

**EFFECT OF TOOL GEOMETRY  
AND NOSE PROFILE MICRO-DEVIATION  
ON SURFACE ROUGHNESS IN FINISH TURNING**

**SUNG AUN NAA**

**UNIVERSITY SAINS MALAYSIA**

**2015**

**EFFECT OF TOOL GEOMETRY AND NOSE PROFILE  
MICRO-DEVIATION ON SURFACE ROUGHNESS IN  
FINISH TURNING**

**by**

**SUNG AUN NAA**

**Thesis submitted in fulfillment of the requirements**

**for the degree of**

**doctor of Philosophy**

**AUG 2015**

## **ACKNOWLEDGEMENT**

I would like to thank my supervisor, Prof. Dr. Mani Maran Ratnam. He was supervising me patiently, always guiding me in the right direction and make my Ph.D. experience productive and stimulating. I could not have finished my thesis successfully without his help. Prof. Dr. Mani Maran Ratnam is profound knowledge in image processing and his positive spirit has been a great source of inspiration to me. Special thanks are also given to my co-supervisor Dr. Loh Wei Ping for her help and encouragement in my work.

I would like to acknowledge the financial, academic and technical support of the University. This work was funded by the USM Fellowship and the Research University research grant.

Lastly, I would like to thank my family for all their love and encouragement. For my parents Sung Foo Heng and Ng Mooi See, husband William Lee Chiew Sing, brother Sung Yew Chong and Sung Yew Fong and sister Sung Aun Nee, I would like to thank for their unequivocal supports.

# TABLE OF CONTENTS

Acknowledgement.....	ii
Table of Contents.....	iii
List of Tables.....	viii
List of Figures.....	x
List of Algorithms .....	xvi
List of Symbols .....	xvii
List of Abbreviations .....	xxiv
Abstrak.....	xxvi
Abstract.....	xxviii

## CHAPTER 1-INTRODUCTION

1.0 Background.....	1
1.1 Problem statement.....	5
1.2 Objective.....	7
1.3 Scope of research.....	8
1.4 Thesis Outline.....	8

## CHAPTER 2- LITERATURE REVIEW

2.0 Overview.....	10
2.1 Factors affecting surface roughness in finish turning.....	10
2.1.1 Effect of tool geometry on surface roughness .....	12
2.1.1(a) Machining theory based approach.....	12

2.1.1(b)	Empirical based approach.....	17
2.1.2	Effect of nose profile micro-deviation on surface roughness .....	20
2.1.3	Effect of chatter vibration on surface roughness .....	24
2.1.4	Effect of tool wear on surface roughness .....	28
2.2	The existing basic model for $R_t$ , $R_a$ and $R_q$ .....	29
2.2.1	Approximation model.....	30
2.2.2	Implicit model.....	31
2.3	Nose profile extraction method for simulation study .....	34
2.4	The finding from the literature.....	35
2.5	Chapter summary .....	39

### CHAPTER 3-METHODOLOGY

3.0	Overview.....	41
3.1	Develop of new analytical models for surface roughness.....	44
3.1.1	Improved implicit basic model for $R_a$ .....	45
3.1.2	Implicit three-parameter model for $R_a$ and $R_q$ .....	47
	3.1.2 (a)Implicit three-parameter model for $R_a$ .....	47
	3.1.2 (b) Implicit three-parameter model for $R_q$ .....	52
3.2	Develop of Simulation 1 using ideal nose profile.....	53
3.2.1	Generation of surface roughness using Simulation 1.....	54
3.2.2	Values of considered parameters used in Simulation 1.....	62
3.2.3	Conditions for application of the analytical models and Simulation 1 .....	63

3.3	Develop of Simulation 2 using actual nose profile.....	65
3.3.1	Nose profile extraction up to sub-pixel accuracy.....	66
3.3.2	The optimum nose radius determination.....	77
3.3.3	Generation of polar-radius plot of the contact profile geometry.....	82
3.3.4	Generation of surface roughness using Simulation 2.....	86
3.4	Develop of Simulation 3 using actual nose profile by considering chatter vibration.....	88
3.4.1	Filtering of the vibration signal.....	89
3.4.2	Reconstruction of displacement signal from the velocity signal.....	94
3.4.3	Surface profile generation from the nose profile and the vibration data.....	97
3.4.4	Extraction of roughness profile from the unmodified profile.....	100
3.4.5	Generation of surface roughness using Simulation 3.....	103
3.5	Simulation 4 using actual nose profile by considering chatter vibration and nose wear.....	111
3.5.1	Generation of surface roughness using Simulation 4.....	112
3.5.2	Surface roughness prediction interval calculation.....	119
3.6	Experimental setup.....	121
3.6.1	Experiment 1: to compare the roughness data with the analytical models and Simulation 1.....	122
3.6.2	Experiment 2: to compare the roughness data with Simulation 2 to Simulation 4.....	123

3.7	Chapter summary.....	125
-----	----------------------	-----

## CHAPTER 4-RESULTS AND DISCUSSIONS

4.0	Overview.....	127
4.1	Surface roughness data generated from surface roughness evaluation methods based on ideal nose profile .....	128
4.1.1	Comparison of surface roughness data obtained from implicit basic model, approximation basic model and Simulation 1A.....	128
4.1.2	Comparison of surface roughness data obtained from three-parameter model and Simulation 1B.....	133
4.1.3	The applicable conditions of basic and three-parameter models.....	135
4.1.4	Effect of SCEA on surface roughness.....	137
4.1.5	Effect of nose radius on surface roughness.....	139
4.2	Comparison of surface roughness from analytical models, Simulation 1 and experimental results.....	141
4.3	Surface roughness data generated from simulation based on actual nose profile .....	145
4.3.1	Tool nose radius assessment.....	146
4.3.2	Effect of nose profile micro-deviation on surface roughness.....	147
4.3.3	Effect of chatter vibration on surface roughness at different points of workpiece.....	159
4.4	Comparison of surface roughness from Simulation 2 to Simulation 4 and experimental results.....	161

4.4.1	Comparison surface roughness data obtained from Simulation 2 to Simulation 4 and Experiment 2.....	161
4.4.2	Prediction intervals for surface roughness.....	167
4.4.3	The surface roughness values at different points of workpiece.....	170
4.4.4	The applications of Simulation 1C, Simulation 2 and Simulation 3.....	171
4.5	Chapter summary.....	173
CHAPTER 5-CONCLUSIONS AND RECOMMENDATIONS.....		177
5.1	Conclusions.....	177
5.2	Recommendations for future works.....	180
References.....		181
Appendices.....		189
Appendix A- Derivation of improved implicit basic model for $R_a$ .....		189
Appendix B- Derivation of implicit three parameter model for $R_a$ .....		191
Appendix C- Proof of prediction intervals equation.....		194
Appendix D- 24 sets of simulated and actual machined surface Profiles...196		
List of Publications.....		208



## LIST OF TABLES

		Page
Table 2.1	Surface roughness data obtained from the basic models for feed rate is 0.3 mm/rev and nose radius is 0.4 mm	33
Table 2.2	The previous study on the effect of geometrical profile of the contact edge on the surface roughness based on machining theory approach	36
Table 3.1	The developed simulation methods	43
Table 3.2	The types of Simulation 1 based on different considered parameters	54
Table 3.3	Values of tool geometries and feed rate used in Simulation 1B	62
Table 3.4	The specifications of the tool used	78
Table 4.1	The minimum, maximum and mean values in absolute percentage difference $\Delta R_{(i-x)}$ and $\Delta R_{(S1A-i)}$ for $R_t$ , $R_a$ and $R_q$	131
Table 4.2	Comparison of $R_a$ and $R_q$ obtained from three-parameter models and Simulation 1B	134
Table 4.3	The included and major cutting edge angles from manufacturer	136
Table 4.4	The absolute percentage difference for the surface roughness obtained from evaluation methods and experiment, and its mean	143
Table 4.5	Analysis of the comparison of surface roughness data obtained from different simulation methods	156
Table 4.6	The minimum, maximum and mean values in RSD obtained from Simulation 3 and Simulation 4	160
Table 4.7	The test statistic $D_n$ data	168

Table 4.8	Analysis of 24 surface roughness data obtained from Simulation 2 to Simulation 4	168
Table 4.9	The minimum, maximum and mean values in RSD obtained from experiment data	170

## LIST OF FIGURES

		Page
Figure 1.1	(a) The nose radius tolerance zone and (b) the nose profile micro-deviation in the zoomed view of the selected region of (a)	3
Figure 2.1	Ideal surface profile formation based on machining theory	13
Figure 2.2	Illustration of inclination angle and rake angle	19
Figure 2.3	Image of a 3-D tool captured using the <i>Alicona</i> system	21
Figure 3.1	Flow of research methodology	41
Figure 3.2	Geometrical illustration of a surface profile that consists of elliptical arcs	45
Figure 3.3	Geometrical illustration of a surface profile that consists of circular arcs and straight lines	48
Figure 3.4	The flow chart of the algorithm of Simulation 1	55
Figure 3.5	The images of nose profiles for (a) Simulation 1A, (b) Simulation 1B and (c) Simulation 1C	55
Figure 3.6	Nose profile $Z_2$ (blue line) after rotation of inclination and rake angles on nose profile $Z_0$ (black line) (a) in top view and (b) in isometric view	57
Figure 3.7	(a) The $x_d$ and $y_d$ vectors, (b) a respective tool profile	58
Figure 3.8	(a) The added $x_d$ vector, (b) the added $y_d$ vector and (c) the respective repetitive nose profiles	59

Figure 3.9	Condition for application of the analytical models and Simulation 1A to Simulation 1C	64
Figure 3.10	The nose profile $P_e$	66
Figure 3.11	Image of the tool nose	67
Figure 3.12	The algorithm of the nose extraction	68
Figure 3.13	(a) The gradient magnitude image $U_m$ , (b) the enlarged view of the image $U_m$ and (c) the column of pixels obtained from the small rectangle in (b)	70
Figure 3.14	The digitized image $V_b$	72
Figure 3.15	The plot of nose profile $P_e$ (a) in $x$ - $y$ coordinates, (b) the plot superimposed onto the original image and (c) the plot in sub-pixel accuracy	76
Figure 3.16	Flow chart of the algorithm for optimum nose radius determination	77
Figure 3.17	Schematic diagram of a tool nose	79
Figure 3.18	RMSD versus predefined nose radius $r_p$	82
Figure 3.19	Schematic diagram of a tool nose with different labels	83
Figure 3.20	Polar-radius graph of a nose profile at rounded nose	84
Figure 3.21	The angles $\theta_L$ and $\theta_M$ determination	84
Figure 3.22	Polar-radius graph of the contact profile geometry	86
Figure 3.23	The algorithm of Simulation 2	87
Figure 3.24	Surface profile generated	88

Figure 3.25	The filtration of vibration signal to extract the chatter vibration signal	90
Figure 3.26	Three types of mechanical vibration and their causes	93
Figure 3.27	Sample of displacement signal reconstruction from velocity signal	96
Figure 3.28	(a) Workpiece in the presence of chatter vibration in 3-D and (b) open surface views. (c) Ideal surface profile in the absent of chatter vibration. (d) Ideal surface profile in the presence of chatter vibration	98
Figure 3.29	(a) Unmodified profile and mean line and (b) roughness profile	101
Figure 3.30	Weighting function of Gaussian filter	102
Figure 3.31	Flow chart of the algorithm for Simulation 3	104
Figure 3.32	Noise velocity signal in the (a) time and (b) frequency domains	105
Figure 3.33	The amplitude count of the noise velocity signal in the frequency domain	105
Figure 3.34	Noisy velocity signal in the (a) time and (b) frequency domains	106
Figure 3.35	Clean velocity signal in the (a) frequency and (b) time domains	107
Figure 3.36	Displacement-time signal	108
Figure 3.37	(a) Unmodified profile and (b) Gaussian mean line	109
Figure 3.38	Roughness profile (a) with and (b) without end effects	110
Figure 3.39	The image of a tool nose (a) after machining and (b) in the zoomed view of the selected region of (a).	113
Figure 3.40	The algorithm to determinate the nose profile $P_{df}$	114

Figure 3.41	The sample of original nose profile and best fitted nose profiles	115
Figure 3.42	RMSD computation against translation value	117
Figure 3.43	The location of nose profile $P_{df}$ (point $Z$ ) that used to generate surface profile	117
Figure 3.44	The nose profiles $P_{dn}$ (green line), $P_{dw}$ (red line) and $P_{df}$ (blue line)	118
Figure 3.45	Close-up view of the workpiece and the tool	122
Figure 3.46	The setup of Experiment 2	124
Figure 4.1	(a) $R_t$ , (b) $R_a$ and (c) $R_q$ obtained from basic models and Simulation 1	131
Figure 4.2	Applicable conditions of basic and three-parameter models	136
Figure 4.3	Effect of SCEA on (a) $R_a$ and (b) $R_q$ for feed rate = 0.30 mm/rev	138
Figure 4.4	Effect of nose radius on (a) $R_a$ and (b) $R_q$ based on basic and three-parameter models for SCEA = 5°	140
Figure 4.5	(a) $R_t$ , (b) $R_a$ and (c) $R_q$ obtained from implicit basic model, three parameter model, Simulation 1, and experiment (nose radius = 0.4 mm, SCEA = 5°, inclination angle = -6° and rake angle = -6°)	142
Figure 4.6	The nose radius from actual nose profiles and the nominal radius	146
Figure 4.7	(a) Nose profile extraction using algorithm in <i>Alicona</i> system and (b) the corresponding extracted nose profile	148

Figure 4.8	Polar-radius plots the nose profile in the entire nose and at the contact edge for tool edges (a) no. 4, (b) no. 9, (c) no. 10 and (d) no. 14	149
Figure 4.9	The nose profile at contact edge and the corresponding surface profile for (a) ideal nose profile, (b) nose profile with micro-deviation at the center of the contact edge and away from the center of the rounded nose, (c) nose profile with micro-deviation at the center of the contact edge and toward to the center of the rounded nose, and (d) nose profile with micro-deviation at the side of the contact edge	151
Figure 4.10	(a) $R_t$ obtained from Simulation 1C to Simulation 4, (b) histogram of difference $\Delta R_{(S2-S1C)}$ for $R_t$ , (c) histogram of difference $\Delta R_{(S3-S1C)}$ for $R_t$ and (d) histogram of difference $\Delta R_{(S4-S1C)}$ for $R_t$	153
Figure 4.11	(a) $R_a$ obtained from Simulations 1C to Simulation 4, (b) histogram of difference $\Delta R_{(S2-S1C)}$ for $R_a$ , (c) histogram of difference $\Delta R_{(S3-S1C)}$ for $R_a$ and (d) histogram of difference $\Delta R_{(S4-S1C)}$ for $R_a$	154
Figure 4.12	(a) $R_q$ obtained from Simulation 1C to Simulation 4, (b) histogram of difference $\Delta R_{(S2-S1C)}$ for $R_q$ , (c) histogram of difference $\Delta R_{(S3-S1C)}$ for $R_q$ and (d) histogram of difference $\Delta R_{(S4-S1C)}$ for $R_q$	155
Figure 4.13	(a) $R_t$ obtained from Simulation 2 to Simulation 4 and Experiment 2, (b) histogram of difference $\Delta R_{(S2-e)}$ for $R_t$ (c) histogram of difference $\Delta R_{(S3-e)}$ for $R_t$ and (d) histogram of difference $\Delta R_{(S4-e)}$ for $R_t$	163
Figure 4.14	(a) $R_a$ obtained from Simulation 2 to Simulation 4 and Experiment 2, (b) histogram of difference $\Delta R_{(S2-e)}$ for $R_a$ (c) histogram of difference $\Delta R_{(S3-e)}$ for $R_a$ and (d) histogram of difference $\Delta R_{(S4-e)}$ for $R_a$	164

- Figure 4.15 (a)  $R_q$  obtained from Simulation 2 to Simulation 4 and Experiment 2, (b) histogram of difference  $\Delta R_{(S2-e)}$  for  $R_q$  (c) histogram of difference  $\Delta R_{(S3-e)}$  for  $R_q$  and (d) histogram of difference  $\Delta R_{(S4-e)}$  for  $R_q$  165
- Figure 4.16 Prediction intervals for (a)  $R_t$ , (b)  $R_a$  and (c)  $R_q$  169



## LIST OF ALGORITHMS

	Page
Algorithm 3.1 The algorithm to obtain image $V_b$	73
Algorithm 3.2 The algorithm to accept image $V_b$	75

## LIST OF SYMBOLS

$5X$	the magnification of the lens
$*$	Convolution operator
$\alpha$	Angle between left straight flank with vertical line (Figure 3.17)
$\kappa_r$	Major cutting edge angle
$\kappa_r'$	Side cutting edge angle
$\lambda$	Inclination angle
$\gamma$	Rake angle
$\epsilon_r$	Included angle
$\Omega$	Rotation angle to locate nose profile at appropriate side cutting edge angle
$\phi$	Angle between $OL$ and vertical line (Figure 3.21)
$\theta_e$	Angle measured counterclockwise between the vertical line and the line connecting the point $O$ to each nose profile point $P_e$ (Figure 3.19)
$\theta_J$	Start angle of rounded nose of edge profile
$\theta_K$	End angle of rounded nose of edge profile
$\theta_L$	Start angle of tool-workpiece interface
$\theta_l$	Angle between left straight flank and the horizontal line (Figure 3.19)
$\theta_M$	End angle of tool-workpiece interface
$\theta_r$	Angle between right straight flank and the horizontal line (Figure 3.19)
$\psi_1$	Possibility of the data not come from a normally distributed population
$\psi_2$	Possibility of the data $R_{S(n_z+1)}$ will fall within the range

$\Delta T$	Sampling interval
$a$	Major semi-axis of elliptical arc
$a_p$	Predefined value for <i>DFP</i>
$b$	Minor semi-axis of elliptical arc
$c_t$	Constant to provide 50% transmission characteristic at the cut-off wavelength
$D$	Diameter of workpiece
$d_a$	Difference between the $x$ -coordinate ( $x_N$ ) of point $N$ and $x$ -coordinate ( $x_E$ ) of point $E$ (Figure 2.1)
$d_b$	Horizontal distance between the peak and adjacent valley of the arc of the surface profile at the cutting portion produced by the rounded nose (Figure 2.1)
$d_e$	Difference between $y$ -coordinate ( $y_e$ ) of the nose profile and $y$ -coordinate ( $y_l$ ) of the last detected pixel at the probable edge point in a column
<i>DFP</i>	Difference between the $y$ -coordinates of the first pixel at the probable edge point that detected from bottom up for two columns in image $V_b$
$D_n$	Lilliefors' test statistic
$d_s$	Tool cutting path in the circumferential direction
$e$	Euler number
$E$	Intersection point of the minor cutting edge and rounded nose as (Figure 2.1)
$e_u$	Threshold value to select the probable edge point in the tool image
$f$	Feed rate
$g_1$	Gradients of left straight flank of a tool
$g_2$	Gradients of right straight flank of a tool
$h(k)$	Displacement-frequency discrete signal

$h(p)$	Displacement-time discrete signal
$h(q)$	Displacement-frequency continuous signal
$h(t)$	Displacement-time continuous signal
$i$	Imaginary number
$j$	Row in image
$L$	Start point of tool-workpiece interface
$l_e$	Surface roughness evaluation length
$l_m$	Total row in image
$l_n$	Total column in image
$l_r$	Length of the tool cutting path in one revolution
$l_s$	Surface roughness sampling length
$l_w$	Length of machined part of a workpiece
$M$	End point of tool-workpiece interface
$\overline{m}_c$	Moments along the pixels at the probable edge points in image $V_b$ , $c$ is 1, 2 or 3
$N$	Lowest point of the nose profile (Figure 2.1)
$n_d$	Number of independent predicted data
$n_p$	Point of workpiece
$n_r$	Number of nose profile points $P_e$ restricted in the rounded nose
$n_s$	Number of selected points at the straight flanks
$n_x$	Number of the pixels at the probable edge points in each column
$n_z$	Sample size

$p_1$	Ratio $d_e$ to $n_x$
$P_d$	Rotated nose profile
$P_{df}$	Nose profile contains the nose profile micro-deviation and nose wear
$P_{dn}$	Rotated nose profile from new tool nose
$P_{dw}$	Rotated nose profile from worn tool nose
$P_e$	Nose profile
$P_m$	Mean line workpiece profile
$P_r$	Roughness workpiece profile
$P_u$	Unmodified workpiece profile
$r$	Nose radius
$R_a$	Arithmetic average roughness
$r_e$	Radial distance
$R_{max}$	Highest peak roughness
$R_{min}$	Lowest valley roughness
$r_n$	Nominal nose radius
$r_{opt}$	Optimum nose radius
$r_p$	Predefined nose radius
$R_q$	Root-mean-square roughness
$R_s$	Average Surface roughness data of a workpiece obtained from simulation
$R_t$	Maximum peak-to-valley roughness
$R_w$	Surface roughness data in each workpiece obtained from simulation
$R_z$	Ten-point roughness

$s_1$	First Sobel operator
$s_2$	Second Sobel operator
$s_k$	Sampling frequency
$s_R$	Standard deviation of the average surface roughness values of different workpiece
$s_w$	Standard deviation of the surface roughness values of different points at workpiece
$t$	Time
$T$	Time period
$t.v$	Translation value
$t_{0.975, n_z-1}$	97.5% quantile of a Student's $t$ -distribution with $n_z-1$ degrees of freedom
$u$	Spindle speed
$U_m$	Image that having pixels with value represent the gradient of gray level in the $x$ - and $y$ -directions of the corresponding pixel in image $V_{gs}$
$U_x$	Image that having pixels with value represent the gradient of gray level in the $x$ -direction of the corresponding pixel in image $V_{gs}$
$U_y$	Image that having pixels with value represent the gradient of gray level in the $y$ -direction of the corresponding pixel in image $V_{gs}$
$V_b$	Image consists of nose edge band
$v_c(k)$	Clean velocity-frequency discrete signal
$v_c(p)$	Clean velocity-time discrete signal
$v_e(k)$	Noise velocity-frequency discrete signal
$v_e(p)$	Noise velocity-time discrete signal

$V_{gs}$	Gray-scale image
$v(p)$	Velocity-time discrete signal
$v(q)$	Velocity-frequency continuous signal
$v(t)$	Velocity-time continuous signal
$v_y(k)$	Noisy velocity-frequency discrete signal
$v_y(p)$	Noisy velocity-time discrete signal
$w$	Weighing function
$W_n$	Cutting edge normal plane
$W_r$	Main reference plane
$W_s$	Tool cutting edge plane
$x_d$	$x$ -coordinate of a point on the rotated nose profile $P_d$
$x_e$	$x$ -coordinate of a point on the nose profile $P_e$
$x_i$	Number of a column in an image
$x'$	Distance from the center (maximum) of the weighing function
$y_d$	$y$ -coordinate of a point on the rotated nose profile $P_d$
$y_{df}$	$y$ -coordinate of a point on the nose profile $P_{df}$
$y_{dw}$	$y$ -coordinate of a point on the nose profile $P_{dw}$
$y_{dn}$	$y$ -coordinate of a point on the nose profile $P_{dn}$
$y_e$	$y$ -coordinate of a point on the nose profile $P_e$
$y_J$	Approximate $y$ -coordinate of the point $J$
$y_i$	Number of a row in an image

- $y_K$     Approximate  $y$ -coordinate of the point  $K$
- $y_{min}$     Minimum  $y$  value
- $y_N$     Maximum  $y$ -coordinate of a point on the nose profile  $P_e$