Study of the Effect of Tool Orientation on Surface Roughness in Five-Axis Milling of 300M Steel

Xianyin Duan¹,a, Sheng Yu²,b, Fangyu Peng³,c, Guozhang Jiang¹,d

¹ Key Laboratory of Metallurgical Equipment and Control Technology, Wuhan University of Science and Technology, Wuhan, China
² Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China
³ State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan, China

a dxy@hust.edu.cn, b 312405191@qq.com c pengfy@hust.edu.cn, d whjgz@wust.edu.cn

Abstract. The tool position deviation will affect the surface quality, especially for ultra high strength and high hardness materials, such as aircraft landing gear, engine impeller of high strength and high hardness of the hard machining aviation parts. The 300M steel is a kind of low alloy medium carbon martensitic reinforced super high strength steel, which is a common material for aircraft landing gear workpiece. The material has a strength of 1900-2100 MPa and hardness of 50 HRC after heat treatment. This material is a typical difficult-to-machine material and can produce large cutting resistance in cutting, resulting in larger tool deviation and vibration, and affects the surface quality of workpiece. Aiming at its complex processing technology, it is particularly important to study the relationship between the surface quality and the process parameters in multi axis milling. The tool orientation, which is represented by the lead angle and the tilt angle of the tool, is representative and influential process parameter. Therefore, experimental study is conducted to reveal the relationship. The surface roughness of the workpiece after multi axis NC machining is measured accurately. The effect of tool orientation on surface roughness is analysed based on the experiment data. The result shows that it is of great significance to optimize the tool orientation, which is represented by the lead angle and the tilt angle of the tool, to improve surface quality.

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, in the marine, aerospace and defense industries, a variety of difficult-to-machine materials are applied because of their improved stiffness and strength properties. This considerably increases the cutting force during processing. Less stiffness and a larger cutting force can result in considerable cutter deflection (defined as the deflected displacement of the cutter location point from its theoretical position). Therefore, it is important to investigate the control of cutting force induced elastic deflection error by tool orientation planning in five-axis machining.
Many advances have been achieved in the research of cutter deflection, form error, and surface integrity. Lee [1] presented an approach to finding the 3D shape-generating profiles of different types of cutters for constructing Geometry buffer models. Dow [2] demonstrated a technique to compensate for deflection of small milling tools. Chanal [3] simulated machined defects due to cutting forces and structural deflection in parallel kinematics machine applications. López de Lacalle [4] developed NC programs to select the tilt angle based on the minimization of cutting forces. Ginting [5] investigated the machined surface integrity of titanium alloy under the dry milling process. Wei [6] presented a form error compensation approach for ball-end milling with a z-level contouring tool path. Rodríguez [7] studied tool deflection by applying the principles of material elasticity to the situation of a tool under a distributed force along its edge while considering a variable deflection along the length of the edge.

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. This paper addresses the study of the effect of tool orientation on surface roughness in five-axis milling of 300M steel.

2. Five axis milling experiment setting
The cutting experimental site is shown in Fig.1. The circular arc cutter SANDVIK R216.24-10050EK22H 1620 with a fillet radius of 2 mm is processed on the MIKRON UCP 800 Duro five axis machining center. The main cutting parameters are as follows: the feed per tooth is 0.04 mm, the spindle speed is 1000 rev/min, the Z direction is 1.4 mm, and the feed speed is 160 m/min. 21 groups of cutting experiments are designed. Except for the first group, the cutting tool attitude of the other 20 groups is the combination of 4 kinds of lead angles and 5 tilt angles (The lead angles and tilt angles are the relative angles between the cutter axis vector and the coordinate axis of the tool contact coordinate system). The lead angles are 10, 20, 30 and 40, respectively, and the tilt angles are 0, 15, 30, 45 and 60, respectively.

3. Measurement experiment of surface roughness
In order to compare the difference of surface roughness between machined grooves under different cutter axis vectors, the influence rule of cutter axis vector on surface roughness was revealed from experiments, and roughness measurement experiment was carried out on Taylor Hobson surface measuring instrument. The measured area is the 15 mm linear distance along the feed direction at each cutting slot of the plane workpiece. At the rate of 0.1 mm/s and the sampling interval of 0.25 m, we get a series of evaluation parameter values, such as arithmetic mean deviation Ra and the value Rz of ten height points of microscopic planeness. The measurement site is shown in Fig.2. Ra is selected to evaluate the surface finish. The measured data are shown in Table 1 as follows.
4. Experimental results and analysis
The influence degree of different factors on the surface roughness can be obtained by the range analysis. Therefore, in order to get the law of the significant degree of the influence of the lead angle and tilt angle on the surface quality, range analysis of the measured data, and get the range analysis chart of the lead angle and the side dip angle is done. The extreme difference formula is expressed as:

\[ W = W_{\text{MAX}} - W_{\text{MIN}} \]

![Fig. 3 When the lead angle changes](image)

![Fig. 4 When the tilt angle changes](image)

Table 1 Experimental design results

| No. | α (deg) | β (deg) | Ra (μm) | No. | α (deg) | β (deg) | Ra (μm) | No. | α (deg) | β (deg) | Ra (μm) |
|-----|---------|---------|---------|-----|---------|---------|---------|-----|---------|---------|---------|
| 1   | 0       | 0       | 0.2839  | 8   | 30      | 15      | 1.5731  | 15  | 20      | 45      | 0.6583  |
| 2   | 10      | 0       | 0.3351  | 9   | 40      | 15      | 1.8205  | 16  | 30      | 45      | 0.6732  |
| 3   | 20      | 0       | 0.6035  | 10  | 10      | 30      | 0.5707  | 17  | 40      | 45      | 0.6905  |
| 4   | 30      | 0       | 0.6558  | 11  | 20      | 30      | 0.773   | 18  | 10      | 60      | 0.6116  |
| 5   | 40      | 0       | 0.986   | 12  | 30      | 30      | 1.2185  | 19  | 20      | 60      | 0.6197  |
| 6   | 10      | 15      | 0.316   | 13  | 40      | 30      | 1.6214  | 20  | 30      | 60      | 0.5642  |
| 7   | 20      | 15      | 0.5919  | 14  | 10      | 45      | 0.9407  | 21  | 40      | 60      | 1.0292  |
From the analysis of Fig. 3 and Fig. 4, it can be seen that when the lead angle is 40 degrees, the change of the tilt angle has a significant effect on the surface quality. When the tilt angle is 15 degrees, the change of the lead angle has a significant effect on the surface quality.

Figure 5 shows the change in the surface roughness of the cutter tilt angle. The index used is arithmetic mean deviation (Ra). The first group is the lead angle and the tilt angle are 0. The minimum value of Ra is 0.2839 μm. At this time, the change of the cant angle does not change the tool-workpiece relative posture, so Ra remains unchanged. This shows that a better surface finish can be obtained by the vertical milling.

As shown in Fig. 6, all the other groups of cutters have their obliquity relative to the workpiece. In these experimental groups, when α=10° and β<20°, the Ra is the smallest, which is 0.316μm. Therefore, for the surface roughness, the blade axis vector space is the best. When α=40° and β=15°, Ra is the largest, which is 1.8205μm. From the view of surface roughness, the group should be avoided as much as possible in the tool axis vector programming. When α<20°, the Ra increases slightly with the increase of the tilt angle. When α>20°, the Ra decreases with the increase of the tilt angle, and the rate of reduction is larger. Therefore, the lead angle is small (less than 20 degrees), roll angle smaller the surface roughness is smaller. If a larger tilt angle is needed, it is possible to make it greater than 45 degrees to maintain a smaller Ra value.
5. Conclusion
Aiming at the five-axis milling of 300M, a super high strength steel for aeronautical parts, the processing experiments and surface roughness measurement experiments under different relative tool positions were designed and conducted. Then the influence of tool orientations on the surface roughness of 300M steel was studied. The research results can provide support for revealing the multi axis cutting mechanism of ultrahigh strength steel for aeronautical parts, and establish a theoretical prediction model for surface roughness considering tool orientations. By optimizing tool orientations, we can control workpiece surface roughness and improve machining surface quality.

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