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Modelling Topology of Freeform Surfaces with Ball-end Milling

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Abstract

Machining of freeform surfaces, viz. dies, moulds, blades, etc. is one the most difficult processes nowadays. Ball-end milling having either the constant tool pitch for flat and oblique surfaces or the variable tool pitch for freeform surfaces is required to improve the surface quality before the final machining. Among other parameters of the surface quality is the surface topology which is described in the paper. Various strategies of the pre-final working passes in ball-end milling of three different types of the machined freeform surfaces (oblique, convex, concave) of three strategies – "along the trace", "across the trace" and "at an angle to the trace" of the rough machining passes are investigated, six different models representing the combination of the freeform surfaces and the trace shape of the topology of the surface before machining are offered. The calculated dependencies allow forecasting of cutting forces, and, hence, the predictability in obtaining the surface accuracy.

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Keywords: Ball-end milling; freeform surface; surface topology; tool trace; surface roughness.

1. Introduction

Freeform surfaces are widely manufactured nowadays. The branches of industry which produce parts with such surfaces are aerospace [1-3], automotive [1-3], die mould [1,3], biomedical [1,3] parts, sensors for micro-electro-mechanical systems [4] and also turbine blades in power engineering [5,6]. To produce freeform surfaces, 3 to 5 NC milling machines are used [1-3]. The tools used to produce freeform surfaces are ball-end mills [1-3]. The manufacturing process is difficult and complex. The tool path generation is generally based on tool path computation, so tool path consecutiveness is not optimum. The sequence is, the CAM preparation for complex surfaces requires up to 50-fold time of the manufacturing itself. The main problem is, as usual, that the shape of the

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final surface does not match the shape of the initial one, so big amount of bulk material is to be removed [6]. Hence, many factors as tool deflection [7-9], feedrate [10,11], surface shape, etc. must be taken into account. Many researchers investigated manufacturing freeform surfaces with respect to speed parameters [10,11], tool deflection [7-9], tool geometry [21], dynamical factors [16], surface roughness [7,12,15,19], even tool wear [12,13,18,22], etc. whereas no research investigating the combination of the geometry of both the tool and the pre-machined surface, have been conducted so far. It is, however, mentioned by many researchers that the trace of the pre-machined surface, on the one hand, and the tool path, on the other, influence surface integrity parameters, such as scallops and dimples [20,22].

The purpose of rough machining passes at three-axis milling is the most productive removal of a metal surplus and the approximation of a blank's shape to a finished part's shape. The purpose of the final machining pass is to remove the scallops remained from previous rough passes and to obtain the required machining accuracy.

In actual practice, the final machining of freeform surfaces uses one of the three machining strategies – "along the trace", "across the trace" and "at an angle to the trace" of the rough machining passes. In the strategy "across the trace", neither cutting zone geometry nor power factors were investigated. In view of the wide (approximately in 70 % out of all machined surfaces) usage of the strategy "across the trace", the need of the investigation of geometrical and power factors at the strategy "across the trace" became particularly urgent.

2. Process Description

The main geometric parameters of three-axis milling: radius R or inclination angle ω of the machined surface to horizontal plane concerning the uppermost for convex (the lowermost for concave) surfaces. The radius of the mill R_m at rough passes is set in view of strength conditions and, as a rule, is invariable. Therefore, to adjust the cutting depth t dominated by the height of "step" B, one can only by set a certain index line feed S_f at the previous pass, which, as a rule, is constant. The deduction of analytic dependence between the cutting depth t, the radius of curvature R of a machined surface, inclination angle ω of the machined surface to horizontal plane, the radius of the mill R_m, the index line feed S_f at the previous pass will allow the further calculation of cutting force components. This, in turn, will derive the value the tool's deflection, and, hence, calculate the machining accuracy.

The technique of calculation of the cutting depth t depending on a set of geometrical parameters B, R, ω, R_m, S_f while machining oblique, convex and concave surfaces in accordance with the strategy "across the trace" after the machining with flat-end and ball-end mills.

3. Oblique surfaces

When the previous pass of an oblique surface was obtained with a ball-end mill, the maximum cutting depth t_{max} is a perpendicular dropped from the intersection point of two arches of 2 circles: the first circle with the radius R being the trace of the machining after the previous pass and the second circle with the radius R_m being the shape of the mill at the current pass (see Fig. 1):

$$t_{\max} = R\left[1-\sin\left(\omega+\kappa_1\right)\right] \tag{1}$$

Where κ_1 is an angle between a horizontal axis and a segment connecting the centre of the first circle with the intersection point of the two circles; it is equal

$$\kappa_1 = -\arccos\left(\frac{S_f}{2R\cos\omega}\right)+\omega. \tag{2}$$

After manipulating, the following dependences calculating the current cutting depth t_i can be derived:

$$\begin{cases} t_i = R_m\left(1-\cos\arcsin\dfrac{l_i}{R_m}\right) & \text{at } l_i \in \left[0; \dfrac{S_f}{2\cos\omega}\right]; \\ t_i = R_m\left(1-\cos\arcsin\left[\dfrac{S_f}{\cos\omega}-\dfrac{l_i}{R_m}\right]\right) & \text{at } l_i \in \left[\dfrac{S_f}{2\cos\omega}; \dfrac{S_f}{\cos\omega}\right]. \end{cases} \tag{3}$$

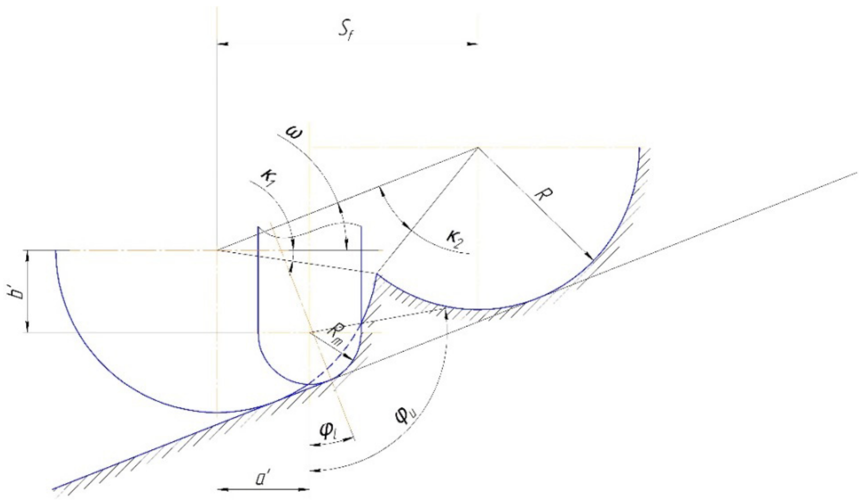

Fig. 1. Geometrical parameters of machining of a flat surface.

4. Convex surfaces

When the previous pass of a convex surface was obtained with a ball-end mill, the maximum depth of cutting t_{max} is calculated by theorem of sines as a segment dropped from the intersection point of two circles normal to the machined surface (Fig. 2):

$$\frac{r+t_{\max}}{\sin\left(\dfrac{\pi}{2}+\omega'-\kappa_2\right)} = \frac{R}{\sin\left(\dfrac{\omega'-\omega''}{2}\right)} \tag{4}$$

Where κ_2 is an angle between a horizontal axis and a straight line connecting the centre of the first (top) circle with the bottom intersection point of the two circles;

ω', ω'' are the inclination angles to vertical plane of straight lines connecting the centre of a circle of the machined surface with the centres of two circles:

$$\begin{cases} \omega' = \arcsin\left(\dfrac{a_1}{r+R}\right); \\ \omega'' = \arcsin\left(\dfrac{a_1+S_f}{r+R}\right), \end{cases} \tag{5}$$

Where a_1 is the displacement of the centre of the first circle concerning the uppermost point of the machined surface.

After manipulating, the following dependences calculating the current cutting depth t_i can be derived:

$$
\begin{cases}
t_i = R\left(1-\cos\arcsin\dfrac{l_i}{R_m}\right)- \\
-l_i\sin\left(\dfrac{\omega'-\omega''}{2}\right) \qquad \text{at } \varphi_i\in\left[0;\dfrac{\omega'-\omega''}{2}\right]; \\
t_i = R\left(1-\cos\arcsin\left[\dfrac{S_f}{\cos\left(\dfrac{\omega'+\omega''}{2}\right)}-\dfrac{l_i}{R_m}\right]\right)- \\
-l_i\sin\left(\dfrac{\omega'-\omega''}{2}\right) \qquad \text{at } \varphi_i\in\left[\dfrac{\omega'-\omega''}{2};\omega'-\omega''\right].
\end{cases}
\tag{6}
$$

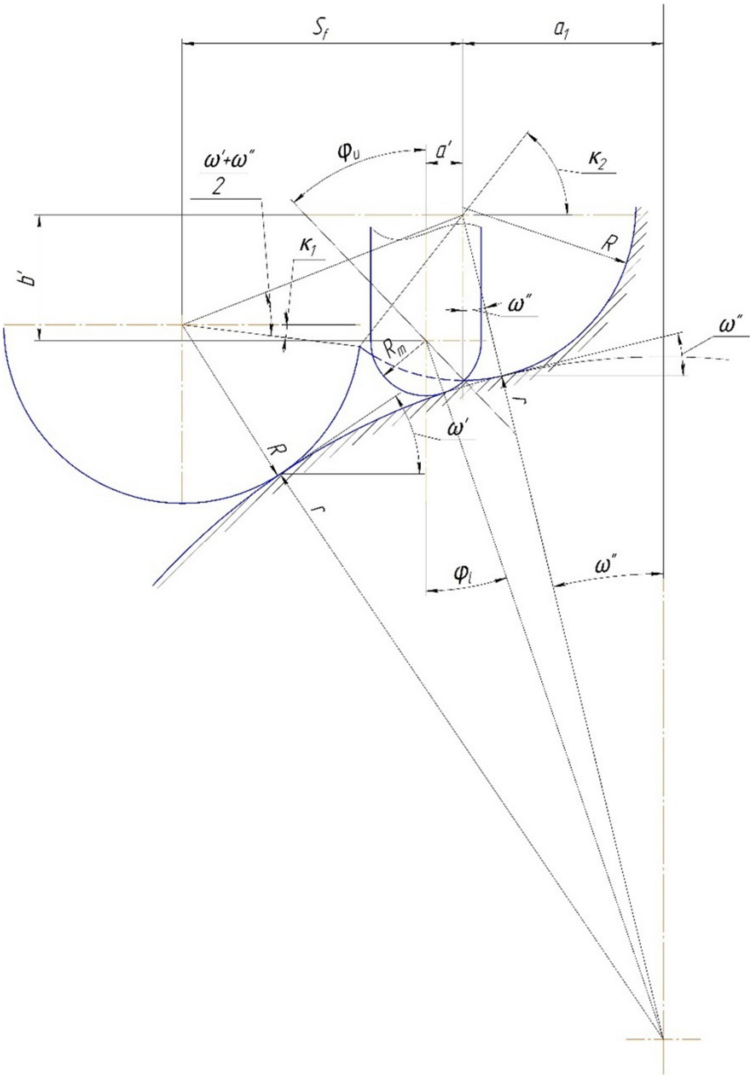

Fig. 2. Geometrical parameters of machining of a convex surface.

5. Concave surfaces

When the previous pass of a convex surface was obtained with a ball-shaped mill, the maximum depth of cutting t_{max} is calculated by theorem of sines as a segment dropped from the intersection point of two circles normal to the machined surface (Fig. 3):

$$\frac{r - t_{\max}}{\sin\left(\frac{\pi}{2} + \omega' + \kappa_1\right)} = \frac{R}{\sin\left(\frac{\omega'' - \omega'}{2}\right)} \tag{7}$$

Where κ_1 is an angle between a horizontal axis and a straight line connecting the centre of the first (bottom) circle with the bottom intersection point of the two circles;

ω', ω'' are the inclination angles to vertical plane of straight lines connecting the centre of a circle of the machined surface with the centres of two circles:

$$\begin{cases} \omega' = \arcsin\left(\dfrac{a_1}{r - R}\right); \\ \omega'' = \arcsin\left(\dfrac{a_1 + S_f}{r - R}\right), \end{cases} \tag{8}$$

Where a_1 is the displacement of the centre of the first circle concerning the lowermost point of the machined surface.

After manipulating, the following dependences calculating the current cutting depth ti can be derived:

$$\begin{cases} t_i = R\left(1 - \cos\arcsin\dfrac{l_i}{R_m}\right) - \\ -l_i \sin\left(\dfrac{\omega'' - \omega'}{2}\right) \qquad \text{at } \varphi_i \in \left[0; \dfrac{\omega'' - \omega'}{2}\right]; \\ t_i = R\left(1 - \cos\arcsin\left[\dfrac{S_f}{\cos\left(\dfrac{\omega' + \omega''}{2}\right)} - \dfrac{l_i}{R_m}\right]\right) - \\ -l_i \sin\left(\dfrac{\omega'' - \omega'}{2}\right) \qquad \text{at } \varphi_i \in \left[\dfrac{\omega'' - \omega'}{2}; \omega'' - \omega'\right]. \end{cases} \tag{9}$$

6. Conclusions

The above calculated dependences describing variation of cutting depth at the machining of freeform surfaces “across the trace" depending on the curvature radius the freeform surface r, the inclination angle ω of the machined freeform surface to the horizontal plane at the current point, the radius of the ball-end mill R and index line feed S_f, are obtained. In case of $S_f << R$, the machining of a freeform surface can be approximated as machining of a finite number of flat surfaces with different inclination angles ω of the machined surface to horizontal plane thereby to simplify further calculations. The above calculated dependencies allow further mathematical modelling of cutting force prediction, which, in due course, will predict the topomorphy and accuracy of the obtaining freeform surface. The practical outcome of the mathematical model will result in determining optimal cutting conditions under finishing freeform surfaces.

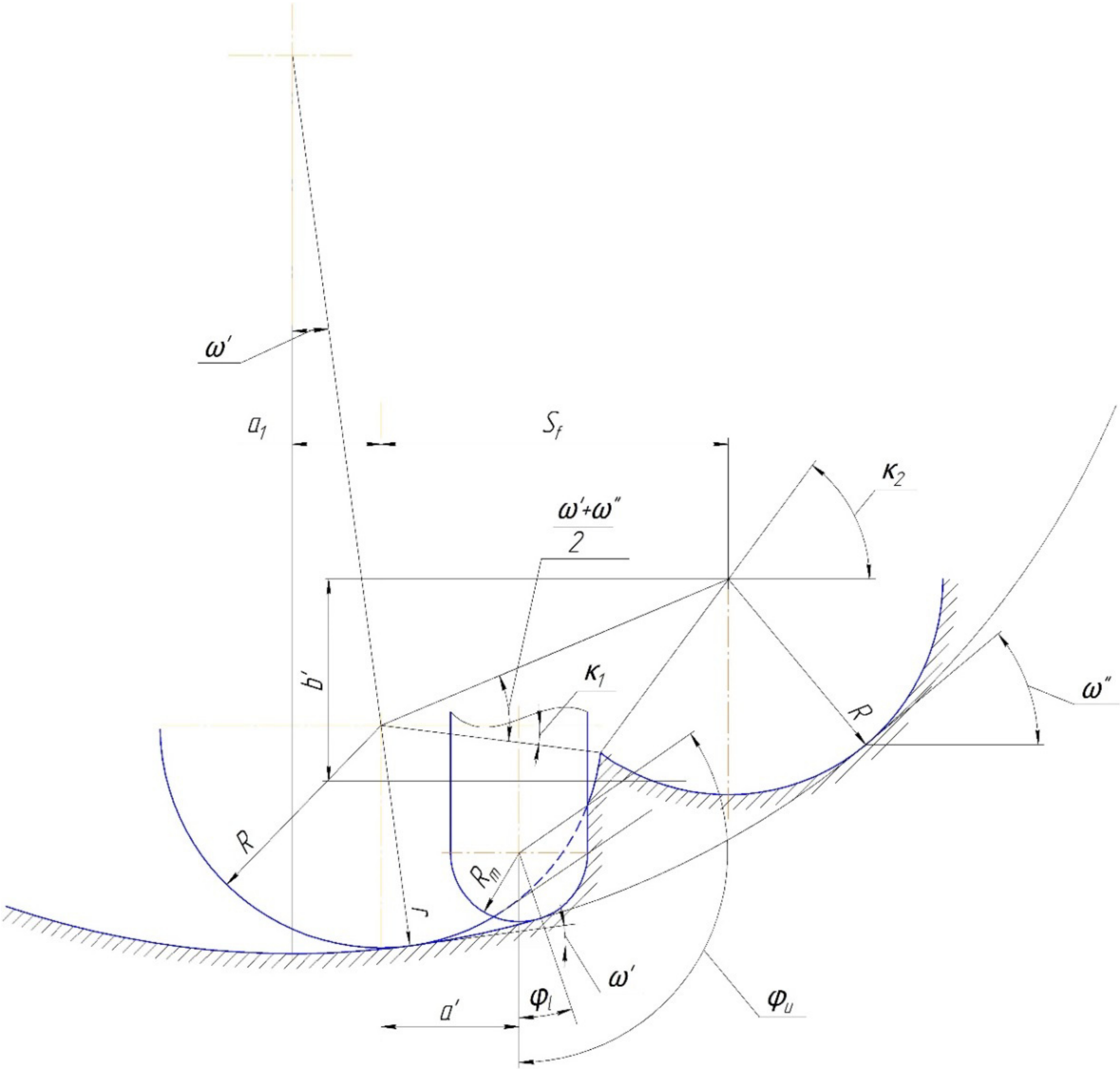

Fig. 3. Geometrical parameters of machining of a concave surface.

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