Change from one Method to Another for Processing by Cutting a Complex Rotary Surfaces

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Abstract. Many authors involved in the processing of materials by cutting make different definitions for complex rotary surface. They are reduced to the definition published in [1]: A complex rotating surface is called one that is composed as a combination of two or more of the following elementary surfaces - conical, frontal, cylindrical, curvilinear. The methods and devices used in machining parts that are constrained by complex rotary surfaces depend on following several factors: type of production (single, serial, mass); type of available equipment and shape accuracy and surface quality.

1. Analysis of the methods for machining complex rotary surfaces.

The considered methods are turning method by using standard turning tools and profile turning tools, milling and broaching method.

1.1. Advantages of turning method: The used standard turning tools are with simplified construction and cutting geometry. They do not require profiling or special equipment; Using of profile turning tools makes the processing possible for the realization of general purpose machines, semi-automatic and automatic lathe machines in serial and mass production.

1.2. Disadvantages of turning method: The machined surface of the workpiece consists of a number of screw grooves obtained from the relative motion of a portion of the points of the cutting edge. Therefore, the quality of these surfaces cannot be assessed as sufficient; Machining which requires the use of a profile cutting tool is not applicable for serial and mass production because the shape of its cutting edge is not self-recovering after sharpening; The three types of radial profile cutting tools are unsuitable when the high requirements for the accuracy shape and size on the machined surfaces are made [1]. The reasons are: The inclusion of all points from the cutting edge at the end of the cutting process adds considerable instability to the whole technological system. For this reason, they are only applicable to machining short work pieces with a large cutting depth; The inclination of the front surface at an angle greater than 0° does not allow all points of the cutting edge to be positioned in the diameter plane of the work piece. For this reason, most of the machined rotary surfaces are deviated from the desired shape and size, with a size that depends on the size of the front angle of the tool.

1.3. Advantages of milling method

Milling tools are with high durability because the cutting of stock allowance is distributed on more cutting teeth; Using of profile milling cutters, allows the original shape of the cutting edges to be restored after each sharpening.
1.4. Disadvantages of milling method:
The combination of the relative trajectory of points from the cutting edge with character of extended hypocycloid and radial beating of the tool mandrel converts the desired rotary surface of the work piece into a polyhedron with parts of hypocycloid. It becomes a real surface with low shape accuracy and bad surface quality; it is difficult to form rational values of the geometrical tool parameters, which are consistent with the nature of the relative trajectory. In some cases, it makes impossible using method into practice.

1.5. Advantages of broaching method:
It is realized with only one movement of the kinematic scheme, which is a prerequisite for using of machine tools with simplified kinematics and construction; The feed movement is achieved with the special design of the tool, as a hidden (constructive) feed movement [2].

1.6. Disadvantages of broaching method:
Moving the tool to the starting position after each work movement makes this processing method low-performing; It is necessary to perform long machine motion, which requires using machines with large dimensions and production areas; The workflow automation capabilities are limited. Compared to the turning and milling methods of complex rotary surfaces, broaching is the most rational method that fully meets the formulated and accepted criteria. Finding the best processing option (if it is possible) after improvement of the broaching method should be done while preserving its advantages and by overcoming to some extent the identified disadvantages.

2. Change from one method to another for processing by cutting a complex rotary surfaces.
The scraping and broaching of flat surfaces are carried out by methods based on the fundamental kinematic cutting schemes (FKCS) as it is already clear [3, 4].

![Figure 1. Change from one to another fundamental kinematic cutting schemes (FKCS).](image1)

![Figure 2. Rotary part processing with different tools, according to FKCS.](image2)

![Figure 3. Change from one method to another for processing a complex rotary surfaces.](image3)
The only rectilinear motion A in the structure of this kinematic scheme is also the main cutting motion and belongs to the tool when the stock is stationary. If movement A is joined by other movement B in the same way but in the opposite direction, a peculiar transition from (Figure 1a) to FKCS (Figure 1b) is made. If the stock moves in accordance with B, this change will cause relative displacement of the stock against to the tool at increased speed and will not lead to any other changes in operating conditions. The two uniform, straight and gradual motions A and B can be regarded as uniformly rotating, with infinitely distant centers of rotation from their straight lines. If the center of rotation of movement A remains infinitely distant and the center of linear motion B approaches its straight line at some distance of finite value, a transition from FKCS (Fig. 1a and Fig. 1b) to FKCS will occur (Figure 1c). With the same belongings of the two movements (A of the tool - feeder, or ancillary and B of the stock - mainly for cutting) and in the ratio of their speed:

\[ \varepsilon = \frac{v_a}{v_B} = 0.005 \]  

(1)

Two methods of machining complex rotary surface are implemented - through tangential cutting tool (Figure 2a) [5] and through the external profile broach (Figure 2b) [6]. The relative trajectory is a flat spiral extending into a circle with a radius equal to the radius of the rotating surface for a given point on the cutting edge. In fact, this trajectory is a special case of an extended cycloid. The uniform nature of the relative trajectories in the final part of the circle-shaped workflow is particularly appropriate because it fully corresponds to the type of stock rotated at each point. The two methods considered have specific features that the rest, built for a similar purpose, do not possess. With regard to the machining of the rotary part, only one point from the cutting edge is theoretically included at work at any point in the work process, and in practice a limited part of it, in the vicinity of the same point. This means that in addition to the two movements A and B (Figure 2), another movement C is involved, which is not included in the structure of the kinematic scheme, but actually moves the contact point from the cutting edge and the stock in two directions: along the cutting edge from one side and against the stock axis in the diameter and the plane on the other. There are two additional motions not figured on the FKCS (Figure 2) but actually realized when machining rotary surface with an external profile extension: in the same sense as in the tangential profile tool and D – due to the special construction of this type of tool – the location of each cutting edge is higher than the previous one with a value corresponding to the transverse feed motion of one tooth. Whereas, when considering the machining of planar surfaces, the flat broach is regarded as a set of scraper blades arranged with the so-called "Tooth lifting". Whereas, when machining rotary surfaces, the outer profile extensions can be considered as a set of tangential blades, also with the teeth lifted relative to one another. If it is assumed that the radius of the linear motion A of the FKCS of Figure 1 gradually loses its infinite value and at some point is established with a finite radius, there will be a new transition from one kinematic cutting scheme to another, this time from Figure 1c, to the FKS (Figure 1d) - with two uniform rotary motions A and B with the same direction of rotation. Changing the type of kinematic scheme causes a change in the design of the tool. In the transition from FKCS (Figure 1c to Figure 1d), the outer profile broach (from Figure 3a) with a straight line movement A is transformed into an arc (sector) from Figure 3b, with a uniform rotary motion A. If the radius of the arc extends to a radius of even smaller value, there is transformation from an arc to a helical broach (Figure 3c). In order to answer the question unequivocally, whether or not the construction of a method of machining complex rotary surfaces with helical broaches is possible or not. Determining the character of the relative path of a point on the cutting edge and to determine the extent and according to the type of the processed surface of the stock at various values of the ratio:

\[ \varepsilon = \frac{v_a}{v_B} \]  

(2)

To determine whether it possible to form the elements of the cutting mode and the geometrical parameters of the tool within rational limits, tailored to the nature of the relative trajectory and characteristics of workflow. If the affiliation of both motions is in accordance with “A” of the tool (figure 3c) and “B” of the stock with \( V_u \) and \( V_g \) are indicated respectively the peripheral speeds of the tool and the stock, the first value of the ratio \( \varepsilon_1 \) will be of the value:

\[ \varepsilon_1 = \frac{v_g}{v_u} < 1 \]  

(3)
At sufficiently small values of $\varepsilon_1$ any point on the cutting edge of any tooth of the helical broach will make contact with the stock on the arc with the beginning of the first and last points of contact. This is possible by rotating the broach with angle $\omega_u$ in a counter-clockwise direction and by rotating the part with angle $\omega_g$ in the same direction. The maximum thickness of the chip $a_z$ can fit in the range $a_z=0.003$-0.2 mm.

Under these restrictive conditions, the workflow is possible, but it would hardly make practical sense, since the stock has an irregular curved multi-wall outline in a cross-section that differs significantly from the original design. The working process of machining complex rotary surfaces with a helical broach fully imitates the milling process, since in both cases the character of the relative trajectory is an extended hypocycloid [7]. The trajectory and the outline of the stock can be illustrated (Figure 4) if the center of the tool with radius $r$ contacts the center with the center of a circle with radius $A_0$ rolling without slipping to another with radius $B_0$ and with a center coinciding with the center of the stock of radius $r$.

The indicated nature of the relative trajectory will be obtained if the conditions are met:

$$\frac{A_0}{B_0} \ll 1 \text{ and } R \gg A_0$$

(Figure 4. Relative trajectories at broaching of rotary parts with helix broach.

If the ratio (1) is increased to $\varepsilon_2$ but so that:

$$\varepsilon_2 = \frac{V_p}{V_u} < 1, \text{ but } \varepsilon_2 > \varepsilon_1$$

The maximum thickness of the chip is obtained with the values according to the equation:

$$a_z > 0.2 \text{ mm}$$

It turns out that at this value of $a_z$ the thickness of the layer of material from the stock taken from one tooth of the helical broach is unacceptably large. This is a circumstance that calls into question the practical implementation of the work process in general. Mathematically, an accurate hypocycloid is obtained under the following conditions:

$$\frac{A_0}{B_0} < 1 \text{ and } R = A_0$$

The processing under the specified restrictive conditions is also devoid of practical meaning, because the curvilinear concave multi-wall outlines of the stock in cross-section (Figure 4b) are completely inconsistent with the contours of a rotary surface in the shape of a circle in the same section. Emerging mathematical - accurate hypocycloid reduce progressively their curvature with increasing ratio $A_0 / B_0$. In relation to:

$$\frac{A_0}{B_0} < 0.5 \text{ and } R = A_0$$

the relative trajectory is a straight line. This particular case is a theoretical but not practical interest because processing is impossible. The stock has zero dimensions, so there is no stock at all. Further increase of the ratio $A_0 / B_0$ and decrease of $R$ in relation to $A_0$ gives the appearance of the relative trajectory, while maintaining its character of a shortened hypocycloid. In the new relation $\varepsilon_3$.

$$\varepsilon_3 = \frac{V_p}{V_u} < 1, \text{ but } \varepsilon_3 > \varepsilon_2 > \varepsilon_1$$
The relative trajectory has the look of a concave (Figure 4c), upright (Figure 4d), and convex (Figure 5a) truncate hypocycloid. For the reasons described above, machining carried out in accordance with the above restrictive conditions is irrelevant when stretching rotary surfaces and is therefore not subject to analysis. Another particular case occurs at the same rotational speed of the two elements of the kinematic pair:

$$\frac{A_0}{B_0} = 1$$

(10)

Theoretically, the type of relative trajectory is a point, but in practice the realization of the machining is impossible because the centers of the tool and the stock coincide, so that the distance L between them is in accordance with the equation:

$$L = 0$$

(11)

In order to use all possible inter-positions of the centers of the tool and the stock, the ratio between their peripheral speeds continues to increase. It already has a new value - as follows:

$$\epsilon_4 = \frac{v_B}{v_u} > 1$$

(12)

The relative trajectory (Figure 5b) changes from hypo to epicycloid, and the rotational movements A and B of the tool and the stock are now an auxiliary and major cutting movement. And this relative trajectory does not correspond in nature to the type of surface being treated and is not subject to further examination. If the ratio $\epsilon$ to values is increased, according to the equation:

$$\epsilon_5 = \frac{v_B}{v_u} > 100$$

(13)

The relative trajectory (Figure 6) is a peri-cycloid with a planar spiral, cyclically extending into a circle with a radius equal to the radius of the rotary stock for a given point on the cutting edge of the helical broach. Constructing a similar trajectory by known analytical and graphical methods is a technically difficult task, almost always leading to gross errors that corrupt the end result. In this case, the complex peri-cycloid [8] curve was constructed using computer software. It turns out that the character of the obtained relative trajectory, completely corresponds to the type of rotary surface of the stock. Its outline in the form of a circle in cross section for each point of the cutting edge defines the same outline of the machined rotary surface, also in cross section. As for the ability to make value-appropriate elements of cutting modes, it can be answered in the affirmative. The magnitude of the cutting speed frequency depends solely on the speed of the rotation stock, given the low speed rotation frequency of the tool. Submission, which is concealed (constructive), is determined by the value of the tooth lift. This is a value that depends on the type of material being machined, and the depth of cut depends on the half difference between the largest and smallest diameter of the stock. It is not a problem to form the geometrical parameters of the cutting part of the tool with rational values, in view of the wide
recommended ranges for the different machinable materials. In order to fully complete the present study, the degree of accuracy of the resulting complex rotary surface resulting from the application of the treatment method under consideration should also be evaluated. Existing common features in machining rotary parts with a tangential profile blade and spiral broach, as this tool is considered to be composed of a number of tangential blades with teeth raised relative to one another. The magnitude of the deviations in this machining method does not exceed 0.002 mm for parts with a maximum diameter of the rotating surface equal to 80 mm.

3. Analysis and conclusions.
The nature of the relative trajectory obtained corresponds entirely to the type of rotary surface of the stock. The outline and the shape of a circle in cross section for each point of the cutting edge, determines the high quality of the machined surface; Insignificant deviations from the precise geometric shape of the complex rotary surface, even for relatively large-sized parts, make this method of processing uncompromising; The helical broach retains all the benefits of a flat broach and ranks among the instruments with a high degree of structural perfection [9]; The two movements included in the structure of the kinematic scheme are a prerequisite for the relaxed kinematics and construction of the machine tool used, and the additional two movements outside it, but actually realized due to the special design of the tool, predetermine the facilitated working conditions. The spiral broach overcomes the three drawbacks of machining:
- The idle of the tool in the initial position and the associated loss of production time are eliminated. Upon completion of the next duty cycle, the next immediately begins;
- The metal-cutting machines used are of overall dimensions, which do not require large production areas;
- The method allows the workflow to be automated if necessary.

Extension and the associated method of machining complex rotary surfaces with helical broach are determined to be optimal when compared to other methods used like turning and milling. This conclusion is made after analyzing all the methods and associated means of treating the surfaces indicated. It is also related to the current level of branches of science and technology that are relevant to machining by cutting.

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