Milling complex surfaces with cutting edge displacement towards the cut surface

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Abstract. The article presents the prospective milling methods with non-linear correlation of feed motions enabling sliding of the cutting edge towards the cut surface, temperature decrease in the cut area and increase of the milling cutter wear resistance.

1. Introduction

Milling problems of complex surfaces, such as dies and molds, arise due to a large volume of chipped material and, as a result, significant expenditures on expensive end and disc radial milling cutters having an accelerated wear.

The most common method of milling the internal surfaces, such as notches and pockets, as well as external profiled surfaces, for instance, punches, cams or turbine blades is cutting with ball-nose end milling cutters made of high-speed steel or solid hard-alloy steel, as well as modular milling cutters with two petal-type plates or one plate with two sided CoroMill-type cutting edges. The latter are rotated by 10° – 15° to vertical to increase the cutting speed. The tool path relative the work piece shall correspond to the radial location of the machined surface, which significantly simplifies the development of control software. In the course of process development, a milling cutter diameter (\(d_m\)) is chosen first, which, according to Sandvik Coromant, shall not exceed 1.5…1.0 times a spherical radius of pocket profile \(R_p\), where the milling width is 0.2\(d_m\), enabling an embrace angle optimal range of 100° to 80° for purposes of angle vibration minimization. However, it raises the cut off layer thickness due to the accelerated feed rate, which is inevitable while milling with a programmed radius. To provide authentic conditions during machining of linear and radial pocket sections the feed rate is decreased while moving along the programmed area to obtain equistability of tooling. The decrease of the milling cutter diameter below \(R_p\) unreasonably reduces the machining capacity. Pockets milling starts with the processing of the hole in the center of the pocket, so that the depth of milling does not exceed a double diameter of the milling cutter. In these conditions machining is performed spirally from the center toward outside with the programmed radial areas of tracing radius \(r_t = R_p - 0.5 \cdot d_m\), with feed rate decreased.

Over recent years many new milling methods have appeared, for example, a highly efficient method of pocket plunger milling with one axial feed movement, which contradicts the definition of a milling cutter and a milling process formulated by GOST 25721-83: ‘A milling cutter is an edge tool for machining performed by the main rotational cutting movement of the tool without a possibility to change the radius of this motion and with at least one feed motion direction not corresponding to the rotational axis’.
While machining flat surfaces with face milling cutters, it is reasonable to set the curved cutting enabling minimal thickness of the layer to be cut off by the tooth when leaving the machining area. First of all, this reduces the length of the tool path. Secondly, it raises significantly the resistance of hard-alloy cutting teeth. The decrease of the cut off layer thickness results in the mitigation of the unloading impact occurring after machining by the cutting edge because of the sharp fall in the chip supporting force at the final point of cutting. This causes chip bending, that is, changes the flow pattern of force on the front surface and eventually changes the stress pattern on the front surface of the tooth from compression to elongation. In case of linear cut the thickness of the cut off layer when the tool is at the end of the cut area remains high until the moment of milling cutter penetration into the work piece by 0.5d.

According to the experimental research carried out by Sandvik Coromant, curved cutting and tracing of angles increase the resistance of cutting hard solid plates 2 up to 16 times while machining steel work pieces.

Therefore, many new machining methods have appeared over recent years, the specifics of these methods being a new kinematic forming diagram characterized by the complex correlation of forming motions with a variable feed value and direction, aimed at an increase in machining resistance and capacity.

Rolling complexly correlated feed motions result in higher milling cutter resistance due to smaller stripe dimensions. Curved cutting with complex correlation at the moment of face milling cutter penetration into the work piece reduces the negative influence of unloading impact on the cutting edge. A gradual decrease of the feed rate along with the cutting edge embraces an angle increase in the pocket angle, tracing points lessen the machining vibrations.

One of the prospectives and new fields of investigation can be presented by methods enabling continuous displacement of the cutting edge toward the cut surface. Displacement of the cutting edge, ensuring non-linear generating of the machined surface as well as generating with sliding, helps to continually involve new areas of the cutting edge not operative before and to reduce heat density at the top of the cutting edge by high-speed sliding. Besides, it increases the contact and general length of the cutting edges and also contributes to even wear of the cutting edges owing to their uniform displacement.

2. Non-linear form-generating milling method
One of the most universal non-linear form-generating methods of the machined surface is a method of complex curved surfaces machining (patent No. 2167746 of the RF), performed by a tool with two taper or one toroidal surfaces (Figure 1), as it enables machining of the profiles intersecting at any angle.

Tool linear generators are machined at an \( \alpha \) angle, with the value equal or below minimum angle \( \beta_{\text{min}} \) between the tangent lines to the opposite sides of the machining surface profile at the points of interference with the profile concave areas.

![Figure 1. Complex profile generating diagram with a composite profile tool.](image-url)
Machining of the profile convex side is performed by the linear corresponding side of the tool profile, while the part profile concave area is machined by the radial toroidal surface of the tool. Machining is performed by three simultaneous forming motions with non-linear correlation lying in the same profiling plane. One of them, rotational $\omega_{X1}$, is effected so that the linear generator of the tool is serial to the tangent line in each point of the machined profile. Two other motions, $S_Z$ and $S_Y$, correlate with rotational $\omega_{X1}$, so that the linear generators can roll over the machined surface while machining the profile areas. The developed method of complex surface machining contributes to a better accuracy owing to part profile generating by linear tool generators. Furthermore, this method is universal and highly-efficient.

3. Milling with a screw feed motion
For machining profiled concave surfaces with variable profile such as grooves, a new method (patent No. 22008502 of the RF) which is performed by a tool in the form of a rotary body with the toroidal generating surface, is developed (Figure 2.). In the course of machining, the tool (work piece) is subject to rotation with $\omega_{OY}$ feed motion and two progressive motions, $S_Y$ and $S_Z$, which are performed simultaneously and lie in the plane perpendicular to the plane of rotational movement. Progressive motions are performed normal ($S_Y$) and parallel ($S_Z$) to the base plane and have a non-linear correlation with rotational motion $\omega_Y$. Rotational feed motion is effected until a periodical and simultaneous contact of the tool is realised within the machined area at two points $M$ and $M_1$ ($M$ and $M_1'$) on the opposite sides of the profile. At the contact moments the rotational feed motion is reversed. The developed method significantly adds to the improved cutting plate resistance and plate wear evenness as the cutting top is displaced along the cutting edge left side to the right once per each turn of the cutting edge, while the work piece is rotated around OY axis and vice versa. This method also enhances work efficiency and smoothness due to the increased number of simultaneously working teeth.

![Figure 2. Groove profile forming diagram.](image)

4. Swinging motion milling
A new machining method with swinging motion of the milling cutter is particularly interesting (patent No. 2497636 of the RF). It enables a continuous displacement of the cutting edge top toward the cut surface, a decrease of the cutting edge heat density, its more even wear and, as a result, a better tool resistance.
Machining is performed by a progressive contact of the tool with generated machining surface, so that the toroidal surface of the tool machines convex, flat and concave areas of the machined profile; in this case, the tool performs swinging feed motions with non-linear sliding of the cutting edge top toward the cut surface.

During forming, the tool and the work piece perform four feed motions, the main motion is $Dr$ (Figure 3), then the tool is moved to the work piece via $X_1$ and $Y_1$ axis displacement so that the tool performs radial penetration till the toroidal profile of the tool reaches initial point $A_1$ of the machined surface profile, that is, to the motion start point. Then, the work piece is subjected to three simultaneously correlated feed motions $Ds(oz_1)$; $Ds(x_1)$; $Ds(y_1)$, so that the tool progressively touches the machined profile at points $A_2$ and $A_3$, simultaneously rolling counterclockwise around the center of the tool toroidal surface profile section (O) through angle $\psi$, which is defined on the one hand, by normal cutting conditions, that is, all the cutting edge length is involved if it is possible, and with consideration of cutting depth $t$, on the other hand, by the conditions of tooling block non-penetration into the work piece.

At point $A_3$ rotational motion $Ds(oz_1)$ is reversed with simultaneous correlation of feed motions $Ds(x_1)$ and $Ds(y_1)$ with the profile, so that the tool progressively contacts the machined profile at the subsequent points with the above conditions observed. Thus, the machining is effected with a relative motion of the tool toward the profile at points $A_4$, $A_5$ etc. and swinging feed motions $Ds(oz_1)$, which enables both conditions.

5. Temperature and wear resistance investigation
Figures 4 and Figures 5 feature the results of various theoretical investigations related to the tool front surface temperature for swinging motion and line-by-line milling methods when one of the parameters is variable and others are constant.

![Figure 4. Distribution of the cutting temperature of the tooth front surface with variable swinging motion rate $V_{sw}$; $V = 150$ m/min; $Sz = 0.12$ m/min; 9XC steel: (a) $V_{sw} = 0.16$ m/min; (b) $V_{sw} = 1.6$ m/min; c – $V_{sw} = 3.2$ m/min.](image-url)
Figure 5. Tooth front surface temperature change: (a) with variable cutting rate \( V \), 45 steel: (1) swinging feed motion milling, (2) line-by-line milling; 9X\( \text{C} \) steel: (3) swinging feed motion milling, (4) line-by-line milling; (b) with variable swinging feed motion rate \( V_{SW} \).

The experimental research of cutting plate wear resistance (Figure 6, 7) and temperatures in the cut area confirm the temperature behavior of the theoretic process model.

Figure 6. Rear-surface tool wear as a function of: (a) cutting rate \( V \), 45 steel: (1) swinging feed motion milling, (2) line-by-line milling, 9X\( \text{C} \) steel: (3) swinging feed motion milling, (4) line-by-line milling; (b) swinging feed motion rates.

Figure 7. Rear surface tool wear (a), swinging feed motion milling (b); line-by-line milling (c).

6. Conclusion
The theoretical model of heat flow distribution in the cutting wedge developed with the aid of Abaqus 6.12 software and applied for two milling methods enabled a decrease of the cutting edge temperature to 330.2…395.5 °C, that is, by 80.6…181.6 °C for 9X\( \text{C} \) steel and to 193.8…285 °C, that is, to 56.6…120.2 °C for 45 steel in comparison with line-by-line milling. It is found that the contact length of the cutting edges is increased by 2.4 times and in these conditions extreme temperature values are localized in the middle part, like in case of line-by-line milling.
The experiment shows that the tool wear at the cutting rate of $V = 100\ldots200$ m/min, tooth feed of $S_z = 0.08\ldots0.16$ mm/tooth, swinging motion rates of $V_{SW} = 0.16\ldots3.2$ m/min is, on the average, 1.7 times less for 45 steel machining and 1.34 times less for 9XC steel machining than in case of line-by-line milling [3-5].

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