Experimental Study in Taguchi Method on Surface Quality Predication of HSM

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Abstract. Based on the study of ball milling mechanism and machining surface formation mechanism, the formation of high speed ball-end milling surface is a time-varying and cumulative Thermos-mechanical coupling process. The nature of this problem is that the uneven stress field and temperature field affect the machined surface process, the performance of the processing parameters in the processing interaction in the elastic-plastic materials produced by the elastic recovery and plastic deformation. The surface quality of machining surface is characterized by multivariable nonlinear system. It is still an indispensable and effective method to study the surface quality of high speed ball milling by experiments.

1. Introduction
High-speed milling is a kind of high-efficiency machining method with small cutting depth, high spindle speed and high feeding speed, which can greatly reduce the processing cost and time, and obtain high surface quality. High-speed milling is advanced manufacturing technology, which is one of the hot research fields in the field of science and industry [1-5].

High-speed machining concept from the famous German Dr. Salomon 1924 began a series of experimental research, with its April 1931 published "Death Valley" zone as a symbol of high-speed machining technology was officially born. More than sixty years, people from the cutting mechanism, machine tool system, tool materials, work piece materials, numerical control technology and other aspects of research, to explore effective, practical and reliable high-speed cutting technology. In general, surface roughness or surface accuracy is often used to represent the surface features after metal cutting, so the study of metal surface roughness is the key to study the surface morphology [6,7].

The theoretical research on surface roughness is based on cutting kinematics and tool parameters. However, there are some problems in the accuracy of the model, and there is a big gap with the experimental results, some theoretical results and the measured results difference of 5 times [8]. The main reason is that, in the milling process, in addition to considering the relative movement of the tool-workpiece, the geometric parameters of the tool, the cutting process vibration, tool wear, cutting deformation, cutting heat and other factors on the surface morphology also has a great impact, the combined effect of factors can not be ignored.

2. HSM Mechanism and Machining Surface Formation Mechanism
According to the Thermos-mechanical coupling theory [9], The plastic deformation, elastic recovery and thermal stress effect of the tool- Making the processing of surface formation process is very complex. In the high-speed ball-end milling process, the work-piece surface is affected by the
mechanical load and the thermal load interaction. The effects of surface residual stress, work hardening and surface roughness are as follows:

Because the grain breakage hinder the metal deformation in the cutting process, slip, under the action of oxidation, although the high-speed milling cutting force is not large, but the surface layer has been hardened. At the same time, under the action of thermal load, thermal expansion in the process and the tool to thermal expansion of the role of materials, further exacerbate the degree of surface hardening. The plastic deformation of the material is hindered during the processing, which affects the surface roughness, and the roughness varies with the processing conditions.

2.1 Ball-end milling machining mechanical load

Based on the thermal-mechanical theory, there is a complex process of the work-piece-tool in contact zone, where occurs an overlap between temperature-force coupling field effects. Because of grain squeezing and friction effects, it make the grain distortion, breakage and extension, there is not same deformation among the grains and their boundary, the mechanical load produces the residual stress, the high temperature in machining contact zone make the residual stress complexity. In the ball milling process, the edge line of the tool-tool contact area is affected by the tool position, the tool path and various cutting parameters, so that the length and position of the edge line are different. Which could be explained by the theory of overload elastic recovery, as shown in Fig. 1.

![Fig.1 The material residual stress of the surface and the layers](image)

Due to the effect of the periodic external force, when the cutting force is mainly under the pressure, the strain will spring back to produce the residual tensile stress. The load applied by the tool on the surface of the workpiece is reflected by the interaction, so the stress on the surface presents the state of alternating tension and compression.

2.2 Ball-end milling effect of thermal load

Generally speaking, in the high-speed cutting, the metal of the cutting layer is subjected to high-speed friction, slip shearing and squeezing while the local temperature of the knife-work contact area rises gradually, because the surface temperature of the workpiece is much higher than the inner layer. The surface layer of local thermal expansion, but by the inner layer of hot metal is not bound, then the surface layer of metal thermal stress, the surface layer to form a temperature gradient, resulting in compression plastic deformation.

3. The Effect of High Speed Milling Parameters on Surface Quality

Table 1. $L_2(5^6)$ ball-end milling cutter high-speed milling orthogonal experiment cutting parameters

| No. | $n$ (r/min) | $f$ (mm/z) | $a_v$ (mm) | $a_p$ (mm) | $\beta_n$ (°) | $\beta_f$ (°) | No. | $n$ (r/min) | $f$ (mm/z) | $a_v$ (mm) | $a_p$ (mm) | $\beta_n$ (°) | $\beta_f$ (°) |
|-----|-------------|-------------|-------------|-------------|---------------|---------------|-----|-------------|-------------|-------------|-------------|---------------|---------------|
| 1   | 7000        | 0.05        | 0.20        | 0.20        | 0             | 0             | 13  | 9000        | 0.10        | 0.05        | 0.15        | 30             | 0             |
| 2   | 7000        | 0.08        | 0.15        | 0.15        | 10            | 10            | 14  | 9000        | 0.15        | 0.20        | 0.10        | 40             | 10            |
| 3   | 7000        | 0.10        | 0.10        | 0.10        | 20            | 20            | 15  | 9000        | 0.20        | 0.15        | 0.08        | 0              | 20            |
| 4   | 7000        | 0.15        | 0.08        | 0.08        | 30            | 30            | 16  | 10000       | 0.05        | 0.08        | 0.15        | 40             | 20            |
| 5   | 7000        | 0.20        | 0.05        | 0.05        | 40            | 40            | 17  | 10000       | 0.08        | 0.05        | 0.10        | 0              | 30            |
| 6   | 8000        | 0.05        | 0.15        | 0.10        | 30            | 40            | 18  | 10000       | 0.10        | 0.20        | 0.08        | 10             | 40            |
| 7   | 8000        | 0.08        | 0.10        | 0.08        | 40            | 0             | 19  | 10000       | 0.15        | 0.15        | 0.05        | 20             | 0             |
| 8   | 8000        | 0.10        | 0.08        | 0.05        | 0             | 10            | 20  | 10000       | 0.20        | 0.10        | 0.20        | 30             | 10            |

Table 1. $L_2(5^6)$ ball-end milling cutter high-speed milling orthogonal experiment cutting parameters
The influence factors of high speed milling include: cutting parameters, tool parameters, control system parameters, machine performance parameters, and work-piece material parameters. Orthogonal experiment is a mature multi-parameter analysis method. In the experiment, the feed rate per tooth, axial depth of cut, radial cutting width, inclination angle, side angle and rotation speed are taken as machining parameters. Surface roughness and work hardening as the criterion of surface quality.

The influence degree of various processing parameters on the surface quality of high speed ball milling was analyzed, and the influence of processing parameters on the surface quality was analyzed. The high-speed machining experiment is carried out in DMU-70V high-speed 5-axis CNC. The work-piece material is hot work die steel H13 (54-56HRC). The tool is solid carbide tool with diameter of 10mm and 2 teeth. The experimental parameters were processed using a standard 6-factor, 5-level, 25-group orthogonal experiment table. The parameters were set as shown in Table 1.

After the end of the high-speed milling experiment, using white light interferometer, hardness tester and other equipment on the test surface, surface roughness and hardness measurements shown in Table 2:

| No. | Ra(μm) | HL | No. | Ra(μm) | HL |
|-----|--------|----|-----|--------|----|
| 1   | 1.739  | 215| 13  | 0.357  | 229|
| 2   | 0.279  | 235| 14  | 0.841  | 232|
| 3   | 0.317  | 230| 15  | 0.495  | 212|
| 4   | 0.307  | 226| 16  | 0.183  | 235|
| 5   | 0.595  | 203| 17  | 0.361  | 250|
| 6   | 0.333  | 235| 18  | 0.447  | 226|
| 7   | 0.395  | 239| 19  | 0.412  | 245|
| 8   | 0.191  | 222| 20  | 0.784  | 244|
| 9   | 0.343  | 238| 21  | 0.22   | 225|
| 10  | 0.736  | 233| 22  | 0.2    | 243|
| 11  | 0.22   | 238| 23  | 0.571  | 245|
| 12  | 0.509  | 240| 24  | 0.243  | 243|
|     |        |    | 25  | 0.296  | 231|

4. High-speed Milling Tool Position on the Impact of Surface Quality

The influence of the tool posture on the surface quality in high speed milling is various, and the effect on the machined surface topography and the work hardening is also more direct. In this section, the workpiece is machined with high speed machining.

| β_f (°) | Ra(μm) | HL | Ra(μm) | HL | Ra(μm) | HL |
|---------|--------|----|--------|----|--------|----|
|         | f=0.1(mm/z) | f=0.2(mm/z) | f=0.3(mm/z) |
| 0       | 0.756  | 103 | 0.669  | 105 | 2.823  | 95 |
| 5       | 1.132  | 100 | 0.849  | 108 | 0.468  | 99 |
| 10      | 1.142  | 119 | 0.953  | 116 | 0.617  | 101|
| 15      | 1.065  | 110 | 1.108  | 105 | 0.546  | 113|
| 20      | 1.521  | 100 | 1.44   | 103 | 0.521  | 107|
| 25      | 1.583  | 118 | 1.307  | 109 | 0.618  | 108|
| 30      | 1.836  | 115 | 1.313  | 102 | 0.671  | 112|
| 35      | 1.471  | 107 | 1.195  | 103 | 0.684  | 103|
| 40      | 1.718  | 92  | 1.309  | 92  | 0.619  | 94 |
4.1 High Speed Ball Milling Experiment
The experiment is the same as above, and the processing is the same. The purpose of the experiment is to measure the roughness and surface hardness of different parameters by changing the position of the tool under steady-state cutting condition, so as to reflect the influence of cutting parameters on roughness.

4.2 Effect of tool posture on roughness
Fig. 2 shows the relationship between the tool posture and the surface roughness. The influence of the inclination angle on the machined surface is not particularly obvious under the condition that the other machining parameters are constant. The surface roughness value increases with the increase of feed per tooth. With the increase of inclination angle, the surface roughness value increases slowly. When fz = 0.1 mm / z, When the angle of inclination is 0 °, the surface roughness value is 2.823 μm, which indicates that the surface quality is poor at this time, and the surface roughness value shows an increasing trend when the inclination angle changes from 5 ° to 45 °.

Further analysis of the experimental results, the establishment of surface roughness and rake angle polynomial fitting formula:

\[ Ra = a \cdot \beta_f^3 + b \cdot \beta_f^2 + c \cdot \beta_f + d \]  

(1)

Where a, b, c and d are polynomial fitting coefficients, and Table 4-5 shows polynomial fitting coefficients for different tooth feed fz (mm / z)

| fz (mm/z) | a    | b    | c    | d    |
|-----------|------|------|------|------|
| 0.3       | 0    | 0.0019 | 0.0097 | 0.8547 |
| 0.2       | 0    | -0.0002 | 0.0392  | 0.654  |
| 0.1       | -0.0001 | 0.0113  | -0.2768 | 2.3815 |

From the analysis of the characteristics of milling, different inclination angle corresponding to different cutting edge, involved in the cutting edge of the material caused by plastic deformation of the surface morphology of the difference.

4.3 Impact of tool posture on surface hardness
Different inclination angle produces different cutting force and cutting heat, especially the change of the arbor, the depth of the hardened layer and the hardness have great changes. The surface hardness is affected by the elastic recovery of the material, and the different tool posture hinders the ability of the surface elastic recovery. Fig. 3 shows the relationship between tool posture and surface hardness.
According to the experimental data, the polynomial fitting coefficient between the surface hardness as shown in Table 5:

| f_z (mm/z) | a  | b   | c    | d   |
|------------|----|-----|------|-----|
| 0.3        | -0.0009 | 0.0229 | 0.4169 | 102.6308 |
| 0.2        | 0.0013 | -0.0917 | 1.4073 | 104.6965 |
| 0.1        | -0.0006 | 0.0007 | 1.0014 | 94.4448 |

From the analysis of Fig. 3: f_z = 0.3mm / z, 0.2mm / z, 0.1mm / z, with the inclination from 0 ° ~ 45 ° increase, the highest surface hardness difference, but the numerical range, And the hardness varied from 85 to 120. When f_z = 0.3mm / z and 0.2mm / z, the peak appeared at the inclination angle of 10 ° and 25 °. And an inclination angle of 15 ° and 30 °. By analyzing the work hardening trend, it is found that the variation of the hardness of the tool is obvious, and its change rule is basically the same as that of the tool posture. The reason is mainly due to the accumulation effect of the plastic deformation in the feed direction. Residual stress has the same cumulative effect.

5. Conclusions
The effect of processing parameters on the surface quality was studied in this paper from the experimental point of high speed ball milling. The effect of processing parameters on the surface quality was analyzed according to the orthogonal experiment. The influence of processing parameters on surface quality was analyzed. According to the influence characteristics of the tool posture, the rule of the surface roughness and the surface hardness of the tool posture are studied. The polynomial fitting formula is given, which provides the theoretical basis for the surface quality prediction.

6. References
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