Investigation of formation of cut off layers and productivity of screw milling process

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Abstract. The article presents studies of a new method for complex milling surfaces with a screw feed motion. Using the apparatus of algebra of logic, the process of formation of cut metal layers and processing capacity is presented.

1. Introduction

There are known methods of milling complex shaped surfaces, which are carried out both by the method of rolling the generator (milling by forming) and using end radius cutters working by the method of line milling [1-4]. The processing of complex shaped surfaces is associated with large volumes of material being removed and this leads to an accelerated wear of expensive tools. A trajectory of motion using end mills is an equidistant of the profile being processed [5-7]. But these methods do not have high productivity and do not provide high quality of the treated surface. With a progressive feed, the roughness is determined mainly by the value of the line feed and the cutter radius. The disadvantage is that the milling cutter must be tilted at certain angles to the plane of the machine table. Sandvik Coromant cutters can work with an angle of 10° - 15° to the axis perpendicular to the plane of the table. A somewhat greater productivity is provided by the methods of milling complex shaped surfaces with the use of disk shaped mills with a semicircular profile with a toroidal generating surface. However, they, as well as end mills, do not allow ensuring the quality of the surface obtained. The milling methods carried out by the roll forming methods with the displacement of the cutting edge relative to the cutting surface [8-10] are the most productive, accurate and they increase the resistance of tools, but require the development of complex control programs. At the same time, the complex kinematics of shaping requires extraordinary methods of studying these methods: the forms of the cut metal layers, the productivity of the processes and the changes in the load on the cutting edge.

2. Investigation methods

To develop a 3D model of the processing of shaped surfaces with displacement of the cutting edge relative to the cutting surface in order to compile control programs, to study the formation of cut layers, and to determine the productivity of the process, algebraic R-functions of V.L. Rvachev were used. The elementary metal layer cut by each tooth is described by a logical formula obtained as a result of the intersection of two producing surfaces of mills (for their two adjacent positions) and the treated surface. At different stages of processing, the parameters and shape of the cut layers are different.
3. Method of screw milling
The method for processing the surfaces of dies with screw feed motion [8] (Figure 1) is carried out by a tool in the form of a body of rotation with a toroidal generating surface to which two simultaneous translational nonlinearly matched shaping motions and rotational feed motion are reported. The rotational feed motion is carried out in a plane perpendicular to the plane of translational motions which are carried out normally and in parallel to the basal plane and are nonlinearly matched with the rotational feed motion for periodically touching the machined surface with the tool simultaneously at two points on opposite sides of the profile, the feed movement is reversed. In this case, the toroidal generating surface is selected with a radius of curvature less than the minimum radius of curvature of the part, and the tool diameter is larger than the width of the profile being processed. Such method of processing with a screw reciprocating feed motion allows the maximum use of the peripheral portion of the toroidal tool surface with maximum angles when cutting. The lateral portions of the toroidal producing surface with small rear corners work a minor part of the processing time.

Figure 1. Methods of milling complex concave shaped surfaces with rotary feed motion: a - with longitudinal feed, b - with vertical feed

Processing of the producing surface by lateral sections is carried out at the very bottom of the groove. In addition, with the dominant rotational feed, the actual front angles increase due to oblique cutting, while the front surface of the tool has a running contact with the cut-off layers of chips. All of the above-mentioned facts increase the quality of machining and tool durability and expand the technological possibilities of using a universal tool with a toroidal manufacturing surface for processing concave, complex parts. This method can be used for processing both narrow deep and wide shallow grooves.

In this case, milling can be carried out in three ways: with rotary feed motion $\omega_y$, carried out in one direction with a longitudinal feed $S_x$ (Figure 1a), with rotational feed $\omega_y$ and vertical feeding $\omega_z$
(Figure 1b), reversing rotary feed motion $\omega_y$ and longitudinal feed motion $S_x$ (Figure 2). The first method can be used only for wide open and shallow shaped creeks, in these methods the tool rotates through an angle of 360° without reversing the feed rotational motion, and after each rotation of the tool or table with a workpiece by 180° around the Y axis, the incoming milling changes to a passing one. The second method (Figure 1b) is used at the initial stage of processing both narrow and wide closed grooves. The third method (Figure 2) can handle both deep and wide shallow shaped creeks. When processing narrow grooves, the tool touches the profile at two points on opposite sides of the groove, and angle of reversal $\varphi$ depends on the width of the brook and the diameter of the cutter. When making wide shallow grooves, the profile is touched in one lower or lateral point of the part profile with one side of the tool. After the entire length of the stream, the cutter descends the profile for the next pass.

4. 3D modeling of the process of cutting metal layers and milling performance

To develop a 3D model of the processing grooves with the use of screw milling for the purpose of compiling control programs, as well as to determine the productivity of the process, the algebraic R-functions of V.L. Rvachev were used. With this purpose, the elementary metal layer cut by each tooth is described by a logical formula obtained as a result of the intersection of two toroidal surfaces (two neighboring positions of the mill) and the treated surface. At different stages of processing, the parameters and shape of the cut layers are different. Figure 3 shows the elements of shear layers for milling with rotary feed motion and vertical feed at different processing stages.

For the element of the cut-off layer shown in Fig. 3a, the logical formula determining its size and shape will have the form:

$$L = f_1 + f_2 + f_3,$$  \hspace{1cm} (1)

where $f_1$ and $f_2$ - functions describing the toroidal producing surface of the milling cutter in two adjacent positions, $f_3$ - function that determines the position of the workpiece plane to be machined.

Figure 4 depicts the element of the sheared layer obtained using the Rvachev's function for longitudinal feed methods $S_x$ (Figure 1a, Figure 2). For the processing method shown in Figure 3a, the logical formula for a metal layer cut by one tooth has the same form as for the element depicted in Figure 3b and differs only in values $d_x, d_x, d_x$. 

![Diagram of milling process](image-url)
Figure 2. Method of milling complex concave shaped surfaces with reversal of rotary feed motion

Figure 3. Elementary forms of cut off layers of metal with vertical feed motion, obtained using the Rvachev's function: a - at the beginning of the treatment (before the formation of the well), b - after the formation of the well

Figure 5 shows the procedure for determining elementary volumes, cut by a tooth, using algebraic functions. The parameters of the elementary cut off layers, as well as their volume, are obtained after determining the belonging of the array of points to the inner and outer regions of the removed volumes of metal by one tooth:

\[ n = \sum L^+_{i,j,k} ; \quad m = \sum L^-_{i,j,k}, \]  

(2)

where; \( n \) – the number of points belonging to the cut layers (chips); \( m \) – the number of points not belonging to the cut off layers in a certain allocated volume. Then the removable volumes of cut off layers by one tooth are equal:

\[ V_i = \frac{n_i}{n_i + m_i}. \]  

(3)

The cross-sectional area in section A-A is:

\[ S_{A-A} = \frac{n_{A-A}}{n_{A-A} + m_{A-A}}. \]  

(4)
Figure 4. Elementary volume of the cut off layer for the first and third methods of screw milling

Figure 5. Representation of an array of points belonging to (+) and not belonging (-) to the volume of a metal layer cut off by one tooth

The sum of all elementary volumes, cut off for a certain processing time, makes it possible to calculate the amount of metal that is cut per unit time, that is, the specific productivity for various methods of milling.

Figure 6 shows the volumes of cut off layers of material per tool rotation for different milling methods with screw feed motion.

Figure 6. The volumes of material to be cut off with different milling methods with rotary feed motion: a - with vertical feed, b - with longitudinal feed, c - with reverse motion
Figure 7 shows the specific performance curves for various kinematic milling schemes, all other things being equal: feeding to the tooth, cutting speed, the diameter of profile cutter $D$, the radius of profile $R$, the number and the pitch of the teeth.

![Figure 7](image)

**Figure 7.** The graph of the dependence of specific productivity ($\text{cm}^3/\text{min}$) on the parameters of the tool ($D$ - the diameter of the milling cutter, $R$ - the profile radius) for different milling methods: 1 - without screw feed, 2 - with screw motion and vertical feed, 3 - with screw motion and with longitudinal feed, 4 - with screw motion and with reversible motion (angle of reversal is $30^\circ$)

5. Conclusions

The analysis of the obtained dependences allows us to conclude that the methods of screw milling are 2 - 2.5 times more efficient than the known and widely used methods of line milling by shaped circular milling cutters of a semicircular profile.

In addition, an increase in tool life up to eight - ten times due to the constant displacement of the tool tip relative to the cutting surface has been experimentally established.

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