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Full Length Research Paper

Monitoring of tool wear and surface roughness in end-milling for intelligent machining

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Recently, cutting tool and product quality management in intelligent machining has been implemented by automated tool and quality monitoring and control systems. These systems utilize born features recognized in indirect signals, which reflect, on-line, the tool and quality conditions. In this research work, study was carried out to analyze the dynamic cutting signals of the end-milling process, in order to establish a force based model extracted from these signals, to monitor the end milling tool flank wear and workpiece surface roughness for intelligent machining. Experimental tests in end milling operations are carried out as a case study to verify the results of the proposed force model. The results showed that the proposed force model is an applicable method to predict the tool wear and surface roughness in end milling.

Key words: End-milling, cutting, forces, monitoring, intelligent-machining, surface roughness, tool wear.

INTRODUCTION

The fast changing global market demands are cost-effective and efficient machining processes to manufacture mechanical components with high accuracy. Sensor fused intelligent machining system is a viable solution for monitoring and optimization of the cutting processes of machines to improve reliability, flexibility, and productivity (Mitsuishi et al., 2001; Ahmed et al., 2006). On-line tool and surface roughness condition monitoring is an important method for optimization of the cutting process, efficient tool change policies, product quality control and lower tool costs (Martin, 1994; Huang et al., 2007; Sarhan et al., 2001). For example, with monitoring cutting system performance and its conditions, time saving in machining and tool changing was reported to reach up to 40% (Dan and Mathew, 1990; Salgado and Alonso, 2007; Sun et al., 2006). Therefore, the development of on-line sensing schemes for tools wear monitoring along with the prediction and control of the work surface roughness level has been an active area of research (Martin, 1994; Huang et al., 2007; Sarhan et al., 2001; Dan and Mathew, 1990; Salgado and Alonso, 2007; Sun et al., 2006; Sarhan et al., 2004).

The most reliable method to monitor the tool and surface roughness condition and adaptively control the cutting process is through the measurement of cutting force signals, as they could tell limits of cutting conditions, accuracy of the workpiece, tool wear, and other process information, which are indispensable for process feedback control. Hence, reliable cutting force measurement systems are investigated (Salgado and Alonso, 2007; Sun et al., 2006; Sarhan et al., 2004; Ahmed et al., 2006; El-Hossainy, 2001; Ramesh et al., 2001; Moriwaki et al., 2006; Kurniawan et al., 2010; El-Tamimi and El-Hossainy, 2008).

In this research work, the sensitive signals in end-milling operations are taken to be radial and tangential cutting forces through the monitoring process. Especially designed and manufactured highly sensitive strain gage dynamometer is used to measure the radial and tangential cutting forces during end-milling process. The cutting force signal harmonics is used to predict surface roughness of the workpiece machined in end milling. Then a force based model simulation is proposed. Experimental tests are carried out to validate the force model simulation and to define the reliability of the

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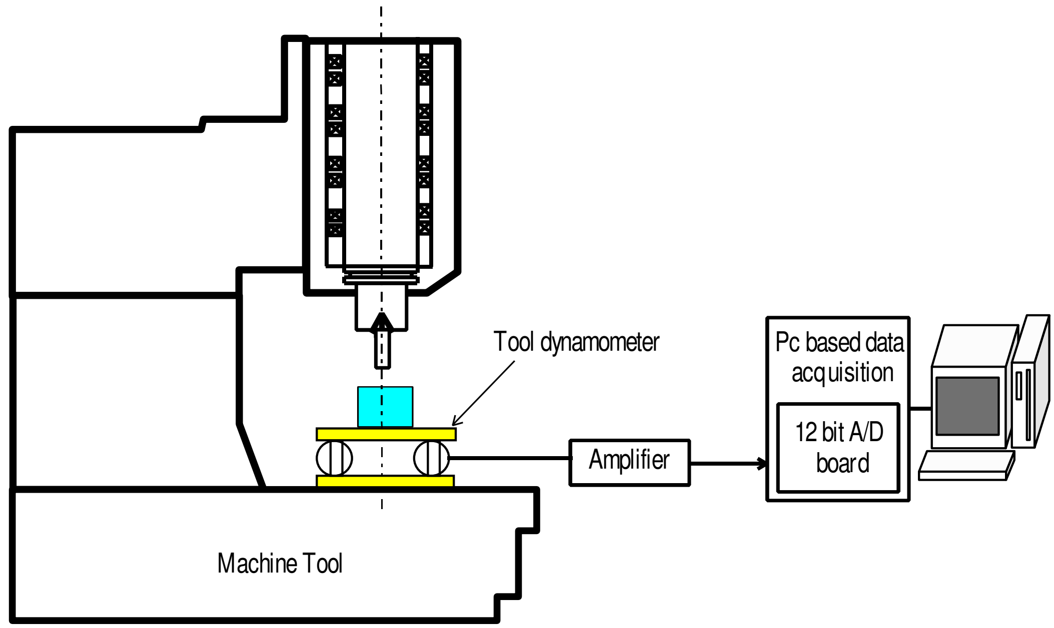


Figure 1. Schematic view of the monitoring system.

system to be employed in monitoring system. The results showed that the proposed force model simulation is an applicable method for monitoring of tool flank wear and surface roughness in end milling for intelligent machining.

METHODOLOGY

For measuring the radial and tangential cutting forces during end-milling process, a especially designed and manufactured highly sensitive strain gage dynamometer is used and the workpieces are made from low carbon steel, 0.2% C, with hardness 90 BHN. Hence, the frequency spectrums of the measured cutting forces are obtained at different cutting conditions using FFT analyzer.

Firstly, to examine the effect of tool wear variation on the magnitude of the cutting force harmonics, a computer simulation approach is constructed. It implies the cutting force as an indirect parameter to predict the tool wear variation. The tool wear is experimentally measured in an off-line manner using the tool maker's microscope and the relationships of cutting force harmonics and tool wear magnitude is constructed and found to be comparable with the computer simulation results.

Secondly, the surface roughness is measured using surface roughness meter (Type Surtronic 3+). Results of the surface roughness from the surface meter are obtained at different values of cutter flank wear width, feed rate per tooth, and axial depth of cut. Then the frequency spectrum of the measuring surface roughness texture is obtained.

Monitoring system and calibration

The schematic view of the monitoring and calibration system used in this research is shown in Figure 1. For measuring the radial and tangential cutting forces during end milling process, an especially designed and manufactured a highly sensitive strain gage dynamometer is used. To obtain the maximum sensitivity of the dynamometer, the rings are designed to carry the maximum permissible value of elastic strain of the strain gage material. The specifications of the dynamometer rings are as follows: the diameter is φ45 mm, the width is 20 mm, and the thickness is 4.5 mm.

Table 1 shows the specifications of the strain gage type (KFG-5-120-C1-11) with measuring grid length of 3 mm, which is used in this research. Automatic compensation of interference effect from temperature change is taken care of through the application of a full bridge connection. Adhesive material type (Z-70), which is a cold adhesive, is used. This type of adhesive gives good characteristics when used with (KFG-5-120-C1-11), such as, low hysteresies, high zero temperature stability, high fatigue limit.

Since both of the dynamic and static components of the cutting signal are significant, the dynamometer is statically and dynamically calibrated. The workpieces used are made from low carbon steel, 0.2% C, with hardness 90 BHN. The test results showed that the dynamometer output has a linear relationship with the load applied in both X and Y directions. In order to convert the dynamometer output signal to the cutting force (called as the measured cutting force hereafter), the following equations are used.

In X-axis direction : $F_X = 1.7742 + 3.2819\, V_X$ (1)

In Y-axis direction : $F_Y = 0.38878 + 1.13778\, V_Y$ (2)

where V_X (v) and V_Y (v) are the dynamometer output in X and Y direction, in Volts respectively, and F_X (N) and F_Y (N) are the measured cutting force in X and Y directions, in Newton respectively.

By using Equations 1 and 2, the cutting force can be estimated with a 95% confidence interval of ±25.9 N in the X-axis direction, and ±30.4 N in the Y-axis direction.

To obtain the dynamic response between the tool tip and the dynamometer rings where the strain gage is located, the dynamometer structure is excited on the table in X and Y directions.

Table 1. The specifications of the strain gage type (KFG-5-120-C1-11).

Gage factor, K	2.05±1%
Resistance, R	120 Ω
Cross sensitivity	-0.1%
Range for dynamic measurement	±200°C
Mechanical hysteresis with adhesive (Z-70) for load cycle	0.5 µm/m
Maximum energizing voltage	9 Vrms.
Maximum elongation (tension or compression)	50000±5% µm/m

An impact force hammer is used as an exciting force. Both impact force hammer and dynamometer force signals are recorded synchronously and processed using a Fourier analyzer system to identify the frequency bandwidth. The sampling frequency used is 5 kHz. The transfer function measurements indicate that the sensor system can respond to cutting forces which bandwidth is 150 Hz whereas the magnitude and phase shift remain almost invariant. Hence, the sensor system can measure the force components precisely at the spindle speeds up to 9000 min^{-1}.

Cutting forces estimation in end-milling

In End-milling, two components of cutting force on each tooth are considered in the plan of cut, the tangential and radial forces. For steady cutting, the estimated tangential, radial, and resultant forces acting on a single cutting straight edge can be obtained as follows (Huang et al., 2007; Sarhan et al., 2001; Dan and Mathew, 1990).

$$F_t = K_s\, a\, S_t \operatorname{Sin}\theta + a\, C_w\, V_b \quad (3)$$

$$F_R = R_1\, K_s\, a\, S_t \operatorname{Sin}\theta + R_2\, a\, C_w\, V_b \quad (4)$$

$$FRR = \sqrt{F_t^2 + F_R^2} \quad (5)$$

where, (R_1 and R_2) are force ratio constants, (K_s) is the specific cutting pressure of workpiece material (N/mm^2), (a) is the axial depth of cut (mm), (S_t) is the feed rate per tooth (mm/tooth), (θ) is the instantaneous angle of rotation (deg.), (C_w) is the edge force constant (N/mm^2), and (V_b) is the flank wear width (mm).

The constant parameters of Equations 3 and 4, (R_1, R_2, K_s, and C_w), are identified by conducting a set of pre-process cutting tests. The dynamometer force signals are measured during cutting of workpieces made from low carbon steel, 0.2% C. The cutting tool used is a new HSS end mill tool such that the average tool flanks wear V_b is very small and can be neglected. The cutting tool diameter is 10 mm with four flutes. The axial depth of cut and the feed rate per tooth used are 0.5 mm and 0.012 mm/tooth, respectively. This test is repeated four times. The dynamometer output signals are digitized with a 12-bit A/D board and filtered by low path filters (10 Hz cut off frequency) and the sampling frequency is set so that 20 point per cycle can be obtained. R_1 and R_2 are found to be 0.5 and 1.0 respectively, K_s is 5100 N/mm^2, and C_w is 150 N/mm^2.

Equations 3 and 4 consist of two parts. The first part represents the formation of the chip while; the second part represents the friction force caused by flank wear land width. The cutting tool flanks wear width are measured experimentally on each tooth of the cutter using a tool maker's microscope and the average tool flanks wear can be obtained as follows:

$$V_b = \frac{1}{Z}\sum_{i=1}^{Z} V_b \quad \text{(i)}$$

where, Z is the number of teeth.

RESULTS

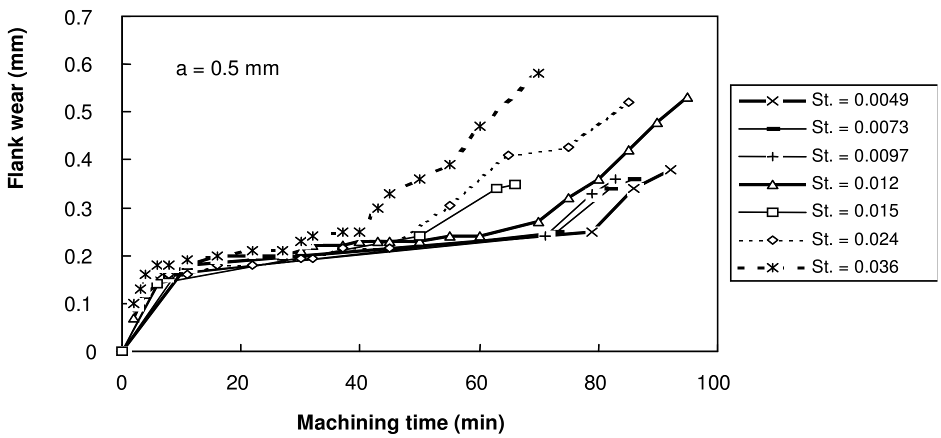
The experimental interrelations between flanks wear land width and machining time is constructed at various cutting conditions as shown in Figure 2. By using Equations 3, 4, and 5, the cutting forces are estimated and compared with the measured one. By using Equations 1 and 2, the dynamometer output signals are interpreted into force. Table 2 shows the cutting conditions used.

Figures 3 and 4 shows an example of the estimated and measured cutting forces in frequency domain, respectively. As can be seen in these figures, the estimated cutting force harmonics are observed and have same frequency and amplitude as the measured one. By comparing the estimated and measured cutting forces in each cut, estimation errors (measured minus estimated cutting forces at same harmonic) are calculated. It is found that the maximum estimated error is less than 27 N which corresponding to about 8 % of the measured force. It is indicated that the proposed estimation method of the cutting forces in end milling process is an applicable method.

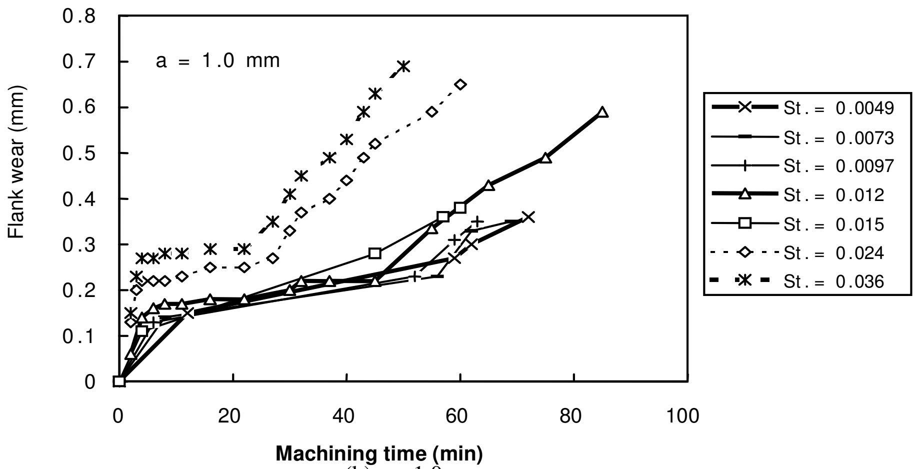
ANALYSIS AND DISCUSSION

Analysis and discussion of the tool wear results

As can be seen in Figures 3 and 4, the magnitudes of the cutting force harmonics change with flanks wear at different rates. Figure 5 shows the relation between the cutting forces harmonics (estimated and measured) and tool flank wear at different cutting conditions. Figure 6 shows the change of the cutting force harmonics with tool flank wear at S_t = 0.036 mm/tooth. As can be seen, the magnitude of the cutting force first harmonic increases



(a) a = 0.5

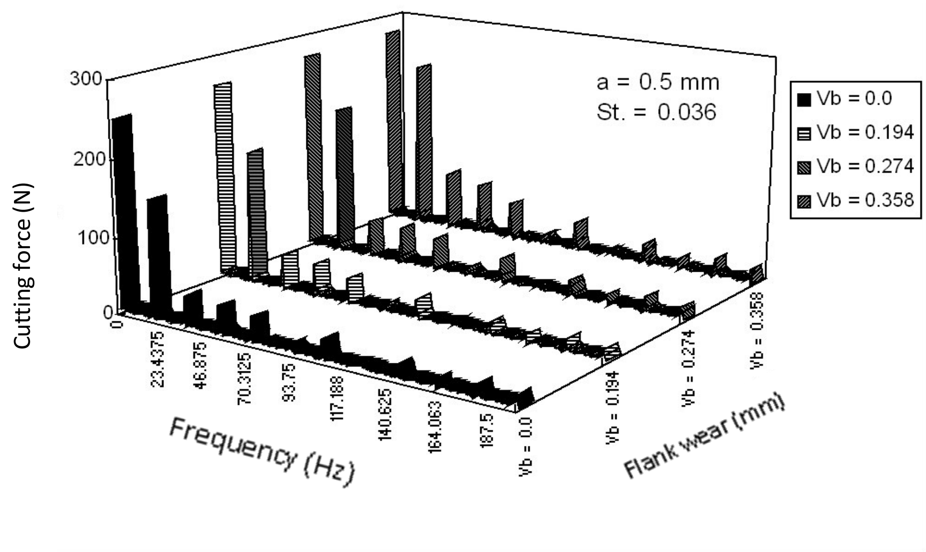


(b) a = 1.0 mm

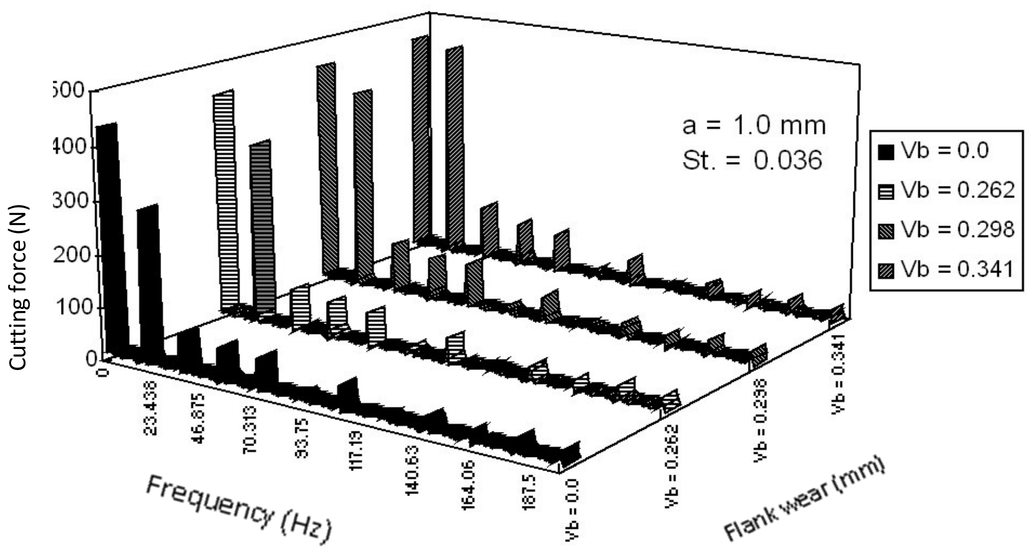
Figure 2. The interrelations between tool flanks wear land width and machining time.

Table 2. The cutting conditions.

Test group no.	a (mm)	N (rpm)	V_f (mm/min)	S_t (mm/tooth)	W.P (material)
G1	0.5	290	28	0.024	
G2	0.5	290	42	0.036	
G3	0.5	580	28	0.012	
G4	0.5	580	42	0.018	
G5	1.0	290	28	0.024	
G6	1.0	290	42	0.036	
G7	1.0	580	28	0.012	Low carbon steel
G8	1.0	580	42	0.018	
G9	0.5	725	28	0.0097	90 BHN
G10	0.5	725	42	0.015	
G11	0.5	1450	28	0.0049	
12	0.5	1450	42	0.0073	
G13	1.0	725	28	0.0097	
G14	1.0	725	42	0.015	
G15	1.0	1450	28	0.0049	
G16	1.0	1450	42	0.0073	



(a) a = 0.5 mm



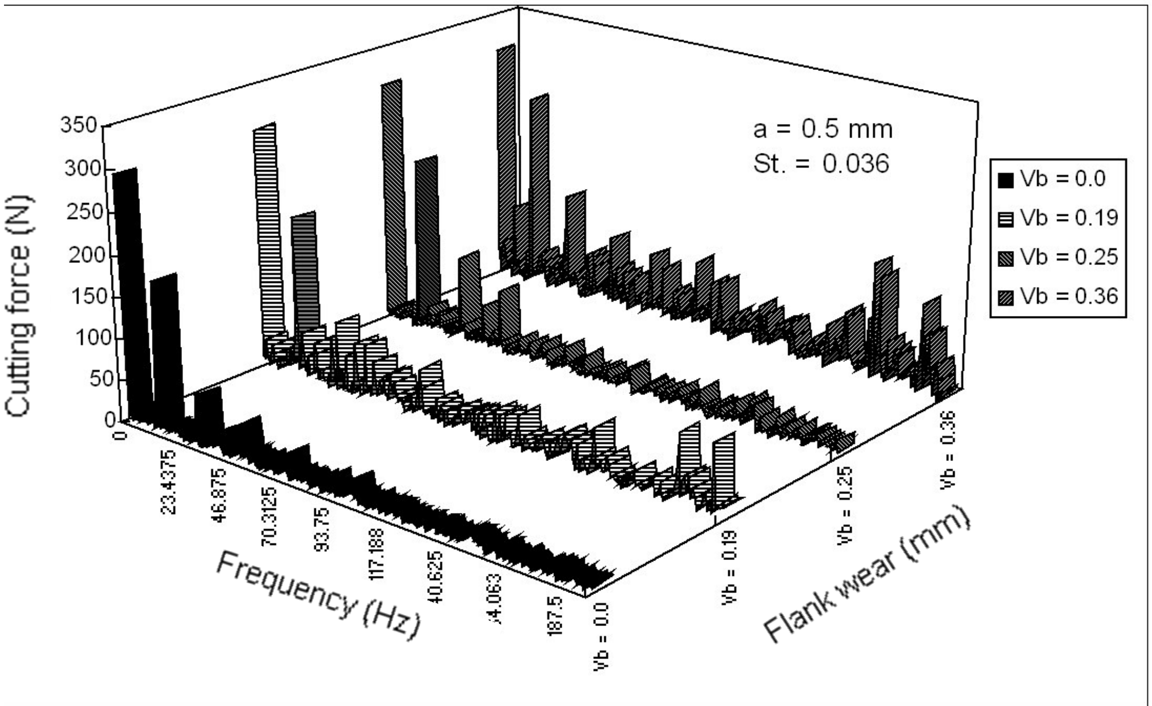
(b) a = 1.0 mm

Figure 3. An example of the estimated cutting forces in frequency domain (St = 0.036 mm/tooth).

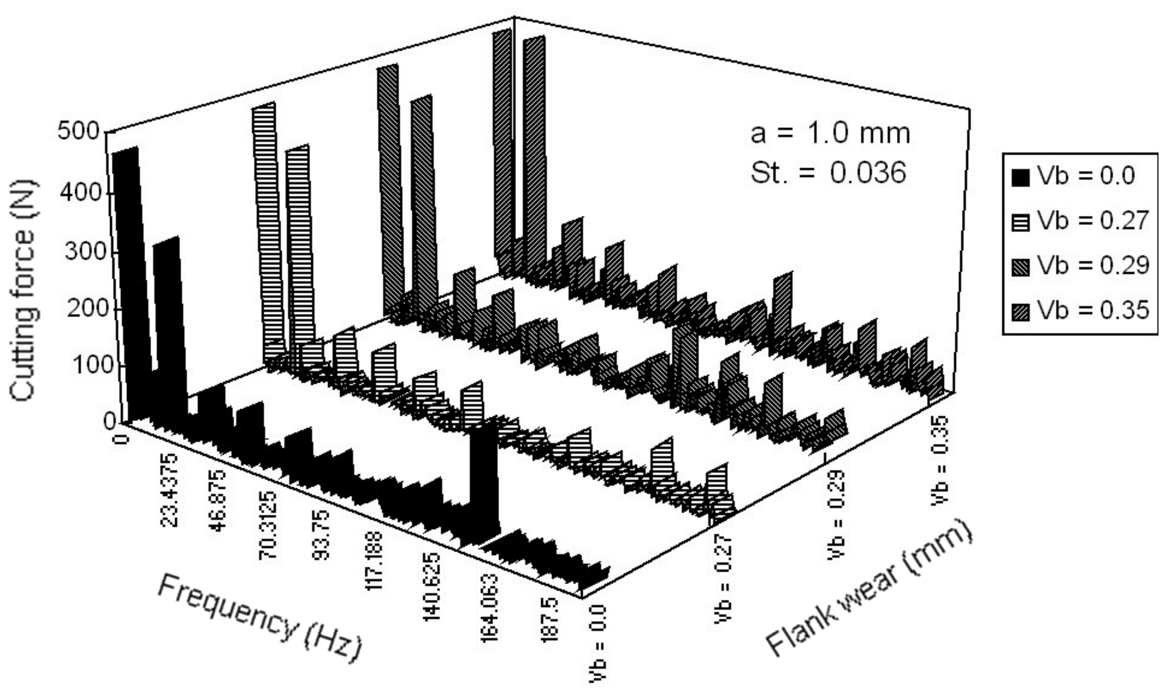
significantly with flank wears, while the second and third force harmonics indicates slight correlation. As other relationships obtained in the different conditions show the same tendency, the cutting force first harmonic is selected to be employed as indicator parameter of the tool flanks wear through the tool flanks wear monitoring strategy as it is significantly sensitive to the tool wear change.

Analysis and discussion of the surface roughness results

In this paper, surface roughness is measured on each cutting process presented before using a surface meter (Type Surtronic 3+). The mean line average of the surface roughness (Ra) is calculated and the frequency spectrums of the measured surfaces roughness texture



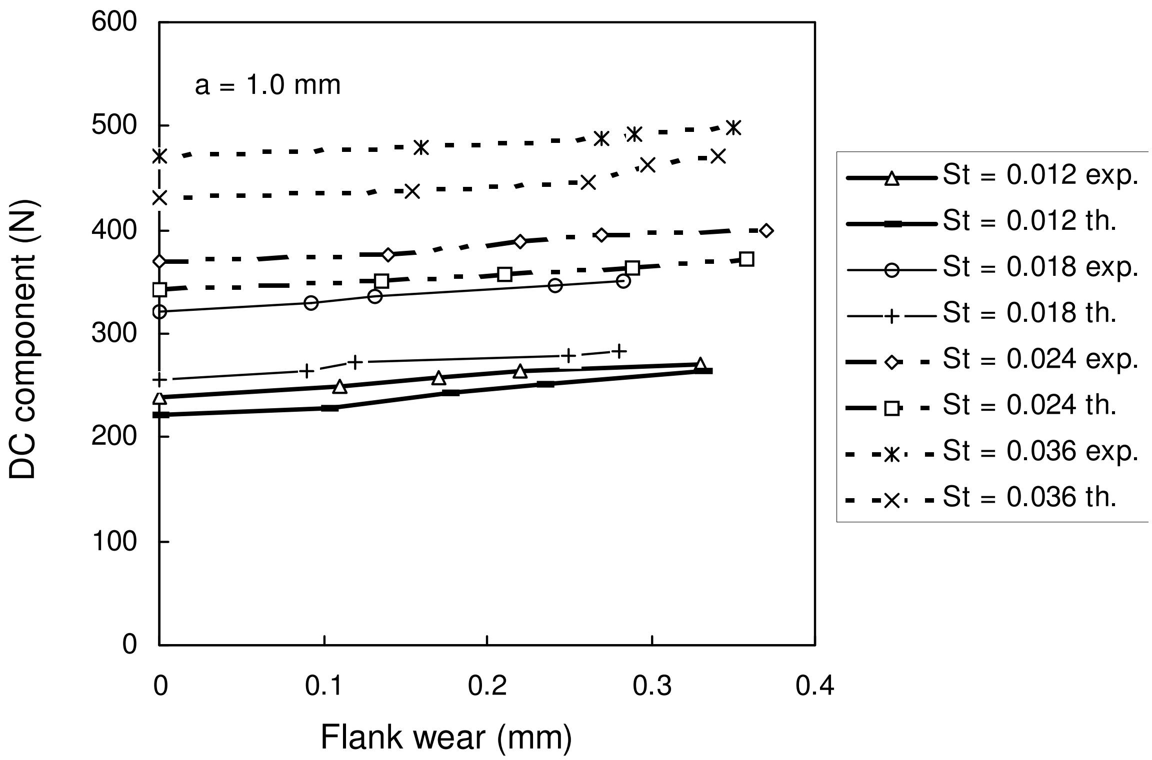
(a) a = 0.5 mm



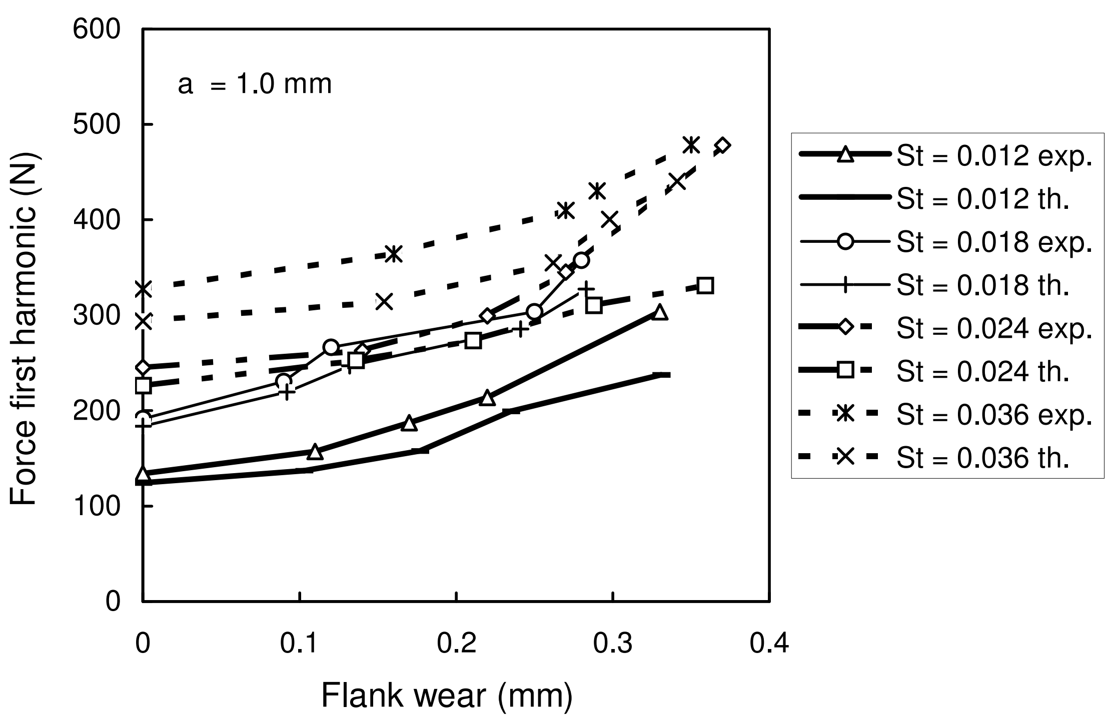
(b) a = 1.0 mm

Figure 4. An example of the measured cutting forces in frequency domain (St = 0.036 mm/tooth).

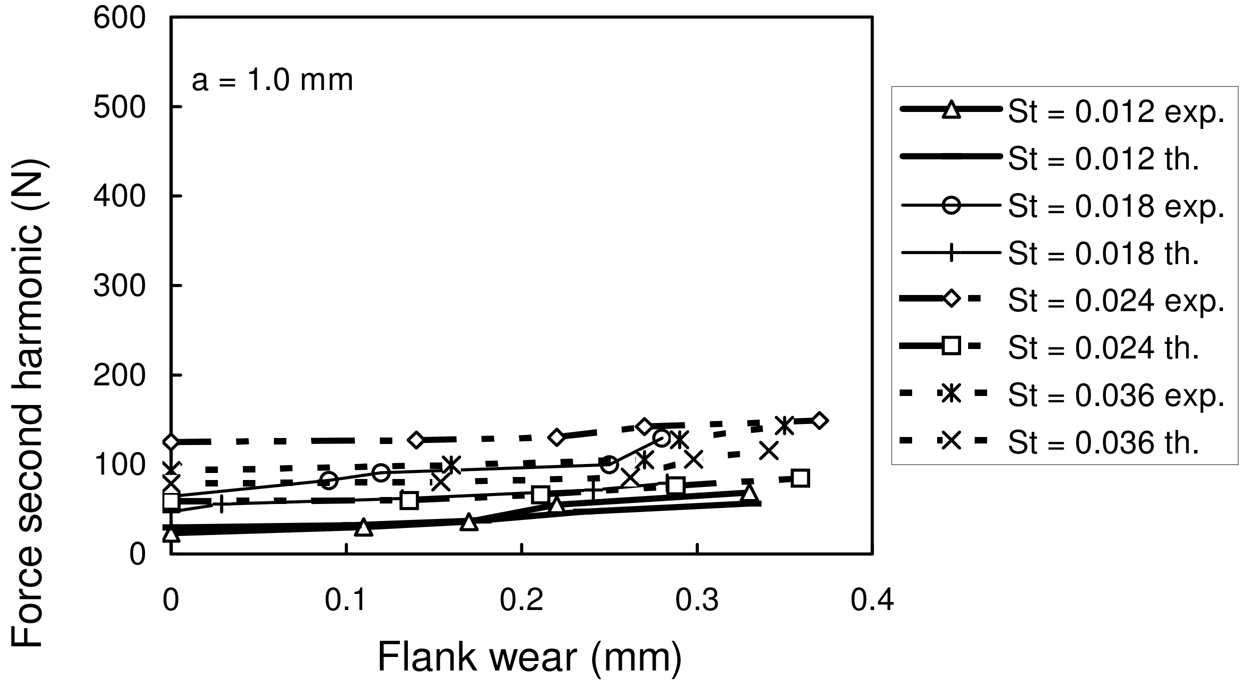
are obtained at different cutting conditions and tools wear. Figure 7 shows an example of the frequency spectrums of the measured surfaces roughness texture. As can be seen in this figure, the surface roughness



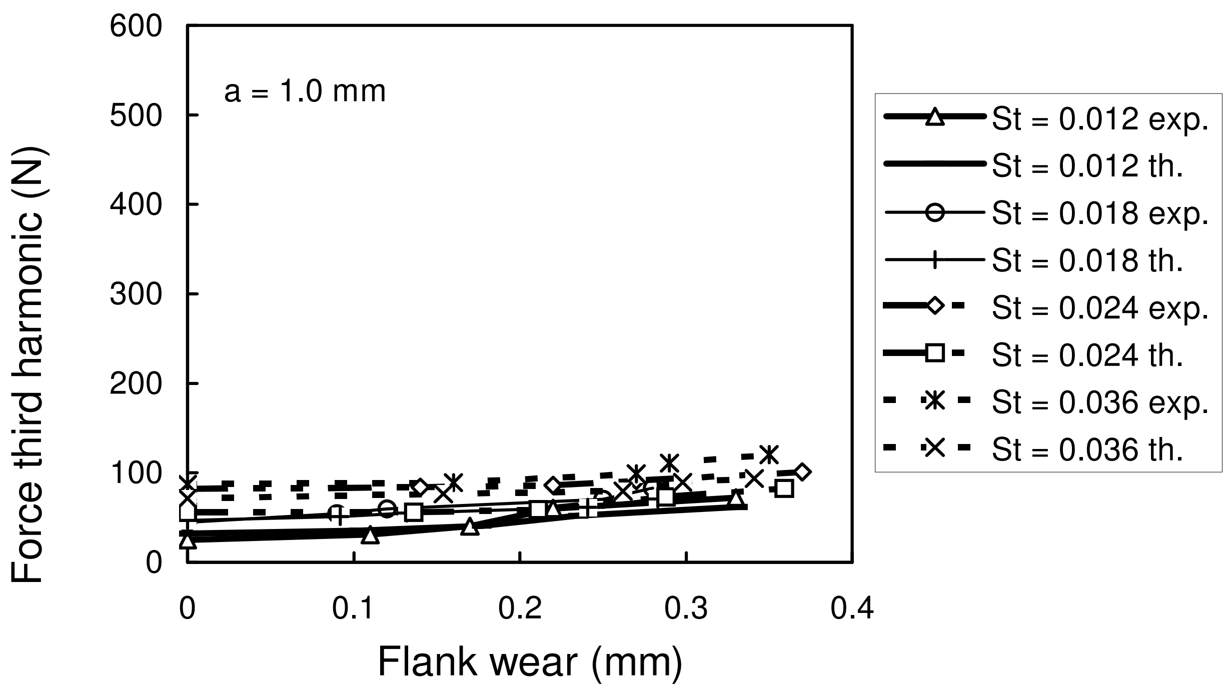
(a) DC component



(b) Force first harmonic



(c) Force second harmonic



(d) Force third harmonic

Figure 5. The relation between DC component, the cutting forces harmonics (estimated and measured) and tool flank wear.

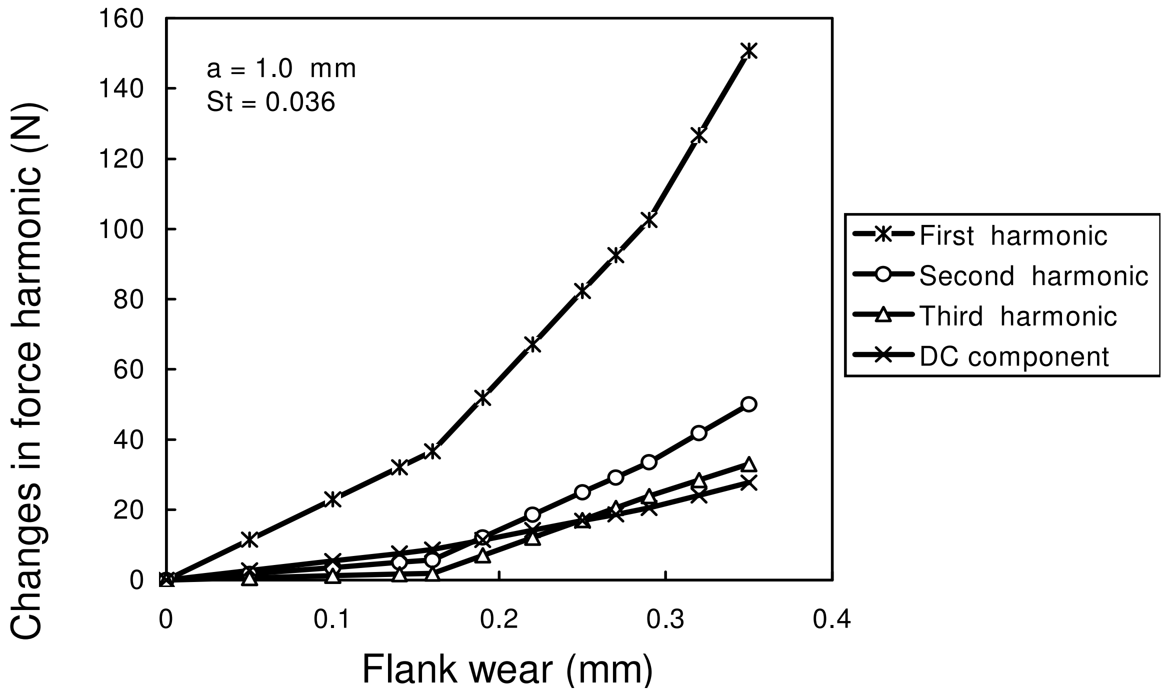


Figure 6. The change of the cutting force harmonics with tool flank wears.

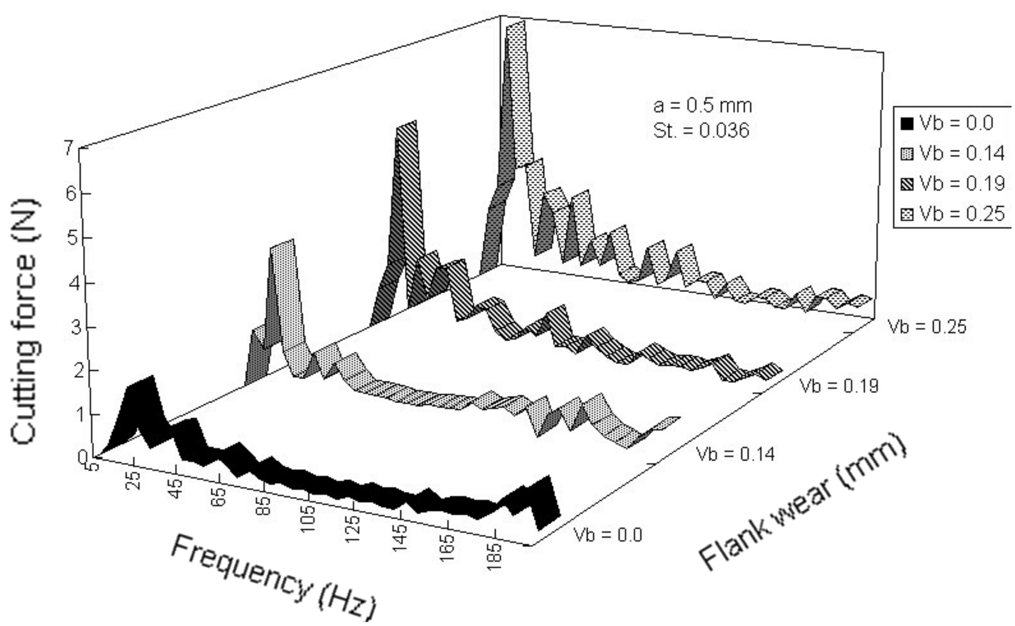


Figure 7. An example of the frequency spectrums of the measured surfaces roughness texture.

harmonics are observed and have same frequency as the measured cutting force shown in Figure 4. This indicates the existence of force-surface roughness relationship at different tool wear.

Figure 8 and 9 shows, the effects of the tool wear change on the mean line average of the surface roughness (Ra) and on the surface roughness harmonics, respectively. As shown in these figures, the surface roughness first harmonic is found to be more sensitive to the change of the cutting conditions and sensitive to the change of the surface roughness texture profile than the mean line average of the surface

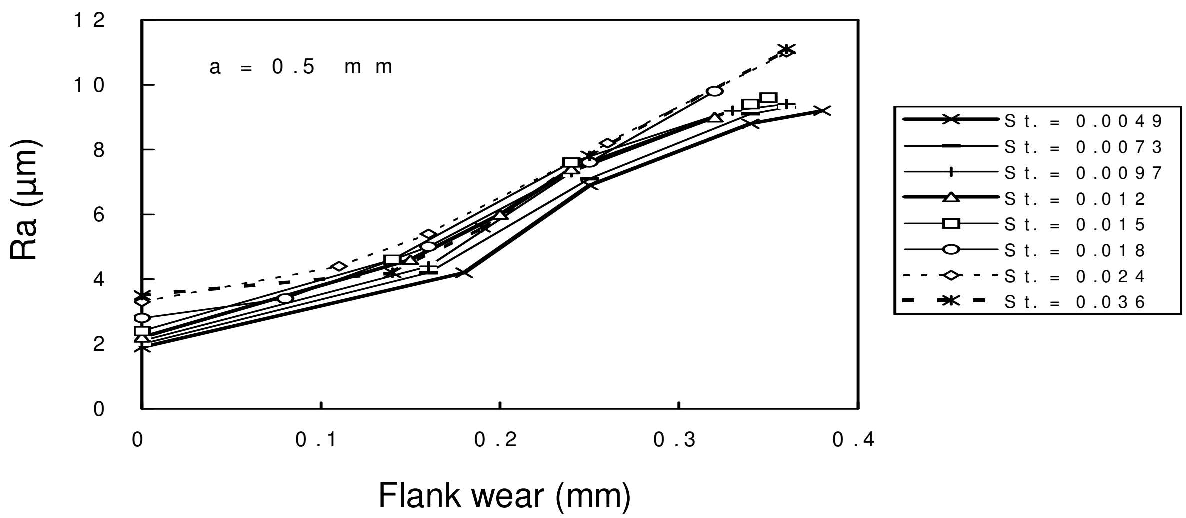
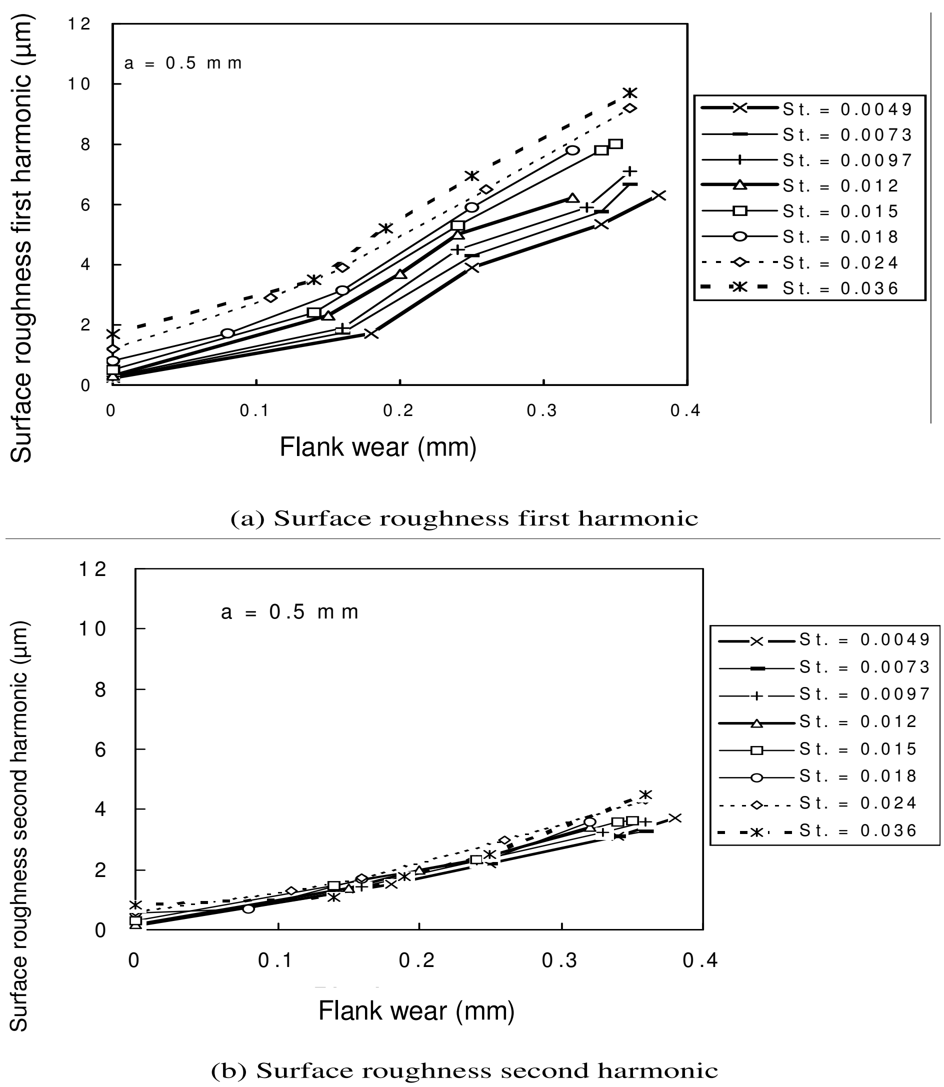
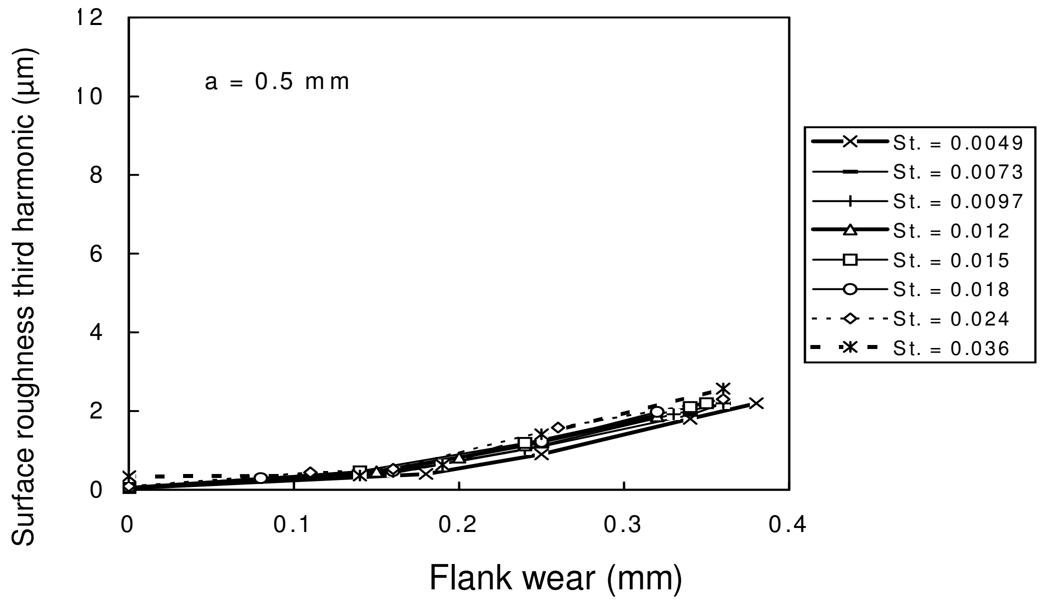


Figure 8. The effects of the tool wear change on the mean line average of the surface roughness (Ra).





C = Surface roughness third harmonic

Figure 9. The effects of the tool wear change on the surface roughness harmonics.

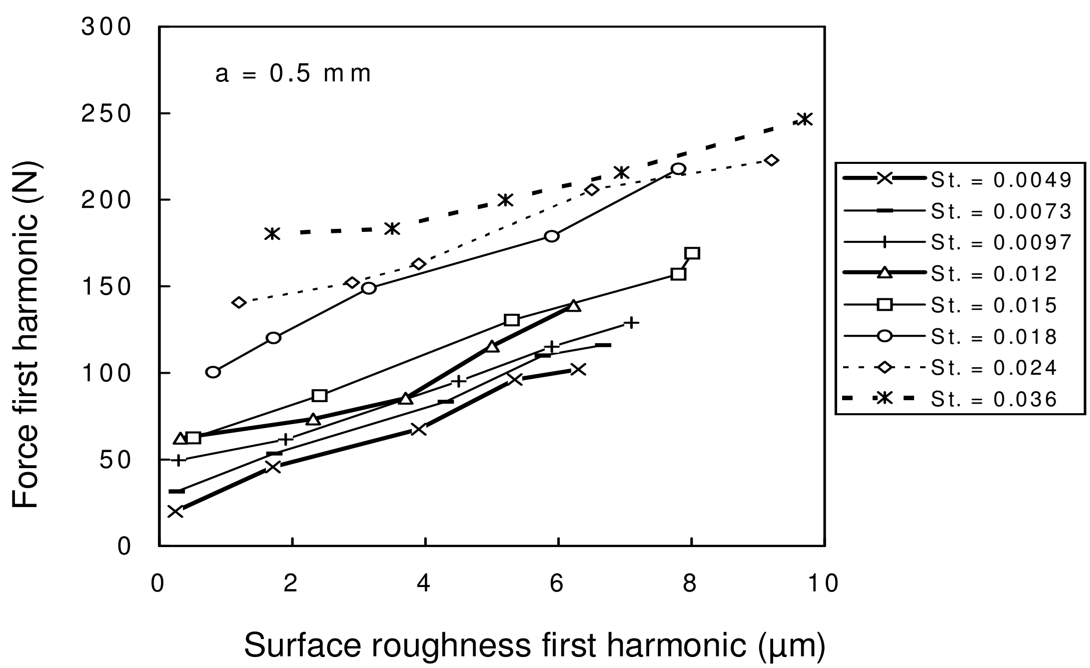


Figure 10. The relation between the cutting force first harmonic and the surface roughness first harmonic.

roughness (Ra). The latter may have same value for different surface roughness texture profiles. On the other hand, the change of the surface roughness second and third harmonics with different cutting condition and tool flank wear are found small compared with the change of the surface roughness first harmonic. Consequently, the surface roughness first harmonic is selected to be used as an indicator parameter to predict the surface roughness.

Figure 10 shows the relation between the cutting force first harmonic and the surface roughness first harmonic. As shown in Figure 10, the cutting force first harmonic is significantly sensitive to the change of the surface roughness first harmonic. However, it is found that, the

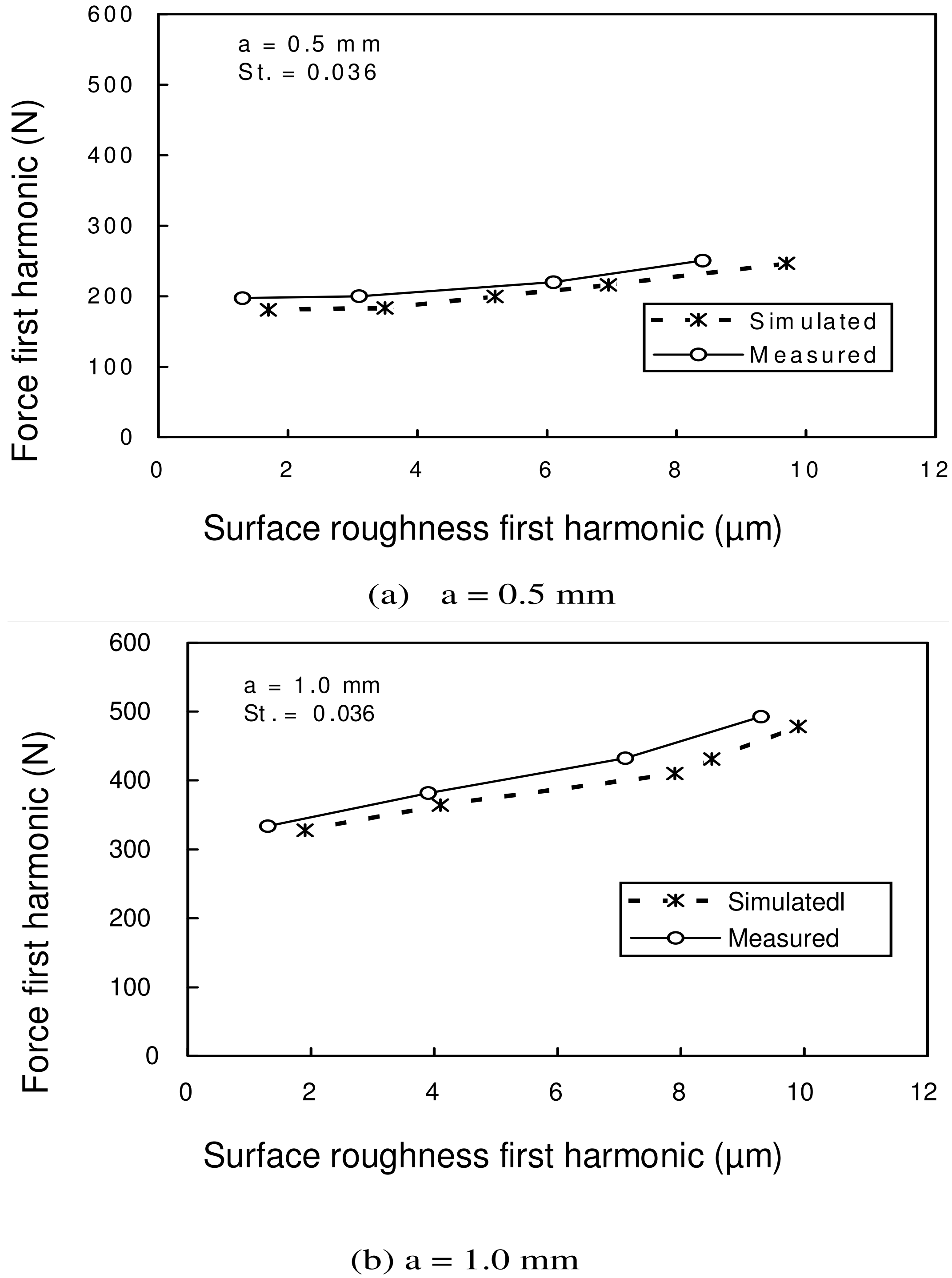


Figure 11. Comparison of simulated and measured cutting force at different values of surface roughness.

second and third force harmonics indicates slight correlation. By applying Least-squares method, a force based model simulation to predict surface roughness in end milling is established using the relation between the cutting force first harmonic and the surface roughness first harmonic.

VALIDATION OF THE MONITORING PERFORMANCE

In this paper, cutting tests are carried out to validate the monitoring performance of the force based model simulation system used in analysis and discussion of the surface roughness results.

We use the same cutting conditions as shown in Table 1. Figure 11 shows a comparison of simulated and measured cutting force at different values of surface roughness. It is found that the maximum deviation between the simulated and measured cutting force is less than 9.6%.

Conclusions

This paper studied the development of sensing system for tools wear monitoring along with the prediction of the work surface roughness. This system utilized the cutting force signals to predict tool flank wear and workpiece surface roughness in end milling.

Firstly, the estimation method of cutting force is presented and then the estimated cutting force is compared with the measured one in each cut. Estimation errors (measured minus estimated cutting forces at same harmonic) are calculated and the maximum estimated error is found to be less than 27 N that corresponding to about 8% of the measured force.

Secondly, to examine the effect of tool wear variation on the magnitude of the cutting force harmonics, flank tool wear is experimentally measured in an off-line manner and the relationships of cutting force harmonics and tool wear magnitude are constructed at different cutting conditions and found to be comparable with the computer simulation results.

Finally, the cutting force signal harmonics is used to predict surface roughness of the workpiece machined in end milling. Then a force based model simulation to predict surface roughness in end milling is proposed. Cutting tests are carried out to validate the monitoring performance of the force based model simulation. By comparing the simulated and measured cutting force at different values of surface roughness, the maximum deviation is found to be less than 9.6%. It is implies that the proposed force based model simulation for monitoring of tool flank wear and surface roughness in end milling is an applicable method.

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