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

Y. Zhang, Y. Gao [a], 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 $Q_w \in$[0.6-0.75ml/s] and $h_m \in$[0.3-0.4mm] 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).

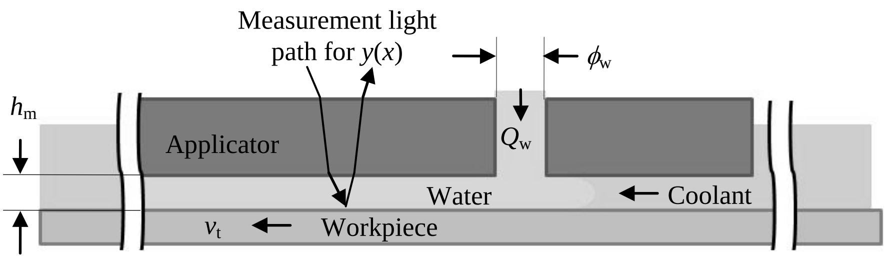

Fig. 1. Form error in-process optical measurement.

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.

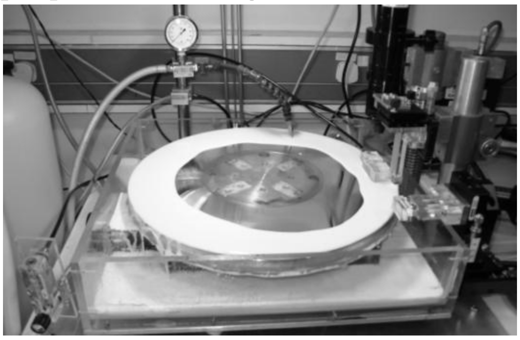

Fig. 2. Experimental setup.

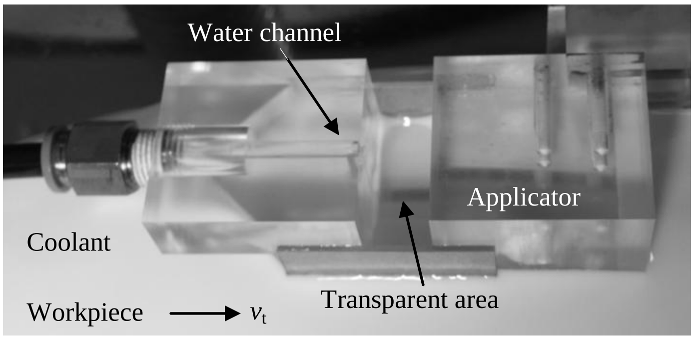

Fig. 3. Transparent window generation.

Table 1. Experimental test conditions.

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

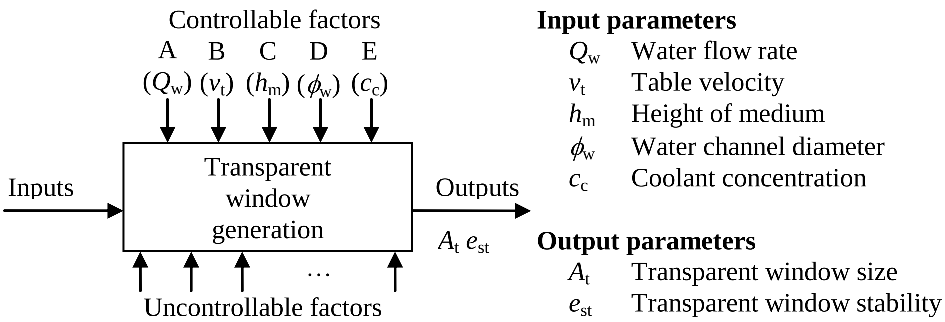

Fig. 4. Model of the factorial test.

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_{IV}^{4-1} factorial test was conducted. The 4 input parameters each had 2 levels (Table 2). The design and the structure of the 2_{IV}^{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 2. Levels of factors.

Level	A (q_w)	B (v_t)	C (ϕ_w)	D (h_m)
+	2.0ml/s	60mm/s	2.0mm	0.2mm
-	1.0ml/s	150mm/s	1.0mm	0.5mm

Table 3. Design and structure of 2_{IV}^{4-1}.

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

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

Std Order	Run Order *	Q_w	v_t	ϕ_w	h_m	A_t (mm^2)	e_{st}
8	1	1	1	1	1	100.530	0.006245
2	2	1	-1	-1	1	73.074	0.084128
7	3	-1	1	1	-1	1.500	1.012623
3	4	-1	1	-1	1	60.321	0.156492
6	5	1	-1	1	-1	67.250	0.080062
1	6	-1	-1	-1	-1	24.704	0.096153
5	7	-1	-1	1	1	34.228	0.204274
4	8	1	1	-1	-1	53.270	0.17179

* 30 data for each run.

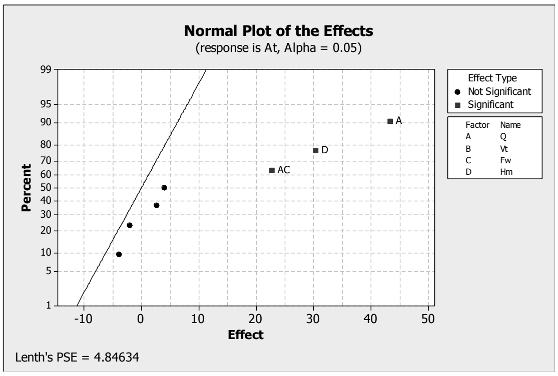

Fig. 5. Normal plot of the effects.

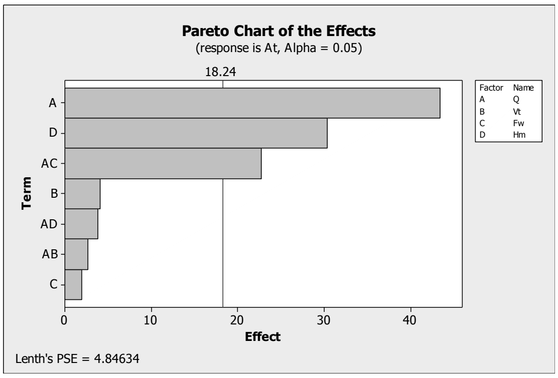

Fig. 6. Pareto chart of the effects.

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.

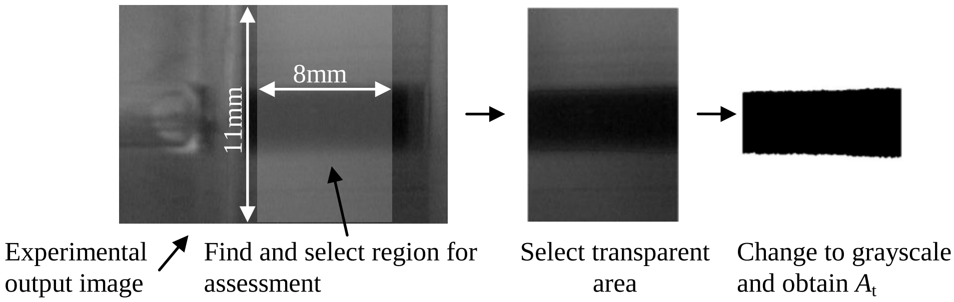

Fig. 7. Image processing steps to obtain A_t.

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).

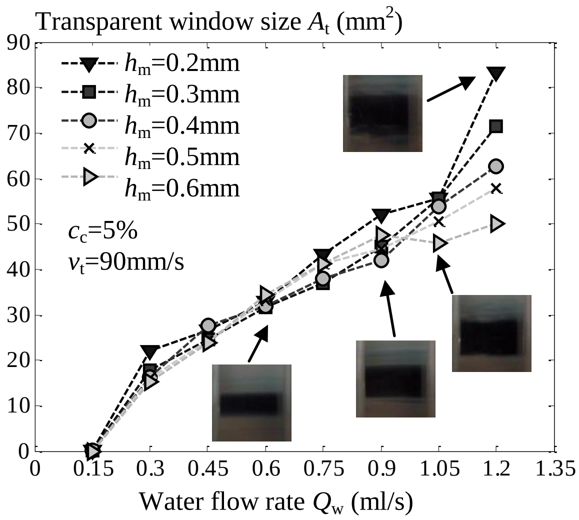

Fig. 8. Experimental results between A_t and Q_w

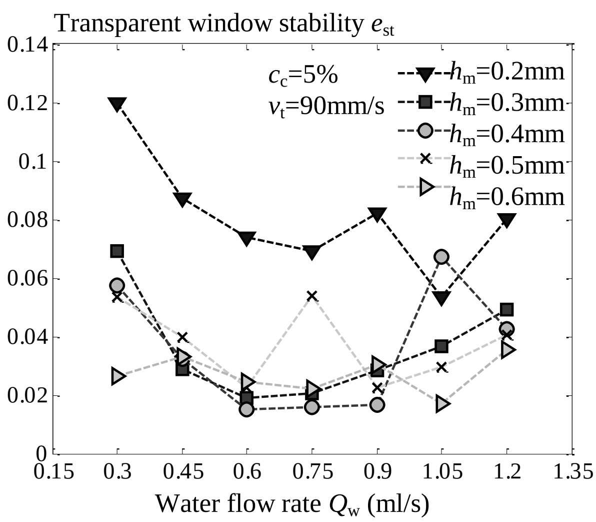

Fig. 9. Experimental results between e_{st} and Q_w.

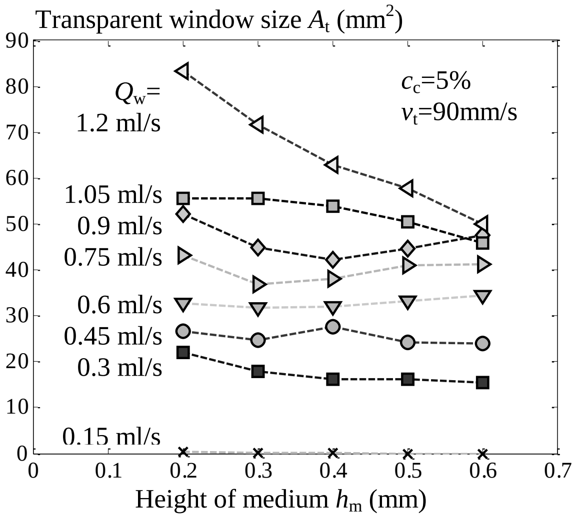

Fig. 10. Experimental results between A_t and h_m.

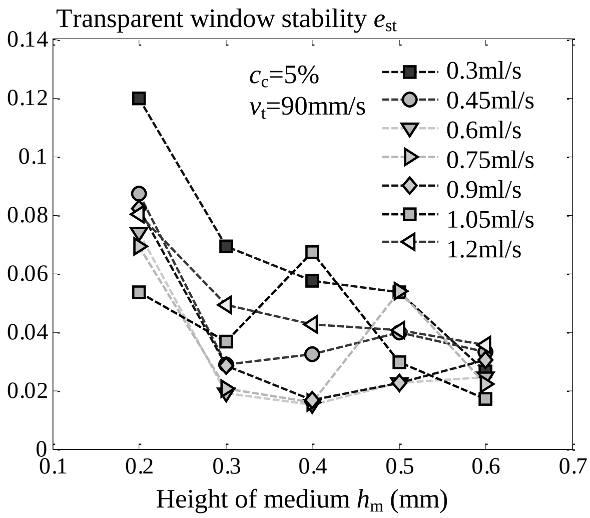

Fig. 11. Experimental results between e_{st} and h_m.

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).

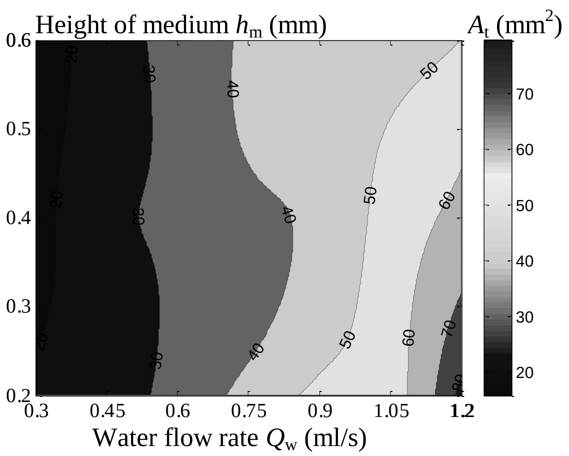

Fig. 12. A_t against h_m and Q_w.

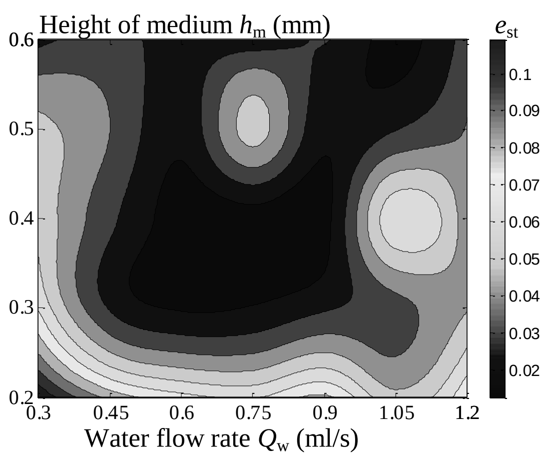

Fig. 13. e_{st} against h_m and Q_w.

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 $Q_w \in$[0.6-0.75ml/s] and $h_m \in$[0.3-0.4mm] 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 $Q_w \in$[0.6-0.75ml/s] and $h_m \in$[0.3-0.4mm] 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

1. Y. Gao, S. Tse and Z. Tao. *Int. Prgrs on Adv. Optics and Sensors*, *Proc EOS 2003.* p. 263.
2. Y. Gao, S. Tse, Z. Tao and X. Xu. *Journal of Materials Processing Technology*. 2002, vol. 129, p. 10.
3. Y. Gao. *Proc ASPE 2001*. vol. 1, p. 329.
4. S. Tse, Y. Gao, Y. Kuen and Z. Tao. *Key Engineering Materials*. 2003, vol. 238-239, p. 199.
5. Y. Gao, Z. Tao and S. Tse. *Key Engineering Materials*. 2003, vol. 238-239, p. 157.
6. Z. Tao. *PhD Thesis*. HKUST, Hong Kong. 2003.
7. Y. Gao, K. Xiao, Y. Zhang and Y.S. Chan. *Key Engineering Materials.* 2008, vol. 381-382, p. 183.
8. Y. Gao, S. Tse and K. Lai. *Proc ISMQC 2001*. p. 89.
9. Y. Gao, S. Tse, W. Li, S. Chan and Z. Tao. *Key Engineering Materials*. 2003, vol. 238-239, p. 163.
10. Y. Zhang and Y. Gao. *Proc. ISPMM 2008.* p. 193.
11. Y.H. Lai, Y. Gao, Y. Zhang and J.X. Wang. *Proc. ISMTII 2009.* submitted.
12. D.C. Montgomery. *Design and analysis of experiments.* John Wiley & Sons, NY. 1991.