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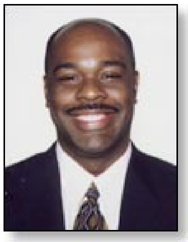

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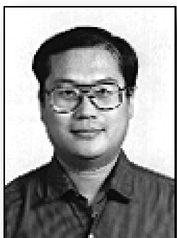

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Effects of Tool Diameter Variations in On-Line Surface Roughness Recognition System

By Dr. Mandara D. Savage & Dr. Joseph C. Chen

Introduction

Metal cutting is one of the most significant manufacturing processes (Chen & Smith, 1997) in the area of material removal. Black (1979) defines metal cutting as the removal of metal from a workpiece in the form of chips in order to obtain a finished product with desired attributes of size, shape, and surface roughness. Drilling, sawing, turning, and milling are some of the processes used to remove material to produce specific products of high quality.

The quality of machined components is evaluated by how closely they adhere to set product specifications of length, width, diameter, surface finish, and reflective properties. High speed turning operations, dimensional accuracy, tool wear, and quality of surface finish are three factors that manufacturers must be able to control (Lahidji, 1997). Among various process conditions, surface finish is central to determining the quality of a workpiece (Coker and Shin, 1996).

Surface roughness is harder to attain and track than physical dimensions are, because relatively many factors affect surface roughness. Some of these factors can be controlled and some cannot. Controllable process parameters include feed, cutting speed, tool geometry, and tool setup. Other factors, such as tool, workpiece and machine vibration, tool wear and degradation, and workpiece and tool material variability cannot be controlled as easily (Coker & Shin, 1996).

The surface parameter used to evaluate surface roughness in this study is the Roughness Average, Ra. This parameter is also known as the arithmetic mean roughness value, arithmetic average (AA), or centerline average (CLA). Ra is recognized universally as the commonest international parameter of roughness, as defined by the following equation:

$$R_a = \frac{1}{L}\int_0^L |Y(x)|\,dx , \quad (1)$$

where L is the sampling length, and y is the ordinate of the curve of the profile, the arithmetic mean of the departure of the roughness profile from the mean line (Lou, 1997).

The goal of the researchers is to develop a system that evaluates surface roughness on-line and in "real time"; however, to develop this system precisely, the key factors related to surface roughness during the machine process must be identified. These factors include feed rate, spindle speed, depth of cut of the process, tool and workpiece materials, and so on. In addition, the dynamics of the machining process generate vibration between the tool and workpiece while the machining process is taking place. This vibration information could be a key factor in the development of the on-line real-time surface roughness recognition system. Therefore, it is important to determine whether the tool diameter and the interaction of the feed rate affect the surface roughness and vibration response.

Purpose of Study

The goal of this research is to evaluate the effects of different tool diameters toward the development of an on-line real-time surface roughness recognition system. This goal will be achieved in three sub-goals.

1. The first sub-goal is to determine if tool diameter affects the surface roughness Ra of machined workpieces produced in a vertical machining center.
2. The second sub-goal is to determine if tool diameter affects the vibration of the workpiece during machining.
3. The final sub-goal is to determine if the process characteristics of tool diameter and feed rate have an interaction effect on Ra and/or workpiece vibration (Vi).

Experimental Setup and Signal Processing

The experimental setup of this study is shown in Figure 1. All machining was done in a Fadal VMC-40 vertical machining center with multiple tool-change capability. This machine is capable of three-axis movement (on x, y, and z planes). Programs can be developed in the VMC cpu, or downloaded from a 3 ½" diskette or a data link. A stylus profilometer was used to measure the surface roughness. This surface roughness measurement device is the most widely used instrument in industry and research laboratories because it is fast, consistent, easy to interpret, and relatively inexpensive (Mitsui, 1986; Shinn, Oh & Coker, 1995). In addition, stylus profilometers are used as a standard for comparing most of the newly-invented surface roughness measuring instruments or techniques. This instrument uses a tracer or pickup incorporating a diamond stylus and a transducer able to generate electrical signals as it moves across the surface to be measured. The electrical signals are then amplified, converted from analog to digital form, processed according to an algorithm, and then displayed. The measurement has a high resolution and a large range that satisfactorily measures the roughness of most manufactured surfaces.

The stylus profilometer does have some limitations. These include long periods of time needed to scan large areas, a restriction to use off-line, and difficulty in measuring non-flat surfaces (Shin, Oh, & Coker, 1995).

Vibration and proximity data were collected using a 353B33 accelerometer and a Micro Switch 922 Series 3-wire DC proximity sensor. The accelerometer was used to collect vibration data generated by the cutting action of the tool. The proximity sensor was used to identify the rotations of the spindle during cutting. The proximity information was graphed along with the accelerometer data, allowing for the identification of vibrations produced during different phases of the cutting sequence. Data from both sensors were converted from analog to digital signals through an Omega DAS-1600 A/D converter. The A/D converter-output was connected to a 486 personal computer via an I/O interface.

Two power supplies were used. A model 480E09 ICP sensor power unit was used to amplify the signal from the accelerometer. This amplified signal was then sent to the A/D board. The second power supply was used to power the proximity sensor and circuitry. The proximity sensor required a minimum of 5 volts for proper operation. The 5-volt signal was represented in the circuit during the switched phase of the proximity sensor. This signal was sent to the A/D board on a channel separate from that used for the accelerometer signal.

A C program was written specifically for calculating vibration and proximity data produced by the accelerometer and proximity sensor. The program was used to convert the analog binary data from each channel of the converter into decimal form. Microsoft Excel was then used to graph and display the decimal data by channel.

Figure 2 shows an example of the proximity and accelerometer data collected from a trial process using a 1.00" diameter tool at a feed rate of 20 inches per minute (ipm). The square wave line represents the revolution proximity data, the erratic line represents the vibration data, and the arrow line indicates the range of one revolution. The average of all these absolute values from the vibration data was ascertained for statistical analysis. Three average vibration values were collected for this experiment. The following equation allows the three average vibration data to be calculated:

$$Vi = \sum_{j=(i-1)*k}^{i*k} |Vibration(j)| / k, \quad i = 1, 2, \text{and } 3, \qquad (2)$$

where k represents the total number of data in each revolution (as indicated in Figure 2). For example, if i = 1, then the Vi is calculated through the vibration data points from point number 0 to point number k (to have a total of k data in one revolution). Vibration (Vi) is measured in units of voltage (as is reflected in Figure 2).

A minimum of seven Ra values was collected from each of the nine workpieces after machining. The median three values were used in the analysis.

Experimental Design

As mentioned earlier, this study seeks to evaluate whether difference of tool diameter affects the development of a surface roughness recognition system. When determining the parameters for

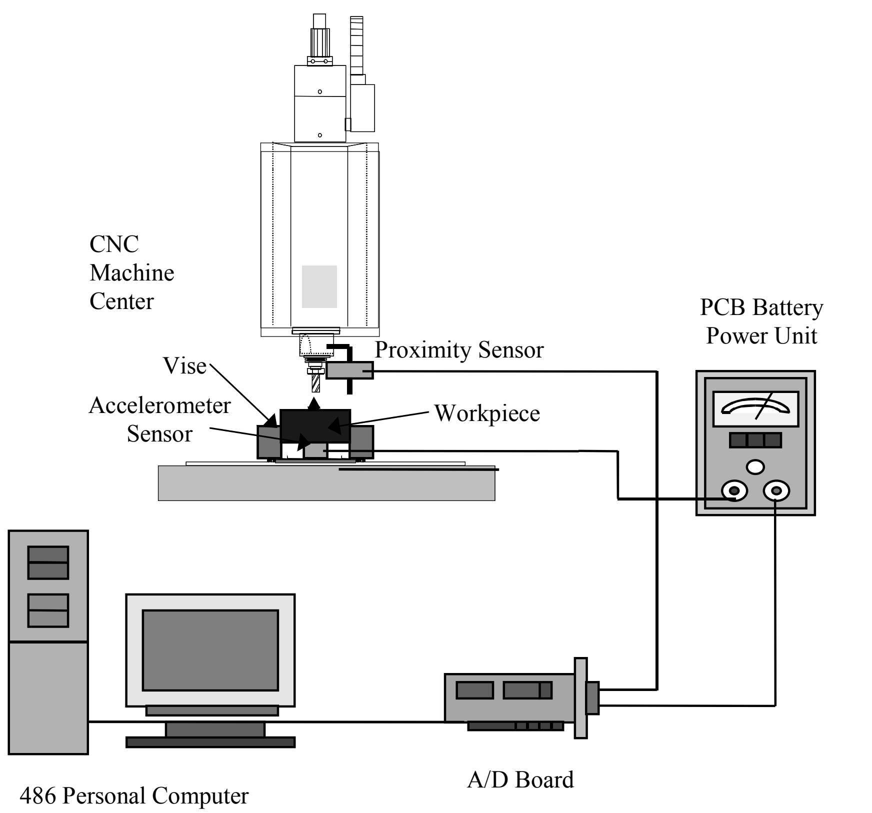

Figure 1. Experimental Setup

testing this effect, spindle speed, depth of cut, and type of work material remained constant. Three tool diameters were evaluated independently of tool design. Each of the three tools used in this research was of a four-flute high-speed steel (HSS) design, in three different tool diameters: 0.5”, 0.75”, and 1.00”. At a spindle speed of 2000 RPM, 0.01” was the depth of cut used on 6061 aluminum blocks, which comprised the work material for all trials. These tool sizes are those used most commonly in industry. Feed rate was also evaluated at three experimental levels of 10, 20, and 30 ipm. Feed rate and the tool diameters were both tested at varying levels. Table 1a displays vibration data at each level of testing. This data is designated by Vi. Table 1b displays the Ra values measured by the surface profilometer.

The experimental model for this study is a 3x3 design. The trials were non-random, having been grouped according to tool diameter. The following hypotheses were tested:

1. Ho_1: $Ra_1 = Ra_2 = Ra_3$
   Ha_1: at least one Ra_i ¹ Ra_j
   where Ra denotes the average surface roughness value in microinches.
2. Ho_2: $Vi_1 = Vi_2 = Vi_3$
   Ha_2: at least one Vi_i ¹ Vi_j
   where Vi denotes the average vibration voltage measured in volts.
3. Ho_3: $Ra'_1 = Ra'_2 = Ra'_3$
   Ha_3: at least one Ra'_i ¹ Ra'_j
   where Ra’, denotes the average surface value for the interaction between tool diameter and feed rate.
4. Ho_4: $Vi'_1 = Vi'_2 = Vi'_3$
   Ho_4: at least one Vi'_i ¹ Vi'_j
   where Vi’, denotes the average vibration voltage for the interaction between tool diameter and feed rate.

Data Analysis

The vibration and Ra data were analyzed in several different ways. In determining the effects of tool diameter and feed rate on Vi and Ra, a correlation table was first generated in order to identify the level of effect on the dependent variables. The results of the

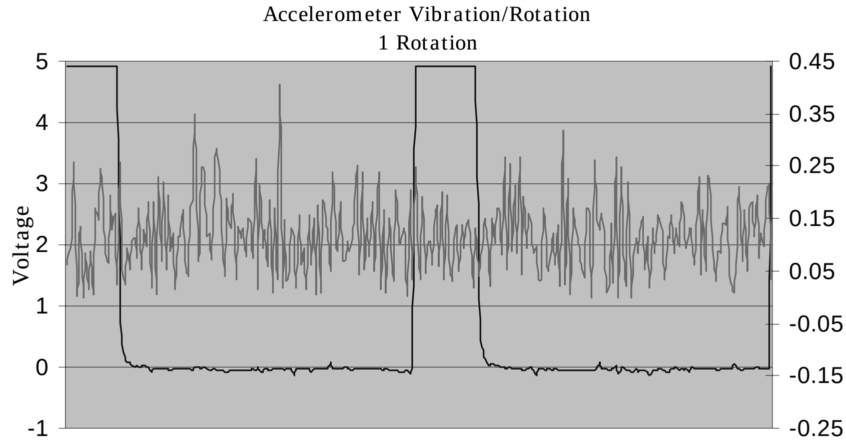

Figure 2. Vibration data from 1 trial run. One-inch diameter tool at 20 ipm Feed rate.

FEED RATE, IPM

TOOL SIZE		10	20	30	Tool Size Averages
	0.5”	0.1918	0.1262	0.0396	.1176922
		0.1904	0.1225	0.0409	
		0.1868	0.1183	0.0426	
	0.75"	0.0614	0.1146	0.1444	.0993689
		0.0550	0.1018	0.1354	
		0.0566	0.1006	0.1247	
	1.00"	0.1250	0.1167	0.0543	.0966900
		0.1273	0.1107	0.0537	
		0.1224	0.1071	0.0530	
	Feed Rate Averages	.1241	.1132	.0765	

Table 1a. Average vibration data given for three revolutions for each combination of feed rate and tool size. Data given in volts.

FEED RATE, IPM

TOOL SIZE		10	20	30	Tool Size Averages
	0.5”	42	29	53	42.33
		42	31	54	
		45	31	54	
	0.75"	32	57	132	84.11
		33	97	134	
		33	97	142	
	1.00"	50	55	79	62.44
		51	56	80	
		52	56	83	
	Feed Rate Averages	42.22	56.55	90.11	

Table 1b. Average surface roughness value Ra given for three revolutions for each combination of feed rate and tool size. Ra values given in microinches.

		Feed rate	Ra	Vi	Dia.
Feed rate	R		.614	-.435	
	p		.001	.023	
Ra	R	.614		.047	.258
	p	.001		.815	.194
Vi	R	-.435	.047		-.195
	p	.023	.815		.337
Dia.	R		.258	-.192	
	p		.194	.337	

Table 2. Partial correlation coefficients (Coefficient / (D.F.) /2-tailed Significance). α = .05

	Vi	Ra
R	-.2725	.3268
p	.1780	.1030

Table 2.1. Partial correlation coefficients Feed rate controlled for diameter (2-tailed significance; α = .05

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	26220.963	8	3277.620	51.571	.000
Intercept	107037.037	1	107037.037	1684.149	.000
FDSPEED	10874.296	2	5437.148	85.550	.000
DIA	7857.852	2	3928.926	61.819	.000
FDSPEED * DIA	7488.815	4	1872.204	29.458	.000
Error	1144	18	63.556		
Total	134402	27			
Corrected Total	27364.963	26			

Table 3a. ANOVA table for Between-Subjects Effects. Dependent Variable is surface smoothness with R square of .958 and .940 for adjusted R square.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	5.327E-02	8	6.659E-03	270.679	.000
Intercept	.295	1	.295	12003.862	.000
FDSPEED	1.118E-02	2	5.592E-03	227.291	.000
DIA	2.352E-03	2	1.176E-03	47.802	.000
FDSPEED * DIA	3.974E-02	4	9.935E-03	403.812	.000
Error	4.428E-04	18	2.460E-05		
Total	.349	27			
Corrected Total	5.372E-02	26			

Table 3b. ANOVA table for Between-Subjects Effects. Dependent Variable is vibration with R square of .992 and .982 for adjusted R square.

Model	Entered	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	Tool Diameter Feed rate	.666	.444	.397	25.1867

Table 4a. Model representing the variance associated with Ra contributed by Tool Diameter and Feed rate. Dependent variable: profilometer Ra. Independent variables: (constant), tool diameter, and feed rate.

correlation table are collected in Table 2. According to the data, feed rate correlates most clearly with Vi (-0.435) and with Ra (0.614). Tool diameter shows some correlation to both Vi (-0.192) and Ra (0.258), with diameter being inversely correlated with Vi.

The result of R = -0.192 for tool diameter and vibration indicates that vibration experienced in the workpiece decreased as the tool diameter increased. The effect of tool diameter is more evident when the effect of feed rate is controlled (table 2a). Note that correlation values for Vi (-0.214) and Ra (0.326) are slightly stronger with tool diameter. The levels of significance for tool diameter and feed rate are listed in Tables 3a and 3b.

Significant factors from Table 3a include feed speed, tool diameter, and interaction between feed speed and tool diameter. These results reject null hypotheses Ho_1 and Ho_3.

With respect to vibration, significant factors in Table 3b include feed speed, tool diameter, and interaction between feed speed and tool diameter. These results reject null hypotheses Ho_2 and Ho_4.

Next, a linear regression analysis was completed on the data. The regression analysis was done in two sets, one using Vi as the dependent variable and the other using Ra as the dependent variable. Results of the regression analysis procedure with Ra as the dependent variable are shown in tables 4a and 4b. Table 4a gives the model summary and Table 4b displays the ANOVA table. Results of the regression analysis procedure with Vi as the dependent variable are shown in tables 5a and 5b. These tables have the same table designation as Tables 4a and 4b. A probability plot is displayed for both dependent variables in Figures 3 and 4, respectively.

A Scheffe' multiple comparison procedure with α = 0.05 was completed with data collected for vibration and profilometer data. When considering vibration data, the greatest significant difference was 0.001, existing between feed rates of 10 and 30 ipm; the second most significant difference was 0.012, existing between feed rates of 20 and 30 ipm.

For the profilometer data, the most significant difference was 0.003, existing between feedrates of 10 and 30 ipm; the second most significant difference was 0.040, existing between feedrates of 20 and 30 ipm.

Summary

The goal of this study was to identify significant effects of tool diameter on tool vibration and workpiece surface roughness in end mill cutting. The data collected demonstrates that tool diameter has a significant effect on vibration generation and surface roughness. Workpiece vibration and surface roughness were significantly affected by the feed rate of the cutting tool. The interaction between tool diameter and feed rate did have a significant effect on Ra and Vi; however, that effect was largely due to feed rate.

Results of this study show that tool diameter should be considered as a major contributing factor in the surface roughness recognition model. Additional studies will evaluate the effect of different work materials and tool material types in order to consider their effects in an overall multi-level on-line surface roughness recognition model. Feed rate will continue to be considered as a contributing factor in future studies involving surface roughness.

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Model 1		Sum of Squares	DOF	Mean Square	F	Sig.
1	Regression	12140.111	2	6070.056	9.56	.001
	Residual	15224.852	23	634.369		
	Total	27364.963	26			

Table 4b. ANOVA table for Ra containing tool diameter and feed rate. Dependent variable is profilometer Ra. Independent Variables are (constant), tool diameter, and feed rate. a = .05.

Model	Entered	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	Tool Diameter Feed rate	.687	.472	.428	3.2108E-02

Table 5a. Model representing the variance associated with Vi contributed by tool diameter and feed rate. Dependent variable is vibration (Vi). Independent variables are (constant), tool diameter, and feed rate.

Model		Sum of Squares	DOF	Mean Square	F	Sig.
1	Regression	2.211E-02	2	1.105E-02	10.722	.000
	Residual	2.474E-02	24	1.031E-03		
	Total	4.685E-02	26			

Table 5b. ANOVA table for Vi containing tool diameter and feed rate. Dependent variable is vibration (Vi). Independent variables are (constant), tool diameter, and feed rate.

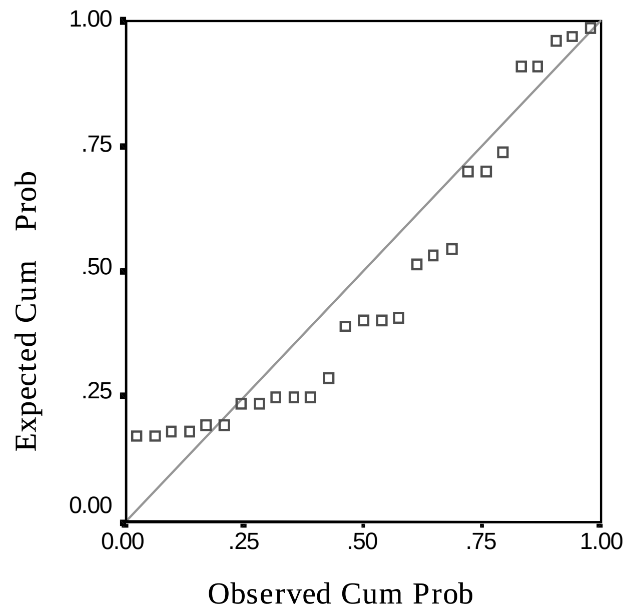

Figure 3. Normal P-P Plot of Regression Standardized Residual Dependent Variable: Profilometer Ra

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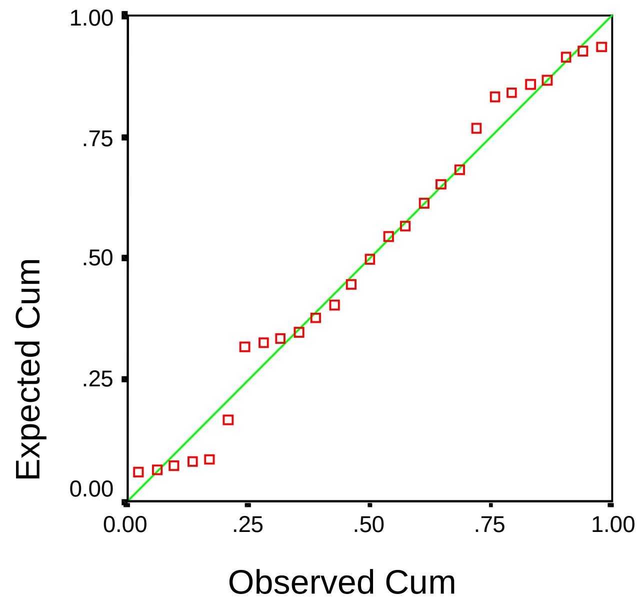

Figure 4. Normal P-P Plot of Regression Standardized Residual Dependent Variable: Vibration Vi