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Reducing Machining Time by Pre-Process Control of Spindle Speed and Feed-Rate in Milling Strategies

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Abstract

This article focuses on the issue of controlling cutting conditions in point milling strategies in order to reduce machining time. Using cutting tools with a circular cutting edge during point milling strategies of complex shape parts the actual contact point between the tool and the workpiece continuously changes. According to this fact the cutting speed also changes continuously and the required cutting speed is not achieved along the toolpath. Therefore, a solution to control the spindle speed has been developed to achieve the constant value of cutting speed and consequently provide a solution to control the feed-rate in order to maintain the constant value of feed per tooth. Application of this optimization technique has been demonstrated by means of a real machining test. The machined surface quality improvement and machining time savings were proven.

Keywords: Milling; Productivity; Computer aided manufacturing; Cutting tool; Postprocessor

1. Introduction

Milling of complex shape parts e.g. molds, blades, impellers, propellers, etc. in most cases requires point milling strategies. An example of point milling strategy can be seen in Fig. 1, specifically a finishing strategy to mill the surface of a blade.

Nomenclature

T_T	tool tip
C_P	contact point between the tool and the workpiece
R	radius of circular cutting edge of the tool
D	tool diameter
R_R	real cutting radius of the tool
$\vec{e}$	vector of tool axis
$\vec{n}$	normal vector of machined surface in contact point
v_c	cutting speed
f	feed-rate

Due to the complexity of surfaces it is necessary for the point milling strategies to use milling tools with a circular cutting edge (ball end mills, toroidal mills, etc.). The machining time of these finishing milling strategies is, in general, long due to high surface roughness demands and the corresponding high

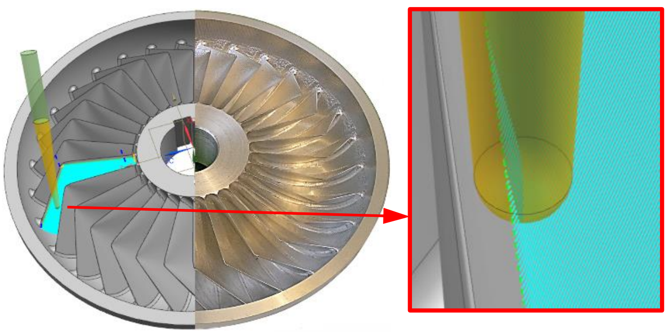

Fig. 1. Point milling strategy of a blade with detail

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number of toolpaths. The number of toolpaths and toolpath points is derived from the surface roughness and the surface accuracy requirement. When the toolpath tolerance value and the number of toolpaths (or scallop) are adjusted to their possible limits, the way to increase productivity is to attain optimal cutting conditions. The preparation of proper cutting conditions issue has been dealt by many authors.

Most papers addressing the issue are focused on cutting condition optimization based on computation of the cutting forces. Authors of lit. [1] implemented the calculation of cutting forces to allow a user to visualize the cutting force map during the preparation of toolpath in the CAM system. Another optimization of cutting conditions is presented in [2] where the author developed a method to calculate the actual contact area between the tool and the workpiece in order to predict the cutting forces. Refined computational models of tools to calculate cutting forces and optimize the feed-rate are mentioned in [3] and [4]. Authors of [5] and [6] use complex models of cutting process that include several parameters from the control system to improve the optimization of cutting conditions. Another approach to optimization is to create toolpaths according to optimized feed direction which is the subject of [7]. Authors of [8] reflect the actual material removal rates of different tool types to control the feed-rate to maintain constant load. The optimization of milling by varying the feed-rate automatically as the tool-workpiece engagements based on the mechanics model is dealt in [9]. The optimization of feed-rate along multi-axis toolpaths which is based on calculation of the actual tool position to rotational axes is mentioned in [10]. However, no work to develop the method for achievement of the desired cutting speed and consequently to optimize feed-rate has been found. Therefore this paper is focused on it.

2. Recalculation of cutting conditions in point milling

Different types of cutting tools can be applied to point milling strategies whether in terms of material or shape or geometry. A specific tool requires a specific set of cutting conditions to achieve maximum efficiency.

2.1. Tools and cutting conditions in point milling strategies

In most cases of point milling strategies tools with a circular cutting edge are used as ball-end mill, bull-nose mill (toroidal), conical, but also the flat-end mill can be principally applied (when tilted against the workpiece). If a tool with a circular cutting edge is used to mill a complex surface the real cutting diameter is not the same as the diameter of the tool. Due to this fact a technologist has to select the right value of spindle speed so that the average cutting speed is reached in the longest section of the toolpath. Several examples of real cutting diameter can be seen in Fig. 2. The issue of real cutting diameter and real cutting speed is more complex because the real cutting diameter continuously changes during the toolpath in most cutting strategies. Only when the tool axis has the same orientation to the machined surface along the toolpath is the real cutting diameter constant.

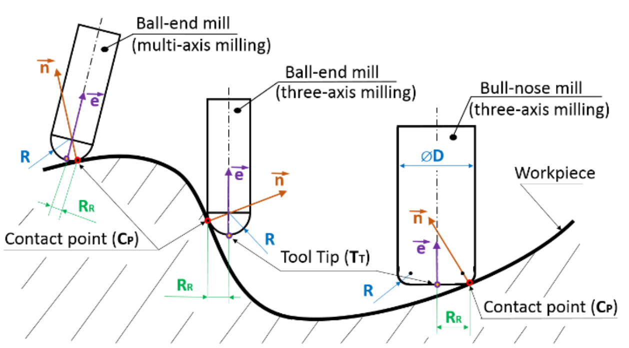

Fig. 2. Examples of a real cutting diameter when milling

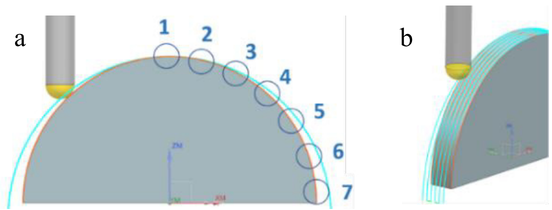

Fig. 3. Sample 3D model and sample toolpath

Continuous change of the real cutting diameter along the toolpath can occur during three-axis milling strategies as well as during multi-axis strategies. The example of a point milling strategy where the issue of continuous change of real cutting diameter occurs can be seen in Fig. 3. The example set-up is as follows. The 3D model is half of a cylinder with a 120 mm diameter and represents a general complex surface, that has to be machined using point milling strategy. The tool is a mill with the ball end with the radius of 5 mm and four teeth. The nominal value of cutting speed is in this case 100 m/min and the feed per tooth is set on the value of 0,05 mm.

From this simple example of a milling strategy the real cutting diameter in an actual toolpath point can be readily analyzed. The characteristic of real cutting diameter along the toolpath can be seen in Fig. 4. It is also clear that the real cutting diameter of the tool along the toolpath continuously changes from the nominal diameter of the tool to zero (the top of the surface) then back to the nominal diameter. This pattern repeats in the next passes. It is clear that the cutting speed also changes from its higher value to zero then back and repeats. Cutting speed changes lead to a non-uniform milled surface and can cause surface defects due to passing the built-up edge region. Moreover the milling strategy is inefficient and not satisfactorily productive.

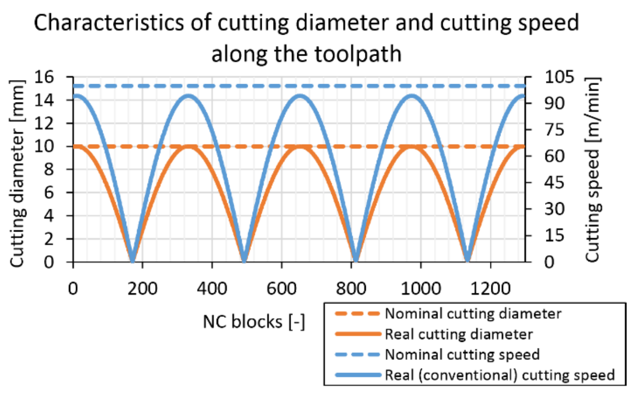

Fig. 4. Characteristics of cutting diameter along the toolpath

2.2. Recalculation of cutting conditions

It is obvious that the spindle speed can be increased along the sample toolpath. If the spindle speed is increased then the feed-rate can be increased too in order to reach the specific value of feed per tooth. This leads to increased productivity.

For the specific workpiece material, specific tool and strategy setup a specific value of cutting speed is required. The constant value of cutting speed can be achieved only when the spindle speed will continuously change according to the real cutting diameter. The real cutting radius of the tool can be calculated using the formula (1). For the calculation it is necessary to know the coordinates of contact point $C_P = (C_{PX}, C_{PY}, C_{PZ})$, coordinates of tool tip $T_T = (T_{TX}, T_{TY}, T_{TZ})$ and components of tool axis vector $\vec{e} = \{e_X;\ e_Y;\ e_Z\}$. The vector from the contact point to the tool tip $\overrightarrow{C_P T_T}$ is then determined using formula (2). Real cutting diameter is then simply computed as real cutting radius R_R multiplied by two.

$$R_R = \frac{|\overrightarrow{C_P T_T} \times \vec{e}|}{|\vec{e}|} \quad (1)$$

$$\overrightarrow{C_P T_T} = \{T_{TX} - C_{PX}; T_{TY} - C_{PY}; T_{TZ} - C_{PZ}\} \quad (2)$$

The specific workpiece material, specific tool and strategy setup needs to achieve a specific value of feed per tooth too. If the spindle speed varies, the feed-rate has to vary to reach the specific value of feed per tooth. Therefore the feed-rate can be recalculated in each toolpath point too. During the recalculation procedure the maximum speed of an actual spindle and the maximum velocities of machine tool axes must be taken into consideration.

3. Recalculation procedure implementation and testing

The recalculation procedure has been implemented to post-processor for a specific machine tool using SW PostBuilder.

3.1. Actual cutting conditions after recalculation

It is necessary for the implementation to know the specific variables with the needed data for recalculation (specified in 2.2). PostBuilder is properly connected with Siemens NX so this needed variables are available for the postprocessor.

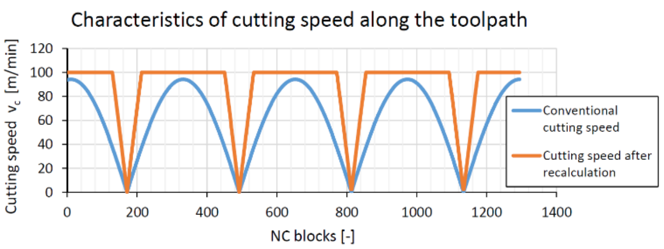

Fig 5. Characteristics of cutting speed along the toolpath

The cutting speed of the sample toolpath mentioned above can be seen in Fig. 5 and it shows that recalculating the spindle speed makes it possible to achieve better cutting speed characteristics (orange char.) than in the conventional case (blue char.). This example of recalculation includes the maximum speed limitation of the actual spindle, in this case 8000 rpm. The spindle speed limitation is the cause of the decreased cutting speed. The fact that the tool tip has a real cutting diameter equal to zero prolongs the decrease of the cutting speed to zero.

The recalculation of feed-rate has been applied for the sample toolpath mentioned above. From the feed-rate characteristics in Fig. 6 it can be seen that the machining time reduction by approx. 30% compared to the original time has been achieved via recalculation of the cutting conditions.

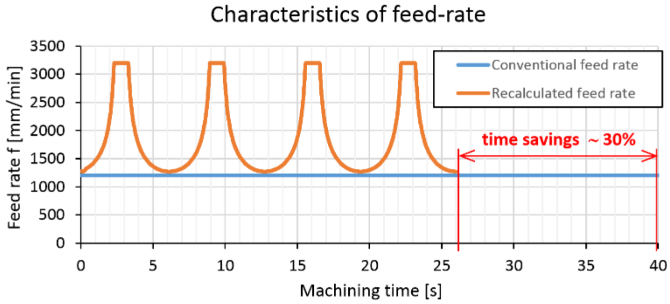

Fig. 6. Characteristics of feed-rate along the toolpath

3.2. Milling test realized on a CNC machine tool

The milling test was based on the sample toolpath mentioned above and realized using a Tajmac-ZPS MCV5050LN machine tool with a Sinumerik 840D control system. The blank was a cylinder of steel C45 (1.0503) with a 120 mm diameter. The tool was a mill with the ball end (Iscar multi-master carbide head) with the radius of 5 mm and four teeth. The nominal value of cutting speed was set on 100 m/min. The feed per tooth was set on the value of 0,05 mm.

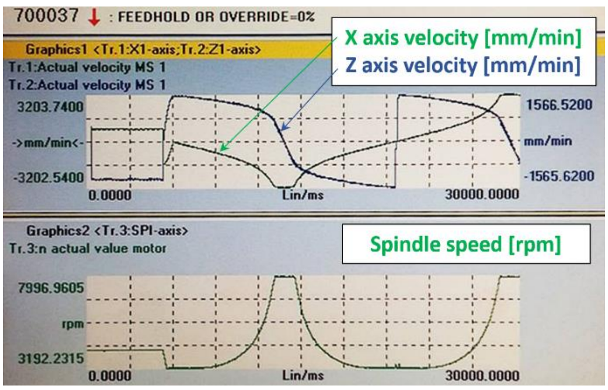

Fig. 7. Measurements of spindle speed and velocities of X and Z axes

During the milling test measurements of spindle speed and velocities of the X and Z axes were carried out. The measurements, as it can be seen in Fig. 7, show that the real spindle speed continuously changes from approx. 3200 rpm to approx. 8000 rpm. Velocities of X and Z axes continuously change too. It is clear that milling is smooth and without stops or shocks. It has been verified that NC programs with dynamic control of spindle speed and feed-rate can be executed on a machine tool.

3.3. Evaluation of the milling test

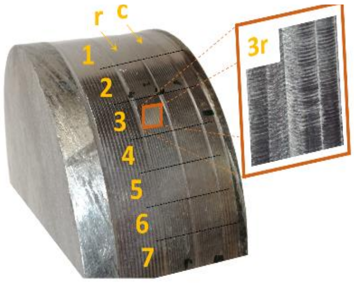

Fig. 8. Workpiece after milling test

The real machining time before recalculation of cutting conditions and also after recalculation has been measured (Tab. 1). It has been proven that the productivity in point milling has increased by approx. 26%. Energy consumption was also measured during the milling. The average value of the actual input power was slightly higher due to the changes of spindle speed. But the total energy consumption was 24% less in the case of recalculated cutting conditions than under the conventional machine tool regime. The measured values can be seen in Tab. 1.

Tab. 1. Measured values during the milling test

Milling	Machining time [min]	Actual input power [W]	Total energy consumption [Wh]	Energy savings [%]
Conventional	8,58	2096	299,77	0
Rec. cut. cond.	6,36	2150	227,53	**24**

A real milling process was found to be equivalent in both cases, without vibrations or shocks. The roughness of both machined surfaces has been measured. The roughness of the surface milled using recalculated cutting condition has been in all areas measured better (e.g. Ra0,6) when compared to the surface milled conventionally (e.g. Ra1,5). Both surfaces have been also analyzed in detail microscopically.

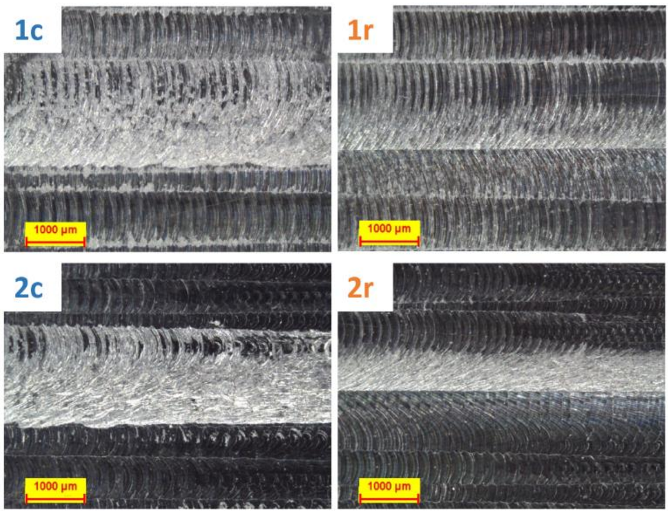

Fig. 9. Surface quality comparison

The surface analysis has been carried out in seven sections as is marked in Fig. 3a and Fig. 8. The comparison of both machined surfaces can be seen in two examples (section 1 and 2) of Fig. 9. Optical observation confirmed that the surface milled by conventional cutting conditions (Fig. 9: 1c and 2c) had a worse quality compared to the surface milled by recalculated cutting conditions (Fig. 9: 1r and 2r).

4. Conclusion

The method for productive control of cutting conditions in a point milling strategy using tools with a circular cutting edge has been proposed and verified. The spindle speed and feed-rate were recalculated to accommodate the real cutting diameter of the tool to achieve a constant cutting speed and feed per tooth. Using this method a significant reduction of machining time and improved surface quality was attained. It is possible to apply this method for three-axis as well as multi-axis strategies. This recalculation of cutting conditions has been applied on finishing strategies of the blades in Fig. 1. It has been proven that the machining time of one blade has been lowered by 2,8 min. In relation to the original machining time (6,5 min) the productivity increased by approx. 43%.

Acknowledgements

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