



Application of Taguchi and response surface methodologies for geometric error in surface grinding process



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Introduction

- 研磨是一個取決於產品種類與需求，在參數有很多交互作用下的複合式加工製程。
- 田口方法和反應曲面法適合用來實驗設計以求出最適研磨製程參數。

Introduction

- Kim(1995)利用田口方法形成實驗分析得到變數相對作用及表面粗糙度最大百分比度的改善。
- Dhavlikar(2003)提出利用田口方法和反應曲面法定義研磨製程最小化粗糙誤差的穩健條件。
- Hashmi(1997)預言反應曲面法是一個用在研磨製程上很有用的工具。
- Suresh(2002)利用反應曲面法和基因演算法預測表面粗糙度和最適製程參數。



Introduction

- 本研究目的是利用田口方法和發展預測幾何誤差之反應曲面模型來評估研磨製程參數對幾何誤差的影響。

Literature review - Taguchi design

- Signal to noise(S/N) ratio (η , dB) 在田口實驗設計代表品質特徵，當S/N ratio越大時，可使幾何誤差越小。

$$\eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (1)$$

y_i ：在第*i*次試行的觀測值 n ：試行次數

由S/N ratio 可得知影響製程的有效參數和最佳製程參數組合。

Literature review - Response surface methodology

- 反應曲面法可以定義設計參數在哪一種水準達到最適化。
- 反應曲面法是將數理及統計方法結合，模式化和分析工程問題。

Literature review - Response surface methodology

■ 反應曲面法設計流程

- (i) 設計一系列的實驗以獲得反應的可靠資料
- (ii) 發展一個二階反應曲面的數學模型
- (iii) 找出能夠產生最大化或最小化反應值的最佳實驗參數組合
- (iv) 代表製程參數透過二和三維的直接和交互作用

Literature review - Response surface methodology

- 假設所有變數皆可衡量，反應曲面為：

$$y = f(x_1, x_2, \dots, x_k) \quad (2)$$

- 目標是要最佳化反應變數 y 。假設獨立變數是連續且可控制。考慮獨立變數和反應曲面之關係下的近似真實函數-二階反應曲面模型如下：

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \quad (3)$$

ε ：隨機誤差 β ：係數

Literature review - Response surface methodology

- 方程式(3)也可以寫成矩陣形式：

$$Y = bX + E \quad (4)$$

- 可藉由矩陣方法得到方程式(4)的解：

$$b = (X^T X)^{-1} X^T Y \quad (5)$$

Experimental details

- 可控制研磨因子包含顆粒大小(M)、砂輪速度(V)、切削深度(D)、桌子速度(S)四個因子，每個因子分為低、中、高三個水準。
- Levels of independent factors

Factors	Units	Symbol	Levels of factors		
			1 (Low)	2 (Middle)	3 (High)
Wheel speed	rpm	<i>V</i>	1500	1800	2100
Table speed	m/min	<i>S</i>	7.5	10	12.5
Depth of cut	μm	<i>D</i>	10	15	20
Grain size	mesh	<i>M</i>	46	120	200

Experimental details

■ L_{27} orthogonal array for experiments

Trial no.	Levels of factors			
	Wheel speed (rpm)	Table speed (m/min)	Depth of cut (μm)	Grain size (mesh)
1	1500	7.5	10	46
2	1500	7.5	15	120
3	1500	7.5	20	200
4	1500	10.0	10	120
5	1500	10.0	15	200
6	1500	10.0	20	46
7	1500	12.5	10	200
8	1500	12.5	15	46
9	1500	12.5	20	120
10	1800	7.5	10	120
11	1800	7.5	20	200
12	1800	7.5	20	46
13	1800	10.0	10	200
14	1800	10.0	15	46
15	1800	10.0	20	120
16	1800	12.5	10	46
17	1800	12.5	15	120
18	1800	12.5	20	200
19	2100	7.5	10	200
20	2100	7.5	15	46
21	2100	7.5	20	120
22	2100	10.0	10	46
23	2100	10.0	15	120
24	2100	10.0	20	200
25	2100	12.5	10	120
26	2100	12.5	15	200
27	2100	12.5	20	46



Experimental results and discussion

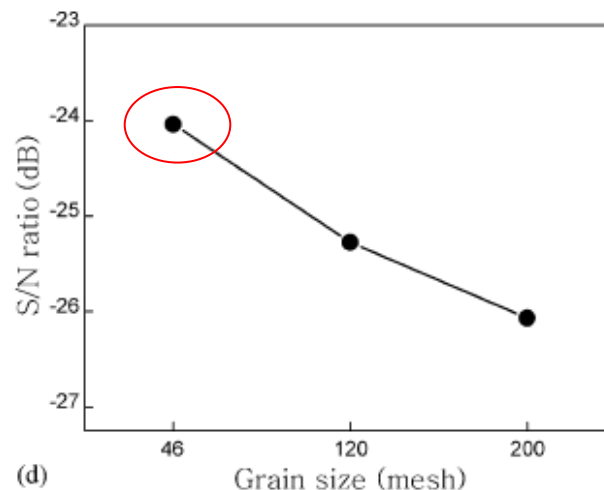
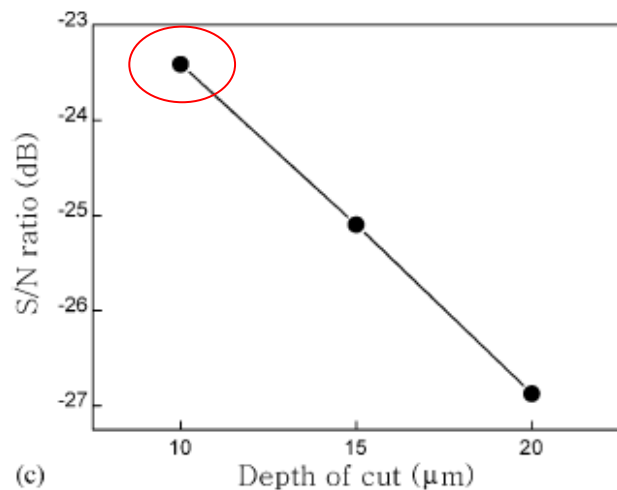
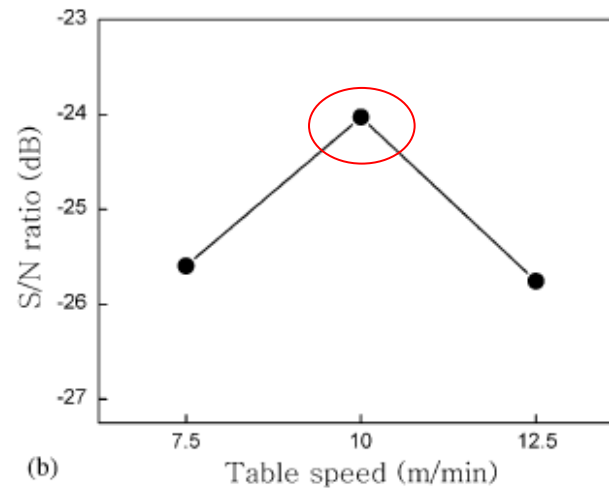
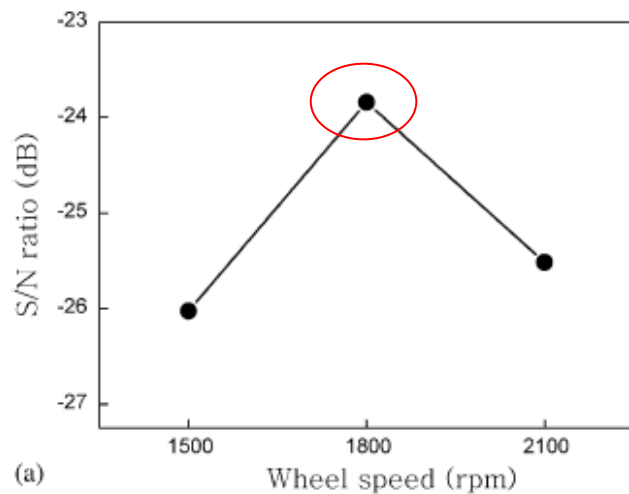
■ Experimental results for geometric error

Trial no.	Levels of factors				Measured values, geometric error (μm)
	Wheel speed (rpm)	Table speed (m/min)	Depth of cut (μm)	Grain size (mesh)	
1	1500	7.5	10	46	15
2	1500	7.5	15	120	23
3	1500	7.5	20	200	29
4	1500	10.0	10	120	14
5	1500	10.0	15	200	20
6	1500	10.0	20	46	17
7	1500	12.5	10	200	22
8	1500	12.5	15	46	19
9	1500	12.5	20	120	26
10	1800	7.5	10	120	16
11	1800	7.5	20	200	16
12	1800	7.5	20	46	20
13	1800	10.0	10	200	11
14	1800	10.0	15	46	13
15	1800	10.0	20	120	20
16	1800	12.5	10	46	12
17	1800	12.5	15	120	18
18	1800	12.5	20	200	17
19	2100	7.5	10	200	21
20	2100	7.5	15	46	14
21	2100	7.5	20	120	22
22	2100	10.0	10	46	12
23	2100	10.0	15	120	16
24	2100	10.0	20	200	25
25	2100	12.5	10	120	14
26	2100	12.5	15	200	27
27	2100	12.5	20	46	26



Experimental results and discussion - Effect of grinding parameters

■ Effect of factors on geometric error



Experimental results and discussion - Effect of grinding parameters

- 當S/N ratio越大時，可使幾何誤差越小，但是考慮到磨製系統的熱度與硬度關係，所以在切削深度和顆粒大小為低等，輪子速度和桌子速度為中等時，幾何誤差最小，其最適條件如下：

砂輪速度(V)：1800 rpm

桌子速度(S)：10.0 m/min

切削深度(D)：10 μm

顆粒大小(M)：46 mesh

Experimental results and discussion-Effect of grinding parameters

■ ANOVA table for S/N ratio of the geometric error

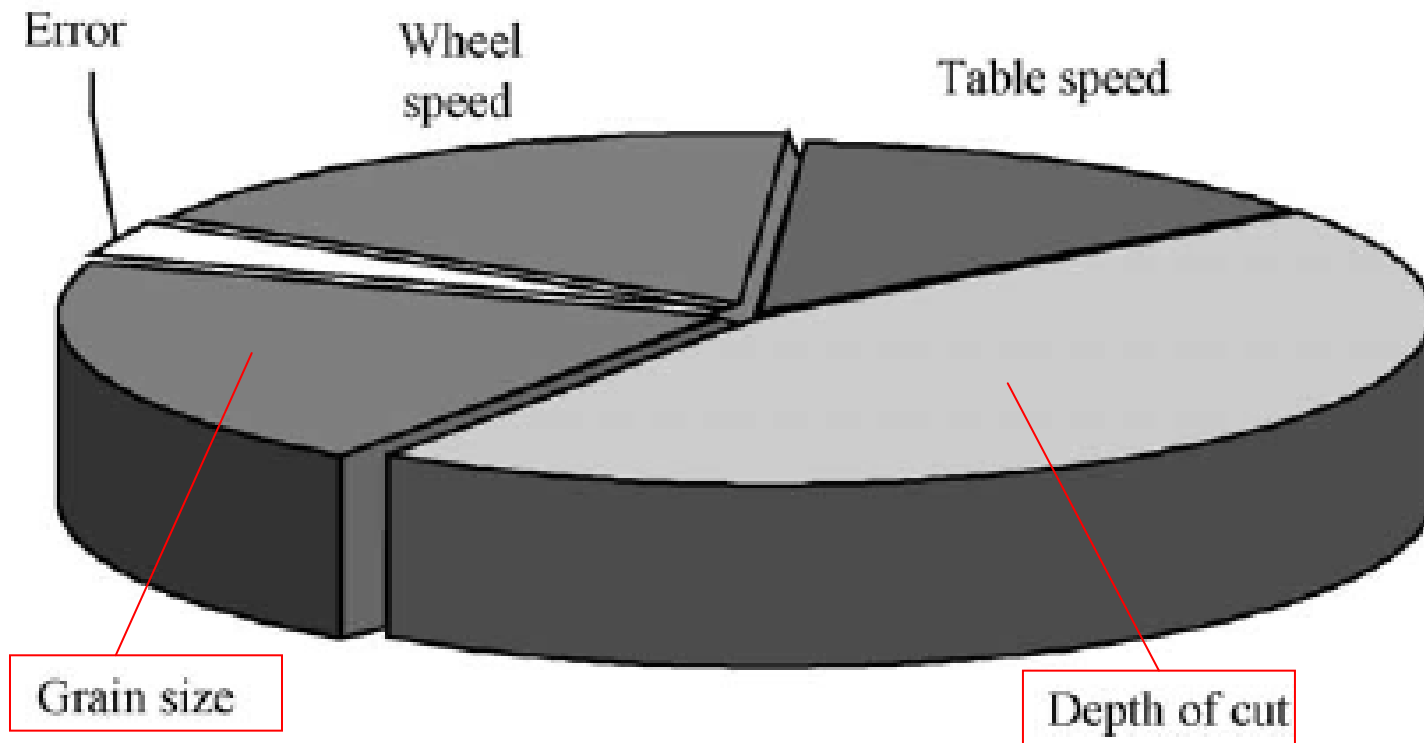
Source	Sum of squares	Degree of freedom	Mean square	<i>F</i> -ratio
<i>V</i>	93.5	2	46.75	5.42 ^a
<i>S</i>	70.7	2	35.35	4.10 ^a
<i>D</i>	236.0	2	118.0	13.69 ^b
<i>M</i>	106.7	2	53.35	6.19 ^b
Error	155.1	18	8.62	
Total	662.0	26		

^a 95% confidence level (3.55).

^b 99% confidence level (6.01).

Experimental results and discussion-Effect of grinding parameters

- Percentage distributions of grinding parameters for the geometric error



Experimental results and discussion -

Response surface analysis

- 考慮幾何誤差和研磨參數關係的二階反應函數：

$$\begin{aligned} Y = & \beta_0 + \beta_1 V + \beta_2 S + \beta_3 D + \beta_4 M + \beta_{11} V^2 \\ & + \beta_{22} S^2 + \beta_{33} D^2 + \beta_{44} M^2 + \beta_{12} VS + \beta_{13} VD \\ & + \beta_{14} VM + \beta_{23} SD + \beta_{24} SM + \beta_{34} DM \end{aligned} \quad (6)$$

Experimental results and discussion -

Response surface analysis

- 代入觀測值，二階反應函數如下：

$$\begin{aligned} Y = & 243.388 - \frac{197.1335}{1000}V - 13.5324S + 0.2184D \\ & + \frac{1}{1000}(128.72M + 0.0484V^2 + 531.463S^2 \\ & - 10.471D^2 - 0.0443M^2 + 1.5583VS \\ & + 0.3889VD - 0.0016VM + 45.516SD \\ & - 0.3661SM - 3.3546DM) \end{aligned} \quad (7)$$

Experimental results and discussion -

Response surface analysis

- ANOVA table for response surface function of the geometric error

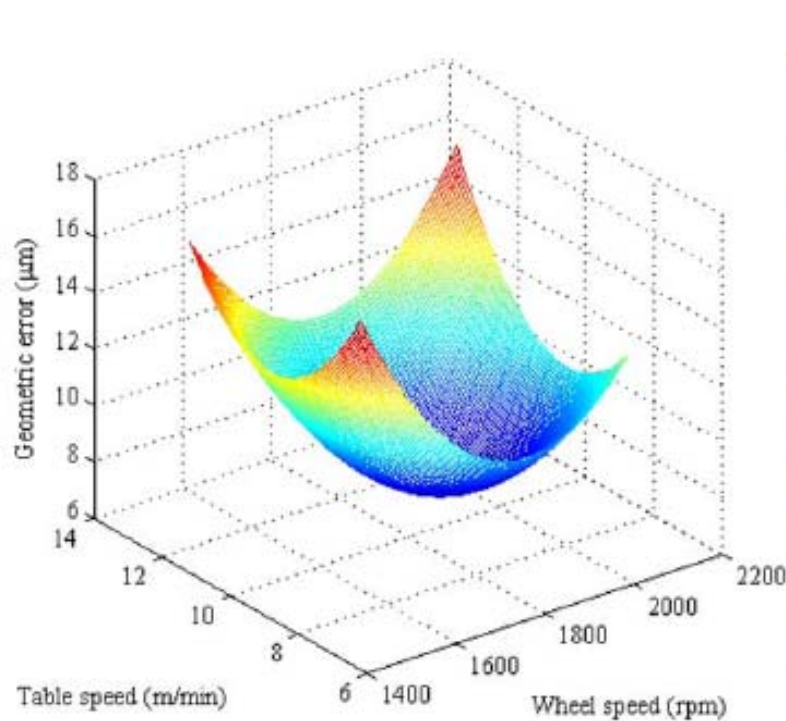
Source	Sum of squares	Degree of freedom	Mean square	<i>F</i> -ratio
Model	513.25	14	36.66	2.97 ^a
Error	147.85	12	12.32	
Total	661.6	26		

^a 95% confidence level (2.64).

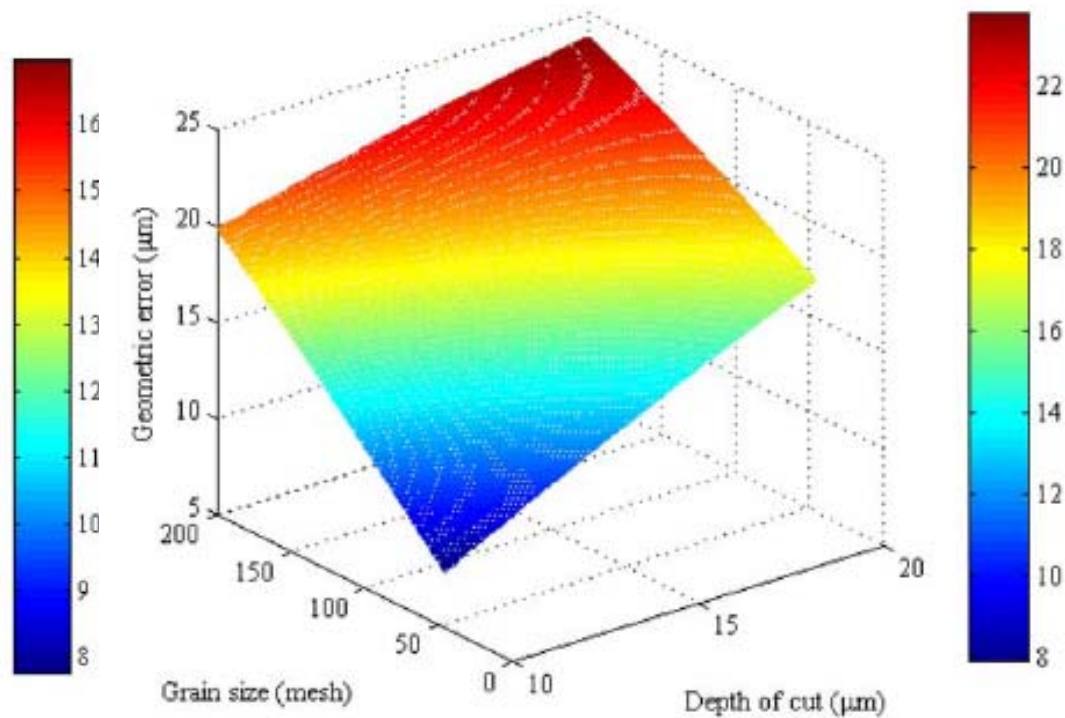
Experimental results and discussion -

Response surface analysis

- 3D plots of the response surface for the geometric error. (a) Depth of cut = $10\text{ }\mu\text{m}$; grain size = 46 mesh. (b) Wheel speed = 1800 rpm; table speed = 10 m/min.



(a)



(b)

Experimental results and discussion -Utilization of the second-order geometric error model

- 從二階反應函數(Eq.7)可以預測幾何誤差並且達到最小化。但是選擇研磨參數時，實際上應該由改進表面粗糙度和物料移動速度來限定。

- 平均表面粗糙度：

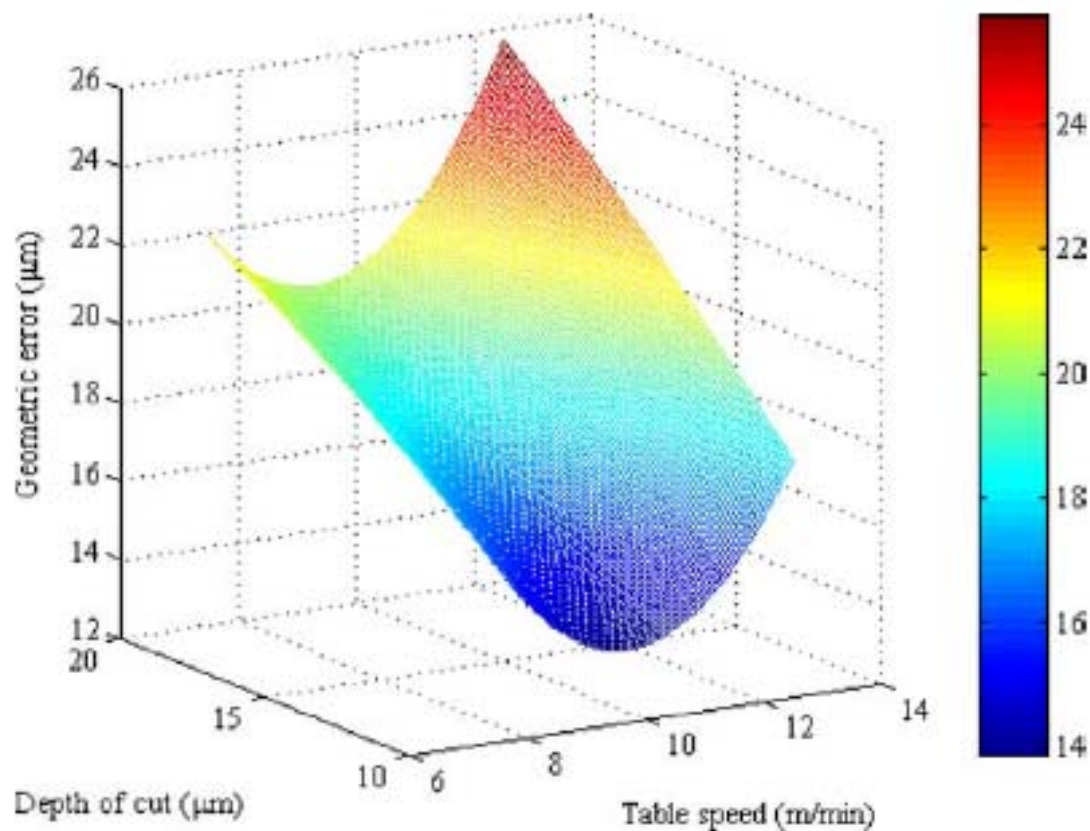
$$R_a = 0.295D^{0.184}S^{0.525}M^{-0.286} \quad (8)$$

- 物料移動速度：

$$Z = SDB \quad (9)$$

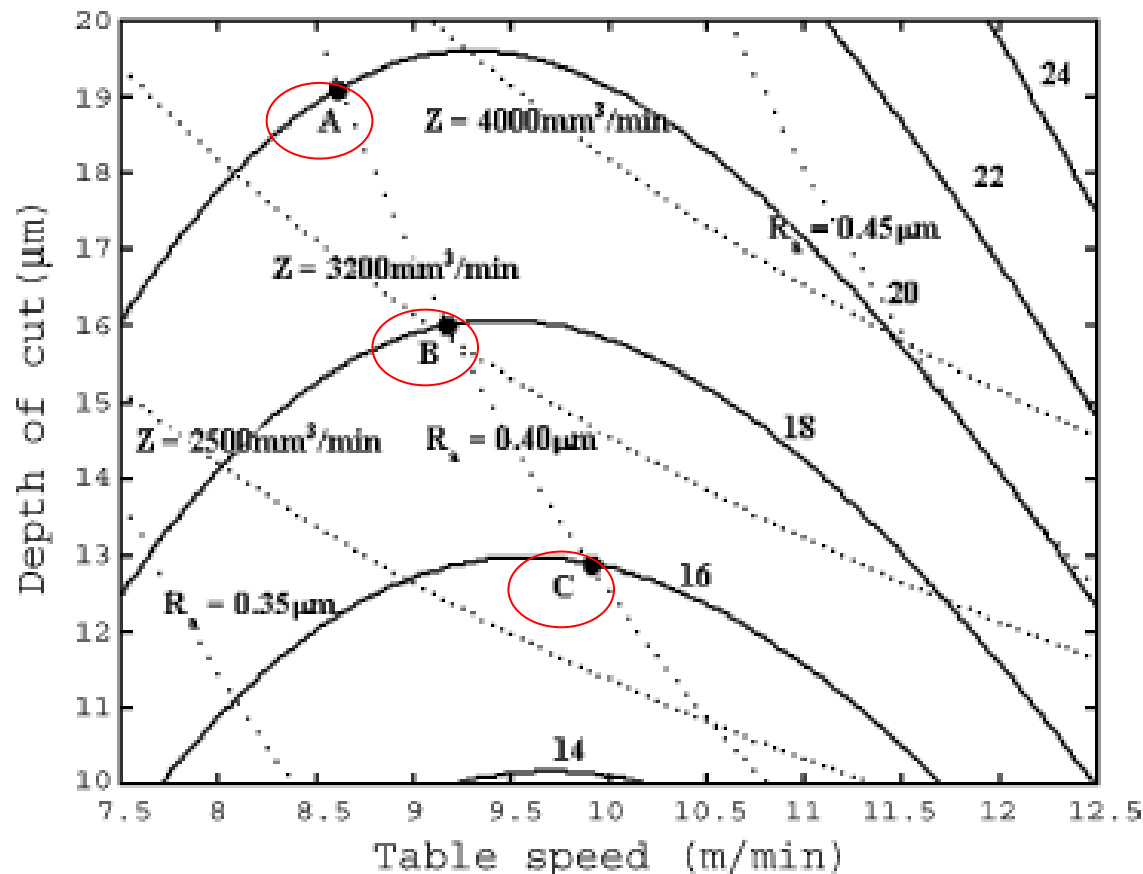
Experimental results and discussion -Utilization of the second-order geometric error model

- Response surface for geometric error with respect to **table speed** and **depth of cut**. (Wheel speed 1800 rpm; grain size 120 mesh).



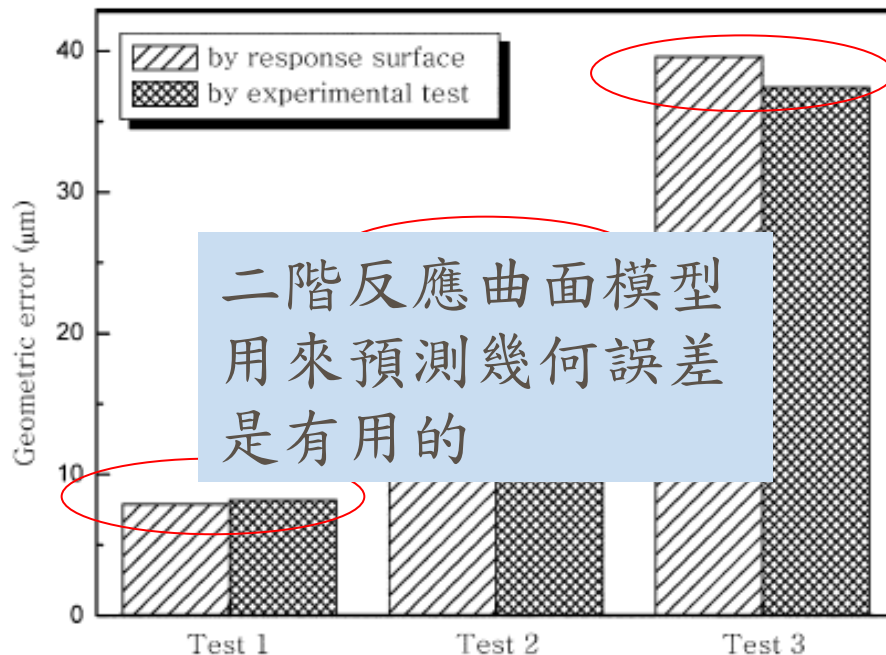
Experimental results and discussion -Utilization of the second-order geometric error model

- Contour plot for geometric error adding surface roughness and material removal rate. (Wheel speed Z 1800 rpm; grain size Z 120 mesh).



Confirmation experiments

- 利用田口方法得到的最佳條件(Test 1)和任意選擇兩種條件(Test 2 and 3)進行二階反應曲面模型的驗證。
- Verification results for the geometric error comparing response surface model with experiments



Conclusions

- 利用田口方法得到對研磨製程的幾何誤差影響最大的是切削深度，其次為顆粒大小。
- 發展幾何誤差的二階反應曲面模型可以用來評估在受限於表面粗糙度和物料移動速度之下的最適研磨條件。
- 經過驗證得知，利用反應曲面法來預測幾何誤差是個很有用的方法。