

Tool orientation planning for minimizing surface error in five-axis machining of copper alloy

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Abstract. Five-axis machining is increasingly applied in manufacturing complicated parts, such as blade of numerous-blade propeller rotor and compressor impeller, benefit from providing enough accessible space of the tool orientation. Then it becomes more important and difficult of tool orientation planning because of more requirements and higher demands. Main purpose of this paper was just to propose a method, which served for tool orientation planning considering the effect of cutting force induced surface error in five-axis machining of copper alloy. Geometric relationship of cutter and workpiece was analysed firstly. Then the proposed tool orientation planning method was described, followed by building the mathematical model. Finally, the effectiveness of the planning methods was verified by experiment of machining a proportionally reduced ten-blade propeller rotor.

1. Introduction

Five-axis machining is widely utilized due to its advantages, including avoiding interference and collision, improving machine efficiency, optimizing tool path, and so forth. However, some problems are emerging with five-axis machining. For example, two additional degrees of freedom elongate the transmission chain, which weakens the stiffness of the machining system. Moreover, a variety of difficult-to-machine parts are applied because of their improved functions and properties in the marine, aerospace and defence industries. This considerably increases the cutting force induced surface error under conditions of less stiffness and larger cutting force during processing. Therefore, it is important to research the control of cutting force induced elastic deflection error by tool orientation planning in five-axis machining.

Changing the angles of the additional two rotational axes, different tool-workpiece orientations can be achieved. In tool orientation planning, Bi [1] proposed a model and algorithm optimizing cutter orientations wholly based on a cutter contact point mesh, in which the cutter orientation smoothnesses along the feed direction and pick-feed direction are both wholly optimized. Fan [2] presented the



theory for optimising the orientation of a flat-end cutter on a quadric to maximize the machined strip. Kim [3] presented an approach for generating optimized collision-free and gouging-free tool paths for 5-axis CNC machining of freeform NURBS surfaces using flat-end and rounded-end tool shaving cylindrical shank. Campatelli [4] developed the approach to reduce the environmental impact of a milling process based on the optimal product positioning and orientation within the workspace. Geng [5] proposed a simulation-based method to identify cutter postures that produce minimum deflection cutting force, which applied to the finish machining process where only the ball part of the cutter would be engaged with the workpiece.

Previous research in tool orientation planning mostly focused on the geometrical relationship of the cutter and the workpiece, the kinematic relationship of the cutter space and the motion axes space, etc. Few studies considered the effect of tool orientation on cutting force induced surface error in five-axis filleted end milling. As the rapid development of marine, aviation, and automobile, parts with complex curved surface are widely utilized in industrial production, which raises the requirement of machining precision in five-axis machining. As a continuation of our preliminary studies on the geometrical error analysis and machine tool characteristics, kinematic relationship [6], cutting force and tool deflection [7-8], the relationship between tool orientation and cutting force induced elastic deflection was analysed and studied.

This paper addresses the optimization of tool orientation at given feed direction and cutter contact point in five-axis free-form surface machining with filleted-end mills. The objective is to efficiently determine a tool orientation that will yield a minimum cutting force induced surface error in the case of avoiding both local and global interference at the contact point.

2. Geometric relationship of cutter and workpiece

The direction vector of three coordinate axes could be determined by.

$$\begin{cases} \mathbf{n} = \frac{\mathbf{r}_u \times \mathbf{r}_v}{\|\mathbf{r}_u \times \mathbf{r}_v\|}, \\ \mathbf{a} = \frac{\mathbf{P}_{L,i+1} - \mathbf{P}_{L,i}}{\|\mathbf{P}_{L,i+1} - \mathbf{P}_{L,i}\|}, \\ \mathbf{t} = \mathbf{n} \times \mathbf{a}. \end{cases} \quad (1)$$

where, \mathbf{r}_u and \mathbf{r}_v were u - tangent vector and v - tangent vector of the workpiece design surface; \mathbf{P}_L and $\mathbf{P}_{L,i+1}$ were position vectors of cutter location points at index $i+1$ and i .

Position and pose of the cutter could be represented by the cutter location point \mathbf{P}_L and tool orientation \mathbf{v} (z_L). And position and pose of the workpiece could be represented by the cutter contact point \mathbf{P}_C and normal vector \mathbf{n} at \mathbf{P}_C . Then transformation relation between poses of cutter and workpiece could be given as

$$\begin{cases} \mathbf{x}_L = \frac{\mathbf{v} \times (\mathbf{P}_{L,i+1} - \mathbf{P}_{L,i}) \times \mathbf{v}}{\|\mathbf{v} \times (\mathbf{P}_{L,i+1} - \mathbf{P}_{L,i}) \times \mathbf{v}\|}, \\ \mathbf{y}_L = \frac{\mathbf{v} \times (\mathbf{P}_{L,i+1} - \mathbf{P}_{L,i})}{\|\mathbf{v} \times (\mathbf{P}_{L,i+1} - \mathbf{P}_{L,i})\|}, \\ \mathbf{z}_L = \frac{\mathbf{v}}{\|\mathbf{v}\|}. \end{cases} \quad (2)$$

Transformation relation between positions of cutter and workpiece could be given as

$$\mathbf{P}_L(\alpha, \beta) = \mathbf{P}_C + r \cdot \mathbf{n} - (D/2 - r) \cdot \mathbf{x}_L - r \cdot \mathbf{z}_L, \quad (3)$$

where, D was diameter of shank of the cutting tool.

3. Tool orientation planning for minimizing surface error

Mathematic model of tool orientation planning was given as

$$\begin{aligned} & \min e_{cz}(\alpha, \beta) \\ & \text{s. t.} \\ & 1. \mathbf{v}(\mathbf{P}_{i,j}, \alpha, \beta) \in V_G(\mathbf{P}_{i,j}), \\ & 2. \mathbf{M}_{i,j} \in [\mathbf{M}_{i,j,\min}, \mathbf{M}_{i,j,\max}], \\ & 3. d(\alpha, \beta) < \delta_d. \end{aligned} \quad (4)$$

where, the optimization objective e_{cz} was cutting force induced surface error, which could be calculated using mapping the cutter deflection model from reference [8] to the normal direction of the surface at the cutter contact point.

The illustration of the three constraint conditions were listed as follows.

(1) Geometrical constraint

In this constraint, $\mathbf{v}(\mathbf{P}_{i,j}, \alpha, \beta)$ represented the tool orientation at point $\mathbf{P}_{i,j}$, which was expression about α and β . $V_G(\mathbf{P}_{i,j})$ represented the interference-free tool orientation set and could be determined by

$$V_G(\mathbf{P}_{i,j}) = V_{Ts}(\mathbf{P}_{i,j}) \cap V_{\kappa}(\mathbf{P}_{i,j}) \cap V_{Tb}(\mathbf{P}_{i,j}) \cap V_M(\mathbf{P}_{i,j}). \quad (5)$$

where, V_{Ts} , V_{κ} , V_{Tb} , and V_M were respectively tool orientation set avoiding global interference, curvature interference, bottom interference, and machine tool interference.

(2) Kinematical constraint

This constraint was to ensure the motion axes were all within reachable coverages, and given as

$$\begin{cases} {}^M a(\mathbf{P}_{i,j}, \alpha, \beta) \in [{}^M a_{\min}, {}^M a_{\max}], \\ {}^M b(\mathbf{P}_{i,j}, \alpha, \beta) \in [{}^M b_{\min}, {}^M b_{\max}], \\ {}^M x(\mathbf{P}_{i,j}, \alpha, \beta) \in [{}^M x_{\min}, {}^M x_{\max}], \\ {}^M y(\mathbf{P}_{i,j}, \alpha, \beta) \in [{}^M y_{\min}, {}^M y_{\max}], \\ {}^M z(\mathbf{P}_{i,j}, \alpha, \beta) \in [{}^M z_{\min}, {}^M z_{\max}]. \end{cases} \quad (6)$$

(3) Physical constraint

In this constraint, $d(\alpha, \beta)$ represented resultant cutter deflection predicted using mathematical model from reference [8]; δd represented admissible resultant cutter deflection set according to the actual condition.

4. Experimental Results and Discussions

Five groups of experiments were designed, and all groups were divided into several tool paths. In group 1, the tool orientation kept along the vertical direction. In group 2, the cutter always fed along the normal direction at all the cutter contact point. In group 3, the lead angle kept as 10° , and the tilt angle kept as 0. The tool orientations in group 4 were smoothed tool orientations in group 3. The last group 5 used the tool orientation by our optimization method.

Main processing conditions used in the experiments were listed as followed: the feed per tooth was 0.0625 mm, the spindle speed was 4000 rev/min, dry cutting was adopted to avoid damaging the measuring equipment (The cooling fluid is necessary in practice).

The groups of data were shown in Figure 1, each of which contained 16 sampling points. From Figure 1, all the error values were more than zero and exhibiting a wavy variation. This showed that undercut was existing in all the groups, which was acceptable and could be cut in follow-up process. The wavy variation could be due to the distribution of sampling points, which were all 4 by 4 equidistant dot matrix at similar position of each blade. It was obvious several high values emerged in group 3, whose reason was large cutting force occurred when the lead angle was fixed at a value. And the variation range was the largest, which meant the worst surface accuracy. The variation range of group 4 was small, which should be due to the function of added smoothing process. But the mean error values of this group was large to about 0.03 mm. that was because there was conflict between objectives of smoothing and small deflection. The mean error values of group 1, group 2, and group 5 had not appeared to be much different from each other. But the values of group 1 and group 2 fluctuated obviously. And the values of group 5 showed the effectiveness of synthetic considering both smoothing and small surface error.

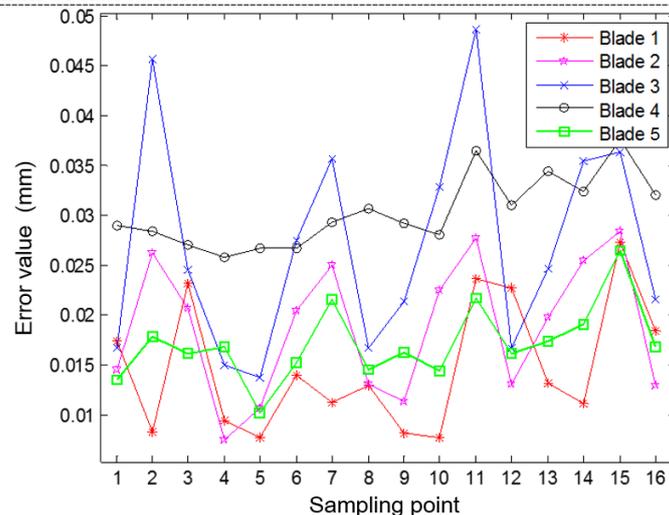


Figure 1. Comparison of surface error.

5. Conclusions

This paper proposed a new tool orientation planning method based on geometrical and kinematic relationship, such as avoiding interference and collision, through adding the influence of cutting force induced elastic surface error. The normal error was set as the optimization objective of the tool orientation planning model. The constraints including requirement of avoiding interference, need of smooth movement, and also controlling of tool deflection, which made the tool orientation planning of five-axis machining more comprehensive. Then a proportionally reduced ten-blade propeller rotor was selected as the experimental workpiece. Experimental results show that the proposed tool orientation planning method can effectively reduce the machining error.

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