Factorial and preliminary parameter tests for the water beam assisted form error in-process optical measurement

Y. Zhang, Y. Gao, Y.H. Lai and J.X. Wang

Department of Mechanical Engineering, Hong Kong University of Science and Technology
Clear Water Bay, Kowloon, Hong Kong SAR, China, E-mail: a meygao@ust.hk

Abstract

In precision machining, it is desirable to measure the workpiece form profiles to provide feedback for control to maintain machining quality. A water beam assisted form error in-process optical measurement approach has been proposed to solve the opaque coolant problem to permit form error in-process optical measurement. To have more comprehensive understanding of the method, factorial and preliminary parameter tests were conducted. It was found that the water flow rate \( Q_w \) and the height of medium \( h_m \) are the two most important parameters affecting the transparent window size \( A_t \). For \( Q_w \), there is a transition of flow state changing from laminar to turbulent. Increasing \( h_m \) generally gives smaller \( A_t \). The preliminary parameter test results also show that the conditions \( Q_w \in [0.6-0.75\text{ml/s}] \) and \( h_m \in [0.3-0.4\text{mm}] \) give better stability for \( A_t \).

Keywords: Workpiece form profile, coolant, form error in-process optical measurement, medium assisted measurement, transparent window, precision machining, factorial test

1. Introduction

In removal machining processes, coolants are used to reduce the thermal effects to avoid thermal deformation. But the opaque optical property of the coolants produces an inaccessibility problem for in-process optical form error measurement of workpiece. To solve the problem, a new measurement approach in which an optically clean zone is generated by fluid beam was proposed [1-11]. This approach was found to be effective for form error in-process optical measurement for maintaining machining quality. In order to determine the system parameter settings and optimize the performance, factorial and preliminary parameter tests were conducted.

Form error in-process optical measurement. A fluid injection system was constructed in order to study the performance of the form error in-process optical measurements method (Fig. 1-3). A clean water beam was ejected from the water channel and the direction is normal to the workpiece surface. Coolant was applied on the workpiece surface. The beam is to generate a transparent window so that the workpiece surface can be accessible by a laser beam and the measurement of the workpiece form profiles can be performed using an optical measurement system (Fig. 1).
2. Factorial test

In order to obtain the ranking of the key parameters to reduce the experimental workload for the relationship of comprehensive parameters, a factorial test was conducted [12].

Experimental setup. A systematic study of the parameters affecting the transparent window size $A_t$ and the transparent window size stability $e_{st}$ will give very useful guidance on design of the practical measurement device. A newly designed testing rig closely resembling the practical surface form profile measurement conditions was designed and established (Fig. 2). The test rig includes two sub systems, the optical measurement system and the coolant and fluid injection system. The optical measurement system includes a triangulation laser sensor and a CCD camera (Fig. 2). Triangulation laser sensor is used to detect the workpiece form profile and the CCD camera is used to record the transparent window generation. The coolant and fluid injection system is to assist the implementation of the form error in-process optical measurement (Fig. 2-3). The experimental test conditions and the input parameters are given in Table 1.

![Experimental setup](image1)

**Fig. 2. Experimental setup.**

![Transparent window generation](image2)

**Fig. 3. Transparent window generation.**

### Table 1. Experimental test conditions.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>CCD Camera</th>
<th>Panasonic industrial color CCD camera GP-KR222 0.3m pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece material</td>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>Workpiece flatness</td>
<td>~8um</td>
<td></td>
</tr>
<tr>
<td>Fluid</td>
<td>Coolant and water</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>22-25°C</td>
<td></td>
</tr>
<tr>
<td>Input parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water flow rate $Q_w$</td>
<td>0.15, 0.3, 0.45,... 1.2ml/s</td>
<td></td>
</tr>
<tr>
<td>Height of medium $h_m$</td>
<td>0.2, 0.3, 0.4,... 0.6mm</td>
<td></td>
</tr>
<tr>
<td>Table velocity $v_t$</td>
<td>60, 90, 120, 150mm/s</td>
<td></td>
</tr>
<tr>
<td>Water channel diameter $\phi_w$</td>
<td>1.0, 1.5, 2.0mm</td>
<td></td>
</tr>
<tr>
<td>Coolant concentration $c_c$</td>
<td>5%</td>
<td></td>
</tr>
</tbody>
</table>

![Model of the factorial test](image3)

**Fig. 4. Model of the factorial test.**
**Factorial test design.** To obtain the ranking of the key parameters to investigate the relationship of the comprehensive parameters, a factorial test was conducted (Fig. 4) to investigate 4 parameters. A $2^{4-1}$ factorial test was conducted. The 4 input parameters each had 2 levels (Table 2). The design and the structure of the $2^{4-1}$ factorial test are given in Table 3. There are totally 8 runs. Each run has 30 data points. To reduce the effect of noise, the run order is randomized.

**Definitions of $A_t$ and $e_{st}$.** The output variables of the test are transparent window size $A_t$ and transparent window size stability $e_{st}$. $A_t$ equals to the average of 30 data points in a run. $e_{st}$ equals to the ratio of the standard deviation of the 30 data points $A_{std}$ and the transparent window size $A_t$.

<table>
<thead>
<tr>
<th>Level</th>
<th>A ($q_w$)</th>
<th>B ($v_t$)</th>
<th>C ($\phi_w$)</th>
<th>D ($h_m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>2.0ml/s</td>
<td>60mm/s</td>
<td>2.0mm</td>
<td>0.2mm</td>
</tr>
<tr>
<td>-</td>
<td>1.0ml/s</td>
<td>150mm/s</td>
<td>1.0mm</td>
<td>0.5mm</td>
</tr>
</tbody>
</table>

**Table 2. Levels of factors.**

**Table 3. Design and structure of $2^{4-1}$**

<table>
<thead>
<tr>
<th>Design of factorial testing</th>
<th>$2^{4-1}$ - 1/2 fraction of 4 factors in 8 runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>IV</td>
</tr>
<tr>
<td>Design generators</td>
<td>D=ABC</td>
</tr>
<tr>
<td>Defining relation</td>
<td>I=ABCD</td>
</tr>
<tr>
<td>Aliases</td>
<td>A=BCD, B=ACD, C=ABD, D=ABC, AB=CD, AC=BD, AD=BC</td>
</tr>
</tbody>
</table>

**Table 4. Construction of the $2^{4-1}$ design and the test results.**

<table>
<thead>
<tr>
<th>Std Order</th>
<th>Run Order *</th>
<th>$Q_w$</th>
<th>$v_t$</th>
<th>$\phi_w$</th>
<th>$h_m$</th>
<th>$A_t$ (mm²)</th>
<th>$e_{st}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>100.530</td>
<td>0.006245</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>73.074</td>
<td>0.084128</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1.500</td>
<td>1.012623</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>60.321</td>
<td>0.156492</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>67.250</td>
<td>0.080062</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>6</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>24.704</td>
<td>0.096153</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>7</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>34.228</td>
<td>0.204274</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>53.270</td>
<td>0.17179</td>
</tr>
</tbody>
</table>

* 30 data for each run.

**Fig. 5. Normal plot of the effects.**

**Fig. 6. Pareto chart of the effects.**
**Factorial test results.** From the results of the factorial test (Table 4), the water flow rate $Q_w$ and height of medium $h_m$ are significant in the normal plot of the effects of the input parameters (Fig. 5). It means the two parameters strongly affect the transparent window size $A_t$ (Fig. 5). The ranking of the key parameters is shown in Fig. 6.

3. Preliminary parameter test

Experimental plan. According to the results of the factorial test, water flow rate $Q_w$ and height of medium $h_m$ were firstly investigated in our experimental study. The range and intervals of $Q_w$ and $h_m$ are given in Table 1. There are totally 40 runs. Each run has 40 data points.

Image processing. The images taken by the CCD camera (Fig. 2-3) were processed by using a MATLAB program. Figure 7 shows the schematic diagram of the image processing procedure.

![Image processing procedure](image)

Fig. 7. Image processing steps to obtain $A_t$.

Experimental results and discussion. Figures 8-11 show the effects of water flow rate $Q_w$ and height of medium $h_m$ on the transparent window size $A_t$ and transparent window stability $e_{st}$. It can be seen that $A_t$ is quite sensitive to the water flow rate $Q_w$ (Fig. 8). If $Q_w$ increases, $A_t$ generally increases. There is a reduction when $Q_w$ is 1.05ml/s (Fig. 8). It is because of the water flow under this flow rate changing from laminar to turbulent. $A_t$ is also affected by the height of medium $h_m$. The effect is much stronger when the water flow rate $Q_w$ is above 0.9ml/s (Fig. 10).

![Experimental results between $A_t$ and $Q_w$](image)

Fig. 8. Experimental results between $A_t$ and $Q_w$.

![Experimental results between $e_{st}$ and $Q_w$](image)

Fig. 9. Experimental results between $e_{st}$ and $Q_w$.  

4-149
The transparent window stability $e_{st}$ became worse when the height of medium $h_m$ is 0.2mm (Fig. 9). If $h_m$ increases, $e_{st}$ generally becomes better (Fig. 11).

From the $e_{st}$ contour for height of medium $h_m$ and water flow rate $Q_w$ (Fig. 13), it can be seen that the conditions $Q_w \in [0.6-0.75\text{ml/s}]$ and $h_m \in [0.3-0.4\text{mm}]$ give better stability (Fig. 13). Under these ranges, the transparent window size $A_t$ is approximately 30-40mm$^2$ (Fig. 12). This value is sufficient for the form error in-process optical measurement.

4. Conclusion

The factorial test results show that the water flow rate $Q_w$ and the height of medium $h_m$ are the two most important parameters affecting the transparent window size $A_t$. For $Q_w$, there is a transition of flow state changing from laminar to turbulent. Increasing $h_m$ generally gives smaller $A_t$. The preliminary parameter test results also show that the conditions $Q_w \in [0.6-0.75\text{ml/s}]$ and $h_m \in [0.3-0.4\text{mm}]$ give better stability for $A_t$.

5. Acknowledgement

This work has been supported by the Research Grants Council of Hong Kong SAR of China.
References