Advanced Materials Research Vol. 576 (2012) pp 28-31
Online available since 2012/Oct/08 at www.scientific.net

doi:10.4028/www.scientific.net/AMR.576.28

Statistical Approach to Modeling & Optimization of Surface Roughness in High Speed End Milling of Silicon with Diamond Coated Tools

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Keywords: High Speed End Milling, Silicon, Air Blowing, Surface Roughness, RSM, Optimization.

Abstract. This research demonstrated the use of conventional milling machines with diamond coated tools, high speed attachments, and air blowing mechanisms for ductile mode machining of silicon and subsequently modeling and optimizing the resultant surface roughness. Spindle speed, depth of cut, and feed rate, ranges: 60,000 to 80,000 rpm, 10 to 20 μm, and 5 to 15 mm/min respectively, were considered as the independent machining parameters for the modeling process. Compressed air at 0.35 MPa was also provided to prevent chip deposition on the finished surfaces. The resultant surfaces were analysed using Optical and Scanning Electron (SEM) Microscopes as well as Wyko NT 1100 and SurfTest SV-500 profilometers. The response, surface roughness, was then modeled using a small Central Composite Design (CCD) in Response Surface Methodology (RSM). The quadratic relation was found to be most suitable following Fit and Summary and ANOVA analyses. The relation was then optimized using Desirability Function (DF) in Design of Expert (DOE) software. The optimum attainable surface roughness, which was validated using experimental runs, was found to be 0.11 μm which may be considered quite satisfactory.

Introduction

Optical silicon surfaces used in the semiconductor and opto-electronics industries need to be free of damage or impurities [1]. Hence, many research endeavours have focused on cutting parameters, surface roughness, chip formation, etc. that can lead to ductile mode machining of silicon. Yan et al. [2] who found that silicon was normally brittle but could be deformed plastically, yielding ductile streaks under the influence of high hydrostatic pressure. Venkatachalam et al. [3] claimed that ductile machining depended on tool geometry (large negative rake angle), process conditions, and workpiece material properties. Dali et al. [4] achieved ductile regime machining in CNC end milling of silicon, using diamond coated tools, by using a combination of high speed spindle (60,000 to 80,000 rpm), low axial depth of cut (10 μm), and low feed (5 mm/min). They produced good surface finish (0.22 μm) and ductile streaks. However, there was significant chip deposition on the machined silicon surface.

Also, most of these researchers employed expensive techniques, costly machineries, or unconventional approaches to obtain ductile mode cutting. The authors claim that inexpensive machining of silicon is achievable if done on conventional milling machines and post machining operations can be eliminated. Also the modeling and optimization process will reduce the time and money spent in trial runs and experimentations. This research utilized a simple conventional mill with a high speed attachment to end mill silicon. It focused on investigating the influence of three machining parameters (spindle speed, depth of cut, and feed) along with compressed air flow on the machined surface quality.

Experimental Details

Machining was conducted on a Universal Milling Machine Deckel FP4M. A NSK Planet 850 high speed attachment (90,000 rpm) was attached to the spindle and connected to the air supply via the Nakanishi AL-0201 Air Line Kit, which controlled the high speed attachment by regulating the compressed air flow. The set-up also consisted of another air supply for the blower and air gun. Fig. 1 shows the experimental set for end milling of silicon with Diamond Coated Tools.

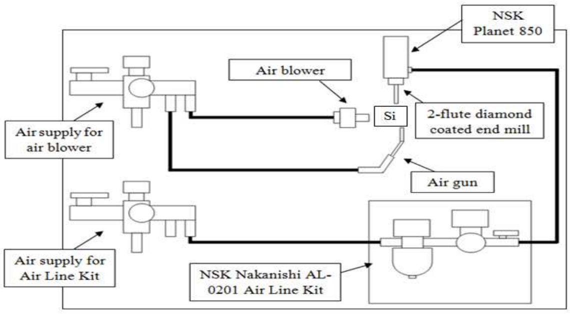

Fig. 1: Experimental set-up with high speed attachment and air blowing system

A 3 factors 5 levels Central Composite Design (CCD) model of Response Surface Methodology (RSM) was used to model surface roughness. The three factors were: spindle speed, depth of cut, and feed rate. These parameters were varied within fixed ranges: 60,000 to 80,000 rpm, 10 to 20 µm, and 5 to 15 mm/min respectively. The air pressure was kept constant at 0.35 MPa. The Design-Expert 6.0.8 software (DOE) generated 15 experimental runs as shown in Table 1.

Table 2: List of 15 experimental runs with the response

Run	Factor 1 A: Spindle speed (rpm)	Factor 2 B: Depth of cut (µm)	Factor 3 C: Feed rate (mm/min)	Response Surface Roughness (µm)	Run	Factor 1 A: Spindle speed (rpm)	Factor 2 B: Depth of cut (µm)	Factor 3 C: Feed rate (mm/min)	Response Surface Roughness (µm)
1	80 000	15	12	0.19	8	70 000	15	12	0.18
2	80 000	10	18	0.16	9	60 000	15	12	0.17
3	70 000	15	18	0.19	10	70 000	15	6	0.19
4	70 000	15	12	0.18	11	60 000	10	6	0.18
5	70 000	20	12	0.18	12	70 000	15	12	0.18
6	70 000	15	12	0.21	13	80 000	20	6	0.15
7	60 000	20	18	0.17	14	70 000	10	12	0.11
					15	70 000	15	12	0.15

Results and Discussion

Model Generation. The Fit and summary test, Table 2, indicated that the quadratic models had the least significant lack of fit (LOF). ANOVA analysis was then carried out to check the validity of the model developed, as displayed in Table 3.

Table 2: Fit and Summary test

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Mean	0.45	1	0.45			
Linear	3.783E-003	3	1.261E-003	3.55	0.0514	
2FI	1.167E-003	3	3.889E-004	1.13	0.3919	
Quadratic	2.534E-003	3	8.445E-004	20.13	0.0032	Suggested
Cubic	9.804E-006	1	9.804E-006	0.20	0.6808	Aliased
Residual	2.000E-004	4	5.000E-005			
Total	0.45	15	0.030			

The ‘Model F-value’ of 20.20 showed that the quadratic model was significant and there was only a 0.04 % chance that a ‘Model F-value’ this large could occur due to random noise. Thus, the quadratic CCD model with a confidence level of more than 95% was selected for modeling the surface roughness (equation 1, below).

$$R_a = 0.18 - 0.005A + 0.012B + 0.005C - 0.029A^2 + 0.011B^2 + 0.011AB + 0.025BC \quad (1)$$

Table 3: Analysis of Variance (ANOVA) test

Source		Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model		7.331E-003	7	1.047E-003	20.20	0.0004	significant
	A	*5.000E-005*	*1*	*5.000E-005*	*0.96*	*0.3587*	
	B	*8.167E-004*	*1*	*8.167E-004*	*15.76*	*0.0054*	
	C	*5.000E-005*	*1*	*5.000E-005*	*0.96*	*0.3587*	
	A^2	*2.404E-003*	*1*	*2.404E-003*	*46.38*	*0.0003*	
	B^2	*3.594E-004*	*1*	*3.594E-004*	*6.93*	*0.0338*	
	AB	*3.000E-004*	*1*	*3.000E-004*	*5.79*	*0.0471*	
	BC	*8.333E-004*	*1*	*8.333E-004*	*16.08*	*0.0051*	
Residual		3.628E-004	7	5.183E-005			
	Lack of Fit	*1.628E-004*	*3*	*5.427E-005*	*1.09*	*0.4508*	*not significant*
	Pure Error	*2.000E-004*	*4*	*5.000E-005*			
Cor Total		7.693E-003	14				

The perturbation plot of the surface roughness, Fig. 2, illustrates the effects of factors in the design. The reference point of the plot is at the intersection of the lines indicated by 0.0. Any shift to the right, towards the +1.0 deviation, denotes an increasing value of the factors and vice versa. It was observed that A and B (spindle speed and depth of cut) had more influence on variation in surface roughness than C (feed). The surface roughness decreased significantly with any change in A, while for B it had the opposite behavior. For C, the surface roughness increased almost linearly with increasing value of C.

Fig. 3 displays the interaction plot between the two main factors A and B and their effect on the response. It was observed, from the curve for A, that at significantly higher spindle speed, the surface roughness was much lower than at the interaction point. Alternately, from the curve for B, it was observed that the surface roughness was sufficiently less, compared to that at the interaction point, for lower depth of cut.

Optimization. Table 4 illustrates the optimum solutions for surface roughness predicted by using desirability function.

Table 4: List of optimized solutions from DOE

Number	Spindle speed	Depth of cut	Feed rate	Surface roughnes	Desirability	
1	79999.91	10.00	18.00	0.110385	0.996	Selected
2	79999.98	10.11	18.00	0.111035	0.990	
3	80000.00	10.00	14.90	0.120714	0.893	
4	79999.99	14.64	6.00	0.140836	0.692	
5	79999.98	14.70	6.00	0.140838	0.692	
6	60000.00	18.08	9.52	0.14964	0.604	
7	60000.01	13.85	14.05	0.156997	0.530	
8	70530.10	17.81	6.00	0.170874	0.391	

Eight (8) optimal solutions were obtained using the desirability function approach. The first solution was as it predicted the lowest surface roughness of 0.110385 µm and had the highest desirability of 99.6%.

The suggested machining parameters were: 80,000 rpm spindle speed (maximum), 10 µm depth of cut (minimum), and 18 mm/min feed rate (maximum). The contour plot for solution 1 is shown in Fig. 4. The optimum predicted R_a value was verified by machining a silicon sample with the recommended machining parameters. The experimentally obtained R_a value was 0.11 µm. The optical microphotograph and 3D contour of the machined surface is illustrated in Fig. 5.

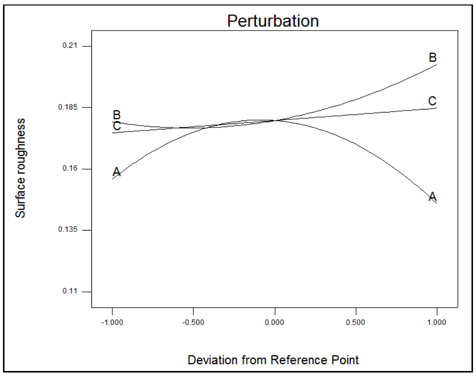

Fig. 2: Perturbation plot of surface roughness vs. spindle speed, depth of cut and feed

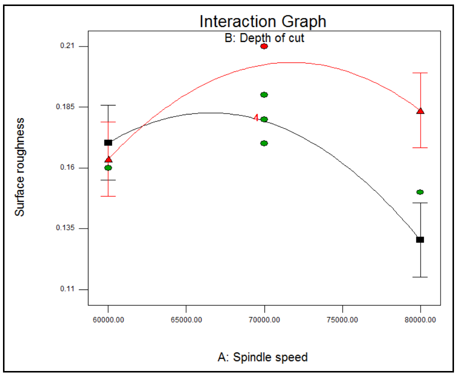

Fig. 3: Interaction plot of surface roughness vs. spindle speed and depth of cut

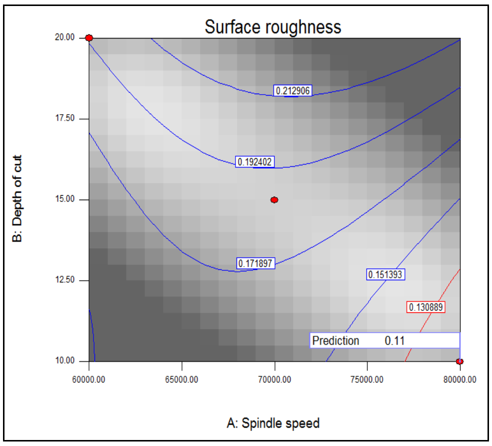

Fig. 4: Surface Roughness Contour plot for Solution Number 1

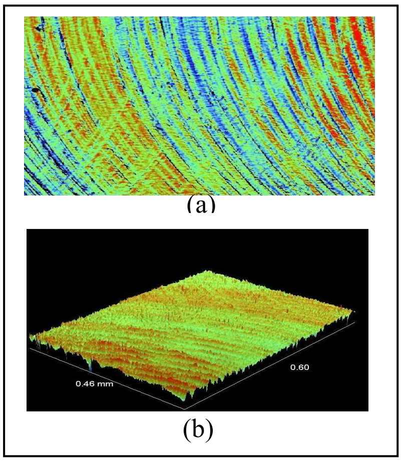

Fig. 5: Surface data and 3 D plots: HSM conducted on conventional milling machine with air blower at P = 0.35 MPa, (R_a = 0.11 µm at v = 80 000 rpm, d = 10 µm and f = 18 mm/min)

Conclusions

The analyses showed that conventional milling machine with high speed attachment, diamond coated tools, and air blower could be used economically to machine silicon in the ductile regime and produce machined surfaces with good surface topography. Also, it can be concluded (from the ductile streaks and lower chip deposition) that the combination of higher spindle speed, lower depth of cut, and higher feed rate enables ductile mode machining.

References

[1] M. Zhou, B.K.A. Ngoi, Z.W. Zhong, C.S. Chin, Brittle-ductile transition in diamond cutting of silicon single crystals, Materials and Manuf. Processes 16 (4) (2001) 447-460.

[2] J. Yan, M. Yoshino, T. Kuriagawa, T. Shirakashi, K. Syoji, R. Komanduri, On the ductile machining of silicon for micro electro-mechanical systems (mems), opto-electronic and optical applications, Material Science and Engineering 297 (1) (2001) 230-234.

[3] S. Venkatachalam, X. Li, S.Y. Liang, Predictive modeling of transition undeformed chip thickness in ductile-regime micro-machining of single crystal brittle materials, J.of Materials Processing Technol. 209 (2009).

[4] Md. Dali, Md. Iqbal, Ductile mode machining of silicon using high speed end milling, Undergraduate Thesis, Department of Manufacturing and Materials Engineering, International Islamic University of Malaysia (IIUM), Gombak, Malaysia (2010).

Advances in Manufacturing and Materials Engineering
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[1] M. Zhou, B.K.A. Ngoi, Z.W. Zhong, C.S. Chin, Brittle-ductile transition in diamond cutting of silicon single crystals, Materials and Manuf. Processes 16 (4) (2001) 447-460.
doi:10.1081/AMP-100108519
[2] J. Yan, M. Yoshino, T. Kuriagawa, T. Shirakashi, K. Syoji, R. Komanduri, On the ductile machining of silicon for micro electro-mechanical systems (mems), opto-electronic and optical applications, Material Science and Engineering 297 (1) (2001).
doi:10.1016/S0921-5093(00)01031-5
[3] S. Venkatachalam, X. Li, S.Y. Liang, Predictive modeling of transition undeformed chip thickness in ductile-regime micro-machining of single crystal brittle materials, J. of Materials Processing Technol. 209 (2009).
doi:10.1016/j.jmatprotec.2008.07.036