functioning of the chip removal system during the milling of the closed profile slots in this research. The set of the developed models makes it possible to determine the required values of the design and operating parameters of devices that ensure the chip removal from the cutting zone as a result of the use of inertial forces and the application of additional compulsory forces.

Research limitations/implications: Theoretical studies were applied for T-shaped slots for milling cutters with diameters from 12.5 mm to 95 mm made of high-speed steel and carbide inserts during steels and cast irons processing. The use of pneumatic hydrodynamic action is limited by the diameters of the nozzle hole from 0.5 mm to 3 mm.

Practical implications: The practical significance of the research lies in the ability to control the process of timely chip removal from the cutting zone and to prevent the repeated ingress of the chip under the milling cutter blade. This is achieved by a set of mathematical models that simulate the chip removal process. Research can be applied in production in slots milling, using a liquid not only to cool the cutting zone but also to remove the chip in a timely manner.

Originality/value: Theoretical studies previously not carried out for closed profile slots are presented in the research.

Keywords: Closed slots, Milling, Chip removal, Mathematical models, Pneumatic hydrodynamic force

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

The timely chip evacuation from the cutting zone is of the utmost importance due to the possibility of repeated cutting of the chip which is actually abrasive [1-6]. The chip removal is of particular relevance during milling of the closed profile slots (T-shaped, dovetail type), curly labyrinths, etc., since the resulting slot, due to its closure, is quickly filled with separated chips. The chip exerts a force effect on the cutting tool with its further arrival and ingresses the cutting zone repeatedly. This leads to a decrease in productivity and processing quality.

At the same time, the processes of the chip filling, circulation, and removal from closed profile slots and their modelling are practically not considered in the well-known works in this area [7-16]. In spite of the fact that various methods can be used for chip removal, including methods that use air or air/coolant mixture jets by feeding its through the channels in the tool body to remove chips [1], by gravitational forces, special tool geometry, plasma treatment [14,17,18], use of magnetic fields of a certain value [19,20], these issues are considered only for the drilling process [21-23]. Therefore, research aimed at studying the chip removal processes with a view to create effective devices for the timely chip removal from the working area is highly relevant.

2. Development of mathematical models

The following assumptions were made in the modelling of processes of the chip filling, circulation, and removal in milling of the closed profile slots:

- the chip element is a ball with the values of density, mass, and state parameters of the surface layer of this element;
- the chip element is an absolutely solid body (the effects associated with its real compliance can be neglected);
- the interaction of the chip elements with each other can be neglected.

The integral model of the functioning of the chip removal system in milling of the closed profile slots includes 6 basic mathematical models (MM):

- MM1 of separation and filling of the space between the milling cutter teeth with the chip;
- MM2 of filling the machined slot with the chip;
- MM3 of removal of the chip element from the space between the milling cutter teeth;
- MM4 of movement of the chip element along the machined slot;
- MM5 of movement of the chip array along the machined slot;
- MM6 of pneumatic hydrodynamic action.

2.1. MM1 of separation and filling of the space between the milling cutter teeth with the chip

MM1 is designed to establish instantaneous values of the volumes of separated chip V_c and space between the milling cutter teeth V_{sp}.

The final dependence of the model has the form

$$k_{fs} = \frac{f_z(d-a)lk_pN}{\frac{l}{3}\left[\frac{h1\left[z+(z+2(l\tan\omega_e))\right]}{2}+\sqrt{\frac{zh1^2\left[z+2(l\tan\omega_e)\right]}{4}}\right]}, \quad (1)$$

where $k_{fs} = \frac{V_c}{V_{sp}}$ is a factor of filling the space between the milling cutter teeth;
f_z is the feed per tooth;
d is the milling cutter diameter;
a is the width of the pre-processed slot;
l is the height of the cutting part of the milling cutter;
k_p is the coefficient of the chip loosening;
N is the number of revolutions of the milling cutter;
$z = h1\tan\beta_n$;
h_1 is the length of the front surface of the cutter tooth;
β_n is the angle between the front surface of the cutter tooth and the surface of the tooth back;
ω_e is a helix angle of the cutter groove.

2.2. MM2 of filling the machined slot with the chip

MM2 is designed to determine the machining length L, corresponding to the filling of the milled slot with the chip.

The final dependencies of the model have the form

$$V_{sp}(x_c, L) = [(x_c + d/2 - \pi d/8) - c \cdot \tan\varepsilon/2] \cdot d \cdot c + \\ + a^2/4 \cdot [\cot\varepsilon(x_c - a/2) - c] + \\ + \cot\varepsilon \cdot a^3/16 + (d \cdot c + \cot\varepsilon \cdot a^2/4) \cdot L \quad (2)$$

$$V_c(L) = (d-a) \cdot l \cdot k_p \cdot L \quad (3)$$

$$L = \frac{[(x_c + d/2 - \pi d/8) - c/2s]dc + a^2/4[s(x_c - a/2) - c] + s \cdot a^3/16}{(d-a) \cdot l \cdot k_p - (d \cdot c + s \cdot a^2/4)}, \quad (4)$$

where $V_{sp}(x_c, L)$ is the volume of the formed slot;
$V_c(L)$ is the volume of the separated chip;
x_c is the distance the chip element moves after it is thrown out of the space between the cutter teeth;
c is the slot height;
$s = \cot\varepsilon$;
ε is an angle of the natural slope of the chip array.

2.3. MM3 of removal of the chip element from the space between the milling cutter teeth

MM3 is designed to determine the distance y and the velocity $\dot{y}$ of movement of the chip element as a result of inertial and (or) forced action on it within the tool (milling cutter).

The final dependences of MM3 have the form

$$y = C_1 \cdot e^{\alpha_1 \cdot t} + C_2 \cdot e^{\alpha_2 \cdot t} + D/B \quad (5)$$

$$\dot{y} = \alpha_1 \cdot C_1 \cdot e^{\alpha_1 \cdot t} + \alpha_2 \cdot C_2 \cdot e^{\alpha_2 \cdot t} \quad (6)$$

where $\alpha_{1,2} = \dfrac{-A \pm \sqrt{A^2 - 4B}}{2}$,

$$C_1 = -\frac{D \cdot \alpha_2}{B \cdot (\alpha_2 - \alpha_1)}, C_2 = \frac{D \cdot \alpha_1}{B \cdot (\alpha_2 - \alpha_1)},$$

where

$$A = 2\omega \cdot f_f, \ B = -\omega^2 \cos\alpha \cdot (\cos\delta - \sin\delta \cdot f_f),$$

$$D = (2F_{ph}/\rho_c \cdot f_z(d-a) \cdot l) \times \\ \times (\cos\beta - \sin\beta \cdot f_f) - g \cdot f_b(1 + \sin\alpha + f_f) + \\ + \omega^2 \left[r_c - (h1 - \sqrt[3]{3(f_z(d-a) \cdot l)/\pi}/2)\cos\alpha \right] \cdot (\cos\delta - \sin\delta \cdot f_f),$$

where y is the length of movement of the chip element along the front surface of the cutter tooth;
$\dot{y}$ is an instantaneous velocity of the chip element;
t is the time of movement of the chip element along the front surface of the cutter tooth;
ω is the angular velocity of the chip element in a bulk motion;
f_f is the friction coefficient of the chip element on the front surface of the cutter tooth;
α is the rake angle of the cutter tooth;
δ is the inclination angle of the vector of the centrifugal force of inertia;
F_{ph} is the force of forced pneumatic hydrodynamic action on the chip element;
β is the inclination angle of the force vector F_{ph} to the front surface of the cutter tooth;
ρ_c is the density of the chip element;
g is the acceleration of gravity;
f_b is the friction coefficient of the chip element along the slot bottom surface;
r_c is the radius of the milling cutter.

2.4. MM4 of movement of the chip element along with the machined slot

MM4 is designed to determine the distance X which the chip element moves as a result of the forced action on it outside the cutter.

The final dependence of the model has the form

$$X = \frac{m \cdot \rho_0 \cdot h^2 \cdot \pi \cdot \mu^2 \cdot d_0^2 \cdot F_{ph}}{4 \cdot F_b \cdot (\frac{\rho_0 \cdot \pi \cdot d_0^2 \cdot h}{4} + m)^2} \quad (7)$$

where ρ_0 is working medium density used to move the chip element along the slot;
m is the mass of the chip element;
h is the length of the jet of the working medium;
F_b is the friction force along the bottom surface of the slot;
d_0 is the diameter of the nozzle hole.

2.5. MM5 of movement of the chip array along the machined slot

MM5 is designed to determine the force of forced pneumatic hydrodynamic impact on the chip depending on the design and technological parameters of the cutting process of the closed profile slots.

The final dependence of MM5 has the form

$$F_{ph} = \frac{f \rho g L}{\cos\alpha}[dH_c + 2fn_l(\frac{2fn_l H_c + fn_l d - fn_l d_m}{H_c d})^{-1}] \times \\ \times (e^{(2fn_l L d^{-1} + fn_l L H_c^{-1} - fn_l d_m L H_c^{-1} d^{-1})} - 1) \cdot [H_c + 0,5(d - d_m)], \quad (8)$$

where f is the resistance coefficient of the chip movement along the surfaces of the machined slot;

ρ is the chip density;
L is the length of the moving body of drawing;
γ is the inclination angle of the working medium jet;
H_c is the cutter height;
n_l is the lateral pressure coefficient;
d_m is the diameter of the end mill cutter (used for roughing operation).

2.6. MM6 of pneumatic hydrodynamic action

MM6 is designed to determine the values of the design and operating parameters of the chip removal devices.

The final dependence of the model has the form

$$y = F_{ph}(d_0, l_j, p_0) = a \cdot d_0^{b_1} \cdot l_j^{b_2} \cdot p_0^{b_3}, \qquad (9)$$

where a is the coefficient of the regression equation;
p_0 is the pressure of the working medium at the nozzle;
b_1, b_2, b_3 are indexes of power for parameters d_0, l_j, p_0, respectively.

The developed mathematical models are implemented using the program "Mathcad". The results and graphical interpretation of their implementation in this program are presented below.

3. Research results and their analysis

3.1. MM1 of separation and filling of the space between the milling cutter teeth with the chip

Graphical interpretation of dependence (1) in the range of changes in design and operating parameters recommended by standards for T-shaped slots machining (Fig. 1) shows that the filling of the free space between the cutter teeth occurs rather quickly: at the number of cutter revolutions $N = 3$ ... 8 in case of steel blanks machining and $N = 2$ ... 20 in case of cast iron blanks machining.

With further implementation of the working process in this case the volume of the separated chip exceeds the volume of free space between the teeth (in the absence of removal) which leads to its circulation and repeated ingress into the cutting zone.

3.2. MM2 of filling the machined slot with the chip

Graphical interpretation of dependencies (2), (3) and (4) in the range of changes in design and operating parameters recommended by standards for T-shaped slots machining (Fig. 2) shows that the filling of the formed slot space occurs at the cutter displacement $L = 1.0$ ... 1.3 cm in case of milling steel blanks and $L = 6$ ... 8 cm in case of milling cast iron blanks. The volume of the separated chip exceeds the volume of the free space of the slot during the further implementation of the working process which leads to the chip compression, circulation and repeated ingress into the cutting zone.

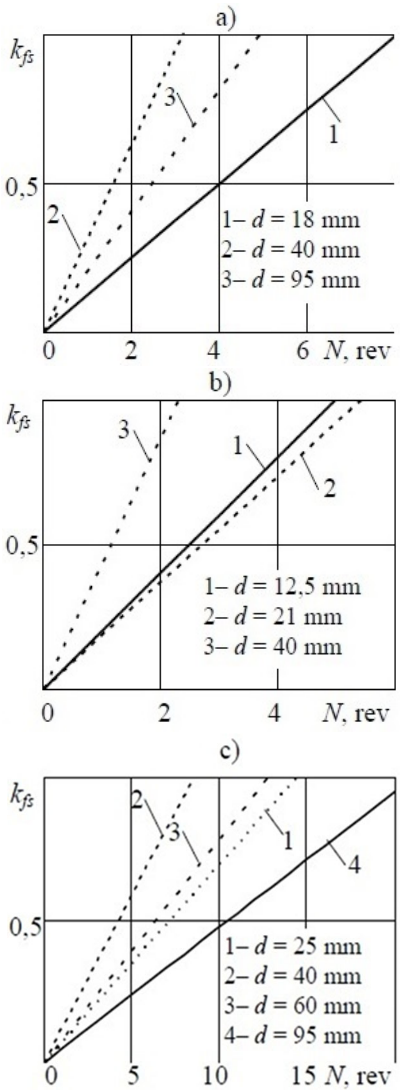

Fig. 1. Graphs of the change of the space filling factor between the cutter teeth k_{fs} as a function of the number of cutter revolutions N: a) for a solid cutter made of high-speed steel during milling steel (v = 25 m/min; f_z = 0.05...0.12 mm/tooth); b) for a solid cutter made of high-speed steel during milling cast iron (v = 15...20 m/min; f_z = 0.03...0.08 mm/tooth); c) for a cutter with brazed carbide inserts during milling cast iron (v = 55...40 m/min; f_z = 0.05...0.12 mm/tooth)

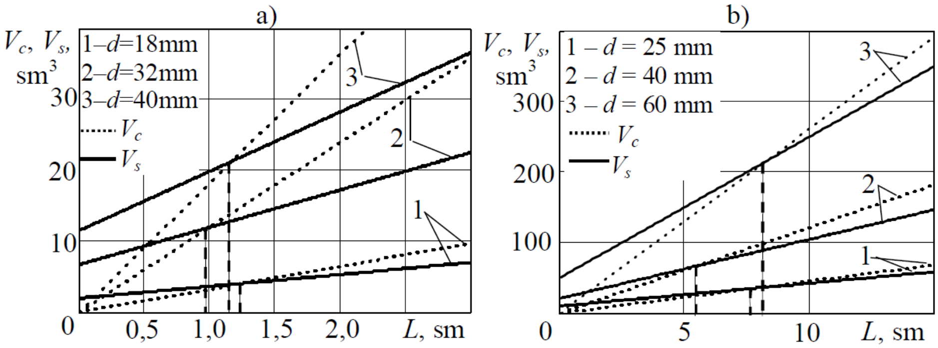

Fig. 2. Graphs of the change in the volumes of the separated the chip V_c and the slot space V_s as a function of the cutter displacement L: a) for a solid cutter made of high-speed steel during milling steel (v = 25 m/min; f_z = 0.05...0.12 mm/tooth); b) for a cutter with brazed carbide inserts during milling cast iron (v = 55...40 m/min; f_z = 0.03...0.06 mm/tooth)

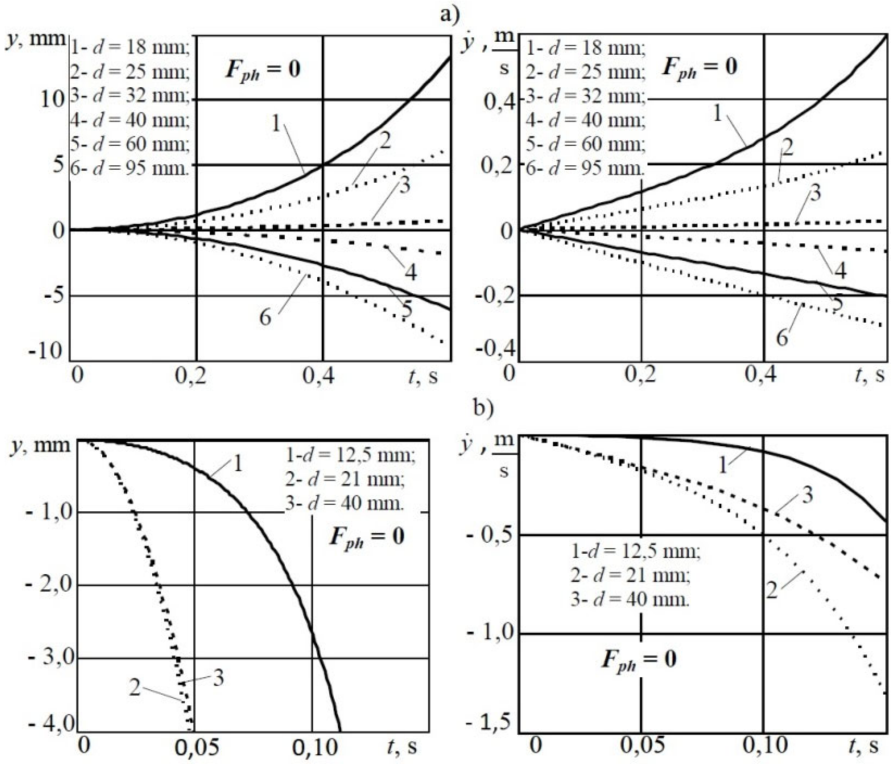

Fig. 3. Graphs of changes in the distance y and $\dot{y}$ the speed of movement of the chip element along the front surface of the cutter tooth as a function of time t for a solid cutter made of high-speed steel during processing: a) steel (F_{ph} = 0); b) cast iron (F_{ph} = 0)

Analysis of MM1 and MM2 shows that the chip after separation fills the space both between the teeth and the formed slot fast enough. This leads to repeated ingress of the chip into the cutting zone which causes a decrease in the quality of the machined surfaces, intense wear of the cutting edges of the tool and a decrease in milling efficiency. Timely removal of the chip is necessary to eliminate these negative consequences.

3.3. MM3 of removal of the chip element from the space between the milling cutter teeth

The graphs of the change in y and $\dot{y}$ (5-6) as a function of t by varying the values of the geometric and operating parameters of the cutting tool in the range recommended by the standards for processing T-shaped slots in the absence of F_{ph} are shown in Figure 3.

Positive values of y and $\dot{y}$ in the absence of a forced action on the chip element indicates its movement in the direction from the centre to the periphery of the tool, which means that it can be removed due to inertial forces (self-removal).

Negative values of y and $\dot{y}$ in the absence of a forced action on the chip element indicate its movement in the opposite direction, which means that there is no self-removal of the chip element from the space between the cutter teeth.

There is no possibility of self-removal in 30 ... 100% of cases in the range of parameters and modes recommended by the standards.

Forced action is necessary to ensure the complete removal of the chip elements from the space between the cutter teeth.

3.4. MM4 of movement of the chip element along the machined slot

The graphs of change in X (7) as a function of F_{ph} by varying values of the nozzle diameter d_0 are shown in Figure 4.

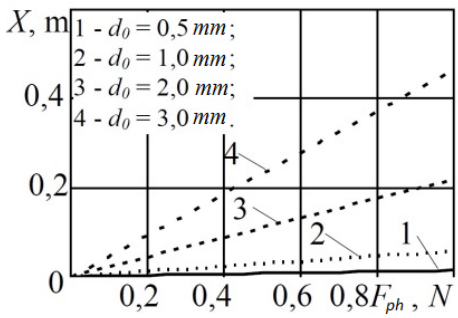

Fig. 4. Graphs of change in the distance X, by which it is necessary to move the chip element along the slot as a function of the force of forced pneumatic hydrodynamic impact F_{ph} during machining steel blanks with a solid cutter made of high-speed steel

3.5. MM5 of movement of the chip array along the machined slot

The graphs of the change in F_{ph} (8) as a function of L with varying values of the cutter diameter d are shown in Figure 5.

From the analysis of the graphs, it follows that the required value of the force of the hydrodynamic action increases with an increase in the cutter diameter, an increase in the diameter by 2 times leads to an increase in the value of F_{ph} by 2 times.

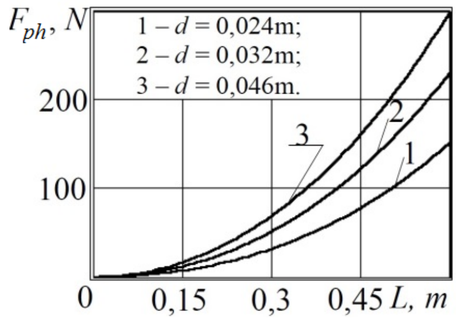

Fig. 5. Graphs of the dependence of the required force of forced pneumatic hydrodynamic impact on the length of the body of drawing (with variable values of the cutter diameter)

3.6. MM6 of pneumatic hydrodynamic action

The value of the force of the forced pneumatic hydrodynamic impact on the chip element as a function of the design and operating parameters of the devices for supplying the working medium is determined on the basis of the regression dependence (9).

Graphical interpretation of dependence (9) is shown in Figure 6. The value of F_{ph} changes insignificantly with an increase in the length of the jet and it increases with an increase in d_0.

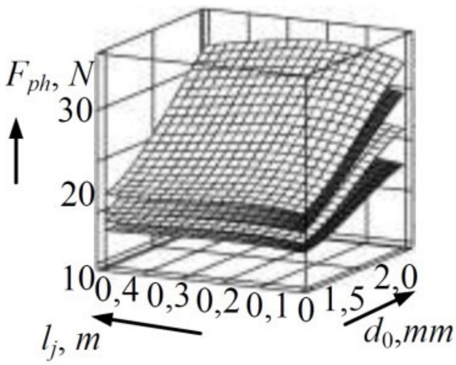

Fig. 6. Graphs of the change in the force of the jet action on the obstacle for the pressure values $p_0 = 2; 3; 4; 5$ *MPa*

4. Conclusions

1. The mathematical models complex for the functioning of the chip removal system in milling closed profile slots is developed.
2. The set of the developed models makes it possible to determine the required values of the design and operating parameters of devices that ensure the chip removal from

the cutting zone as a result of the use of inertial forces and the application of forces of additional compulsory impact.

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