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In-Process Evaluation of Surface Characteristics in Machining

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Abstract—This paper reported research results to develop an algorithm of on-lin evaluation of surface profiles and roughness generated by turning. The developed module consisted of computer simulation of surface profiles using mechanism of cutting mark formation and cutting vibrations, and on-line measurement of cutting vibrations. The relative cutting vibrations between tool and worpkiece were measured through an inductance pickup at the rate of one sample per rotation of the workpiece. The sampling process was monitored using an encoder to avoid conceling out the phase lag between waves. The digital cutting signals from the Analog-to-Digital converter were transferred to the simulation module of surface profile where the surface profiles were generated. The developed algorithm or surface generation in a hard turning was analyzed through computer simulations to consider the stochastic and dynamic nature of cutting process. Cutting tests were performed using AISI 304 Stainless Steel and carbide inserts in practical range of cutting conditions. Experimental results showed good correlation between the surface profiles and roughness obtained using the developed algorithm and the surface texture measured using a surface profilometer. The research provided the feasibility to monitor surface characteristics during tribological tests considering wear effect on surface texture in machining.

1. Introduction

For the automation and mass production in the labor-intensive machining operation, automated production techniques to sense surface finish or damage during the process are needed to be utilized in operation. These devices can be also applied to the tribological experiments for the on-line measurements of wear and surface finish. In-process measurements of quality index without stopping the tests will provide more reliable and consistent data. One of the crucial element of the quality indice is surface roughness. it is necessary to develop a robust and accurate in-process sensor suitable for monitoring a proudct's surface finish to successfully realize full automation in manufacturing.

Surface inspection has been conducted typically as a post-proess operation, which is both time consuming and uneconomical since a number of nonconforming parts can be produced prior to inspections. Although protable instruments have been used to inspect a workpiece without altering the setup, the machine still must be stopped and the tools cleared before any measureements can be taken, a situation which is not conductive to adaptive control and full automation.

In some studies, roughness has been measured directly with a stylus to obtain the surface profile. Thus, a stylus can be used for in-process measurement [1] although use of a stylus results in destruction of the sensor head due to high surface speeds of the workpiece. Tracing has also been accomplished by using a vibratory stylus [2]. However, since the workpiece rotates at relatively high speeds in turning operations, in-process measurements should be taken with non-contact transducers. Usage of an optical instrument has alson been reported for in-process measurement [3,4]. However, optical reflection has been restricted to measurements of relatively smooth surfaces generated by lapping, grinding and other fine machining, and is not applicable for use on the production floor.

Another means of in-process measurement is the use of inductance pick-up [5]. This electromagnetic method relies on the principle that flux linkages vary depending on the length of the air gap between the sensor and the workpiece. Zhao and Webster used a contact type inductance sensor to develop a roughness module to be used in measuring roughness in real time during grinding operations [6]. Although inductance sensors have been studied on a machined workpiece installed in a lathe [5], the measurements were not performed during the machining process because the environmental conditions in the machining center create error in directly measuring surface roughness.

Rather than direct measurement of roughness, indirect estimation of surface roughness using the relative vibration signals between tool and workpiece generated during the turning process has been proposed. [2,7,8]. machining process factors (including machine tool flexibility and workpiece properties) have been shown to cause variations in cutting forces, which eventually generate relative vibration between the tool and the workpiece [7,8]. The relative vibrations were superimposed to generate actual roughness in a proper way using the algorithm by Jang et al [9]. Using the developed algorithm, this research will show how to evaluate surface profiles generated by turning.

2. Algorithm of In-Process Evaluation of Surface Profiles

Machined surface is generated by relative motions between tool and workpiece during machining operation. Under ideal cutting condition, that is, without vibration and any influence of physical factors in the cutting process, the surface profile is formed by the repetition of the tool tip profile at intervals of feed per revolution. In actural truning operation, the surface generation interacts in a complex manner, depending on workpiece properties, cutting conditions, tool vibration and metal shearing during the chip formation [7,8]. Since structures of machine tools are non-rigid and workpiece surface is non-homogeneous, random resistance against cutting causes a stick-slip process between the chip and the tool, and chip breaking, etc. This stick-slip process causes relative vibration between tool and workpiece. Vibration reflects the dynamic reponse of the machine tool structures under cutting forces and in turn affects the surface of workpiece. Due to vibration, the profile of workpiece surface is not merely depending on the kinematic geometry of tool and workpiece, but becoms complex because of the repeated cutting by the tool's cutting minor cutting edge [10].

To begin with simplest case, we consider a single point tool which a nose radius equal to r. Suppose a cylinder is turned under the ideal conditions. that is, without vibration and any influence of physical factors in the cutting process Then, a perfect surface will be formed. The locus of the tool tip relative to the workpiece is a helical surface whose pitch is equal to the feed rate f, as shown in Fig. 1.

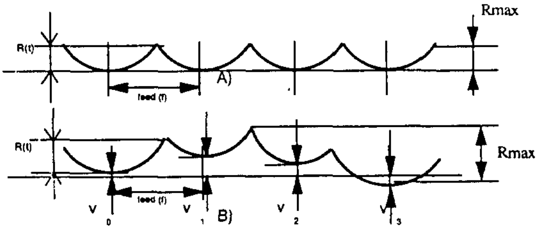


Fig. 1. Vibration effect on surface generation (A) ideal surface without vibration, (B) surface profile with vibrations.

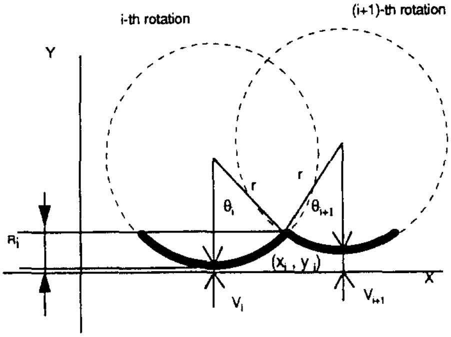


Fig. 2. Surface generation mechanism.

Assume the cutting vibrational signals can be recorded at regular time intervals such as v_1, $v_2(t+T)$, $v_3(t+2T), \cdots v_i(t+(i-1)T)$, where T is the time needed for one revolution of the workpiece. As shown in Fig. 1, surface profiles will be changed due to the relative vibrations. When the nose radius of the cutting tool and relative vibrations in the radial direction of the workpiece are assumed to be responsible for the finished surface geometry, two cross circles, of which radii are equal to r can be imagined to form surface geometry, two cross circles, of which radii are equal to r can be imagined to form surface as shown in Fig. 1. The actual surface profile can be defined by solving two circles' cross points. The equation of surface profile of the i-th rotation can be expressed by:

$$x_i(t, x) = r \cos \theta_i - f \cdot i \tag{1}$$

$$y_i(t, x) = r \sin \theta_i + v_i(t+(i-1)T) \quad (2)$$

Where θ_i is between two adjacent cusps, i is the number of revolution, $x_i(t, x)$ is only a function of the numbder of revolution, and $y_i(t, x)$ is a time function and sampled with sampling period T=60/n (T is the time needed for one revolution of the work-piece). From the idea of the repeated cutting, the crossing points (x_i, y_i)between i-th and (i+1)-th subsequent tool movements will be changed due to the vibrations, v_i and v_{i+1}.

In order to find out the value of θ_i, we need to solve the cross points first. We can define (x_i, y_i) by solving equations of two circles. let (x_c, y_c) is the center coordinate of i-th circle (revolution) and (x_c+f, y_c') is the cendter coordinate of (i+1)-th circle, y_c depends on v_i (t+iT) and y_c' does on $v_{i+1}(t+(i+1)T)$. The equations of two circles can be expressed by:

$$(x_i-x_c)^2 + (y_i-y_c)^2 = r^2 \quad (3)$$

$$[x_i-(x_c+f)]^2 + (y_i-y_c')^2 = r^2 \quad (4)$$

By solving Eqs. (3) and (4), y_i and x_i can be obtained as shown in Eq. (5).

$$y_i = \frac{-(\frac{C_1C_2}{f} - 2C_2 - 2y_c) - \sqrt{\frac{C_1C_2}{f} - 2C_2 - 2y_c)^2 - 4(C_2^2+1)(\frac{C_1}{4f^2} - \frac{C_1}{f}x_c + x_c^2 + y_c^2 - r^2)}}{2(C_2^2+1)} \quad (5)$$

$$x_i = C_2 \left[\frac{-(\frac{C_1C_2}{f} - 2C_2 - 2y_c) - \sqrt{\frac{C_1C_2}{f} - 2C_2 - 2y_c)^2 - 4(C_2^2+1)(\frac{C_1}{4f^2} - \frac{C_1}{f}x_c + x_c^2 + y_c^2 - r^2)}}{2(C_2^2+1)} \right] - \frac{C_1}{2f}$$

where $C_1 = 2x_c f + f^2 - y_c^2 - y_c'^2$, and $C_2 = -\frac{(y_c'-y_c)}{f}$.

Using (x_i, y_i) and (x_c, y_c), angle θ_i can also be obtained as follows;

$$\theta_i = \tan^{-1}(\frac{x_i - x_c}{y_i - y_c}) \quad (6)$$

Through the computer simulation developed based on this proposed algorithm, the actual surface profiles can be simulated using meaasured cutting vibrational signals.

If the number of repeated cutting is m, then the equation of the surface proface profile can be expressed as follows;

$$y(t,x) = \mathrm{MIN}[y_i(t,x), y_{i+1}(t,x) \ldots\ldots, y_{i+m-1}(t,x)] \quad (7)$$

Eq. (7) means that y(t, x) at time t equals the minimum of $y_0(t, x)$, $y_1(t, x)$,.....$y_i(t, x)$,.... In other words the radial position of any point on the cylindrical surface depends on the minimum of the vibration displacements in all revolutions of work-piece as the tool cutting edge passes through this point. Taking t and x as parameters, $y_0(t, x)$, $y_1(t, x)$,......., and $y_i(t, x)$ form a discrete series $\{y_i(t, x), i= 0, 1, 2, \ldots\ldots$ if there exists a minimum positive integer m satisfying following relations.

$$V_i \le r - \sqrt{r^2 - (\frac{mf}{2})^2} \quad (8)$$

$$m \ge \frac{2}{f}\sqrt{r^2 - (r - V_i)^2} \quad (9)$$

The amplitudes of peak-to-valley R^{max}_i can be calculated in the following way:

$$R^{max}_i = \{Y(t,x)\}_{max} - \{Y(t,x)\}_{min} \quad (10)$$

If random vibration was found during cutting operation, surface routghness would become random and has a normal distribution. However, there are more factors which we may need to consider for surface generation process such as build-up edge effect at lower cutting speeds and the tool wear effect at higher cutting speeds. All the factors will make the surface profile more random.

3. Experimental Setup and Cutting Test

An experimental apparatus to measure cutting vibrations was installed in a lathe. The controlling programs of the developed algorithm including data acquisition were written in C language and stored in a 486-computer. As shown in Fig. 3, an Electro-Mike inductiance-type displacement sensor (model 4943 sensors with a PA12D43 converter) was attached to a point immediately adjacent to the cutting tool to detect the relative movement between tool and workpiece during cutting operations. The input power was 12 V dc at 10 mA, and the linear range of sensing was varied between 0.254 mm (0.01 inch) and 2.54 mm (0.10 inch) for a steel target. The nominal gauge factor was 0.25 mm/mV and the linear deviation of sensing was±0.75%. The sensing point was the smooth spot of a workpiece surface, which was prepared through pre-machining. The vibrational signals were represented by the fluctuations of electrical signals from the sensor and were transferred into digital values by an Analog-to-Digital (A/D) board.

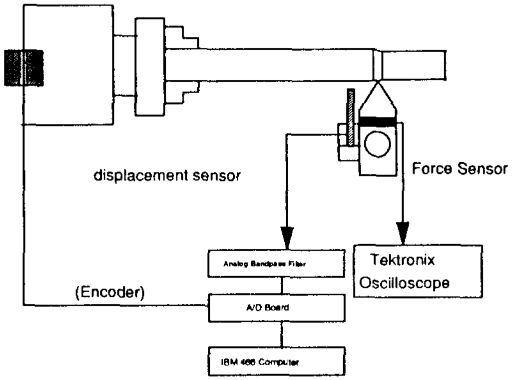


Fig. 3. Experimental setup.

Using a Data Tehnology, Inc. DT25 mechanical encoder, a fixed site was sampled during each rotation for the across-the-lay roughness. Before A/D conversion, the analog signals were filtered using an

Table 1. Cutting conditions for the experiment and experimental results

Cutting conditions	Depth of cut(mm)	Speed (rpm)	Feed rate (mm/rev)	Simulated $R^{max}\pm\sigma$	$R^{max}\pm\sigma$ (measured)
1	0.127	210	0.08	5.6±0.24	6.6±0.33
2	0.127	210	0.13	9.4±1.12	7.6±0.75
3	0.127	210	0.2	13.8±0.58	11.1±0.27
4	0.127	370	0.08	5.2±0.84	7.2±0.68
5	0.127	370	0.13	6.9±.022	8.6±0.93
6	0.127	370	0.2	13.3±0.55	10.9±0.58
7	0.127	700	0.08	4.8±0.74	9.1±0.59
8	0.127	700	0.13	9.2±1.31	9.4±0.53
9	0.127	700	0.2	13.1±0.67	11.9±0.37
10	0.191	210	0.08	5.7±1.07	12.0±1.42
11	0.191	210	0.13	7.6±0.59	12.2±1.67
12	0.191	210	0.2	19.2±0.84	13.4±0.73
13	0.191	370	0.08	6.3±1.05	9.5±0.31
14	0.191	370	0.13	7.9±1.33	11.0±1.65
15	0.191	370	0.2	13.1±1.54	14.2±1.27
16	0.191	700	0.08	6.0±0.74	6.5±1.01
17	0.191	700	0.13	9.2±1.30	8.2±0.87
18	0.191	700	0.2	3.8±1.71	8.2±0.95
19	0.254	210	0.08	5.5±0.95	6.5±0.46
20	0.254	210	0.13	12.8±1.63	7.8±0.28
21	0.254	210	0.2	13.7±1.06	12.0±0.78
22	0.254	370	0.08	6.6±1.08	6.7±0.34
23	0.254	370	0.13	9.0±1.15	8.8±0.36
24	0.254	370	0.2	14.8±1.23	11.3±0.59
25	0.254	700	0.08	5.4±0.52	5.5±0.81
26	0.254	700	0.13	7.1±0.71	6.7±0.27
27	0.254	700	0.2	10.9±0.90	12.2±0.25

Note: σ=standard deviation
all units are μm
Simulated R^{max} is obtained using the developed algorithm

analog highpass filter with cutoff frequency at 1 Hz to eliminate effects on the vibrational signals caused by static deflection and waviness or out-of-roundness of the component. The gap between the sensor and the workpiece was adjusted at the beginning of the cutting operation in order to keep the measured signals from the inductance pick-up within the linear sensing range. The voltage from the inductance pickup was set at about 5 volts. While most of chips were broken away from the cutting edge due to chip breaker, the gap was cleaned using pressurized air in order to avoid and errors caused by loose metal particles (such as chips getting into the gap between the pick-up and surface). A Mitutoyo surface profilometer was used to measure actual R^{max}. This profilometer and its stand were mounted on the tool carriage of a lathe so that roughness could be measured without removing the specimen from the chuck. The surface profilometer was connected to a printer as well as a recorder to record values of roughness as well as the surface profiles of machined specimens.

Dry cutting tests (wither using cutting fluid) were conducted to obtain undistorted cutting vibrations. A mechanical chip breaker (Valenite NCGD4050) was used in the tests. Cutting operations were monitored to avoid chatter using a Tektronix oscilloscope to display cutting force signals from the tool dynamometer.

For the cutting test, AISI 304 Austenite stainless steel workpieces (with a 5.1 cm diameter and 51 cm length) and carbide tool insert (with tool edge radius of 0.794 mm) were used. Each workpiece was premachined for a smooth surface at 0.025 mm (0. 001 inch) depth of cut, 0.08 mm/rev (0.0033 inch/rev) feed rate, and 700 rpm rotational speed. The surface routhness of the premachined workpieces was about 1.5 μm. Since the inductance pickup measured the workpiece vibrational signals from cutting.

All the cutting conditions are summarized in Table1. British units of cutting conditions were used in the cutting tests and they were converted into the S.I. units given in Table 1. To avoid burning effect in machining, low speed and depth of cut were used.

Digital values of the relative vibrations between the tool and the workpiece were transferred directly to the computer during the cutting operations to plot surface profiles in real time according to the developed algorithm. In order to trace the across-the-lay roughness along the workpiece and to avoid canceling out the phase lag between wave forms, the DT25 mechanical encoder was used to sample one data per rotation of the workpiece, the sampling was triggered by the digital signals from the encoder generated at a fixed angular position of rotation.

Actual R^{max} values and surface profiles were measured using a Mitutoyo surface profilometer. The surface profilometer was set for a 0.76 mm cutoff length. During the cutting tests, no chatter was identified. However, relative vibrations were present between the tool and workpiece due to the structural flexibility of a machine tool, an effect caused by the random effects of the machining process different from chatter.

4. Experimental Results and Discussion

Test results are summarized in Table 1 including cutting coditions. 27 different cutting tests have been conducted. Five measurements using the surface profilometer and five in-process evaluations according to the developed algorithm were performed for each cutting condition. The average R^{max}s with their standard deviations from in-process evaluations including actual R^{max} measured using the Mytutoyo surface profilometer are given in Table 1. For example, when cutting conditions were set at 210 rpm, a 0.127 mm depth of cut, and a 0.2 mm feed rate, the average R^{max} from in-process evaluation using the developed algorithm was about 13.8 μm and the R^{max} from measurement was 11.1 μm. As the feed

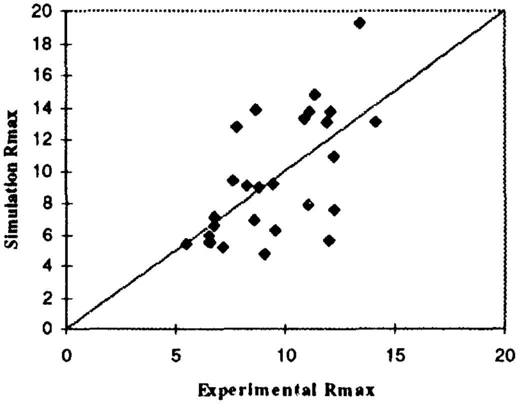
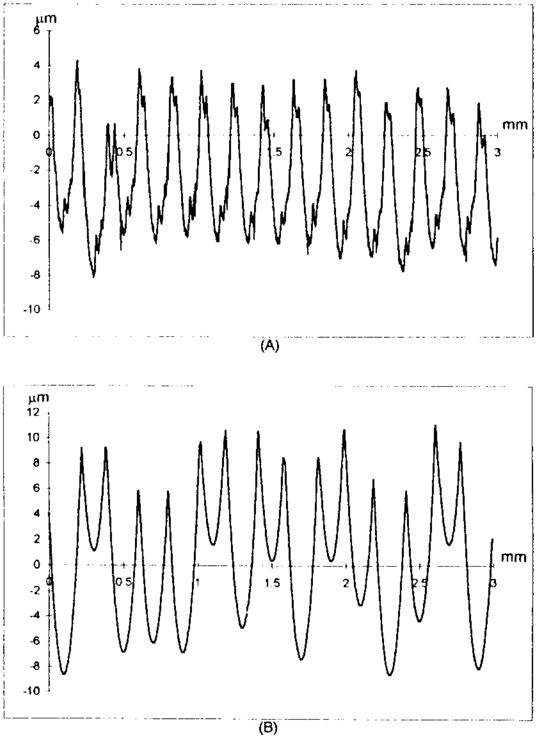


Fig. 4. Correlation between two sets of R^{max}.

rate increased from 0.08 mm to 0.2 mm, R^{max} measured using the surface profilometer increased from 6.6 μm to 11.1 μm for 0.127 mm depth of cut. the general trends showed that for the same depth of cut and feed rate, the roughness decreased as the speed increased. The R^{max}s from in-process evaluations showed the variations similar to R^{max}s measured using the surface profilometer. However, roughness from in-process evaluations were generally lower that those from actual measurements for the low feed rate (0.08 mm/rev). Fig. 4 showed the correlation between two sets of roughness. This might be caused by the vibrations of tool holder in the cutting direction, which caused the displacement probe to sense lower amplitudes of relative vibrations in the radial direction.

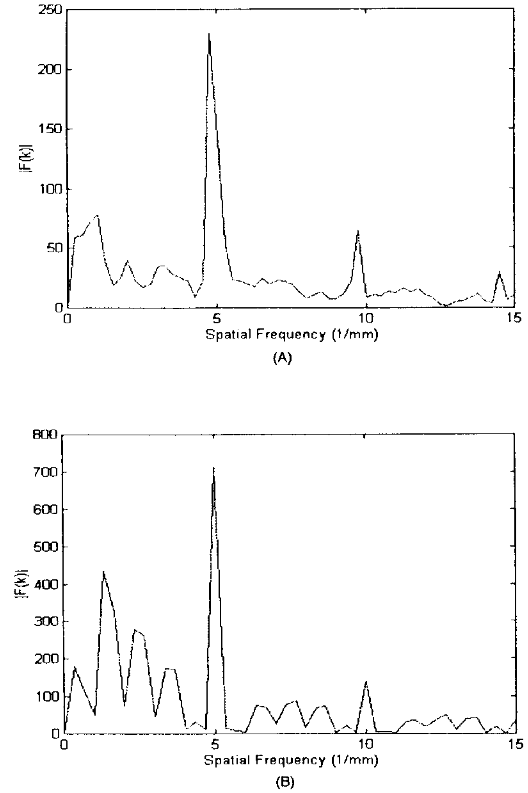
Surface profiles and their spatial freequency spectrums from measurements using the Mytutoyo surface profilometer and in-process evaluation were shown in Figs. 5 to 10. Those figures showed similar lower frequency components in the profiles. When the feed rate was 0.2 mm/rev, feed marks close to 5 cycles/mm were expected in the profile due the geometry of the cutting (Figs. 5, 7, and 9). Although the feed marks at 5 cycles/mm was evident in Figs. 6, 8, and 10, surface profiles from actual measurements showed the variation in the surface profiles due to more than just feed marks. Such frequencies arose because of chip segmentation, work microstructure, etc. from a different mechanism than the one that produces the feed frequency [8,10,11]. However, when the feed rate was lower than tool nose radius, feed marks from in-process evaluation is lower than that from the surface profilometer. The errors were considered to be caused by the graphical difficulty when the tool nose radius in much bigger than the feed rate. Since the nose radius of the tool used in the experiments was 0.794 mm and the feed rate was 0.08



(A)

(B)

Fig. 5. Surface profile at feed=2 mm/rev, speed=210 rpm, depth of cut=127 mm (A) from measurement using surface profilometer (B) from in-process evaluation.



(A)

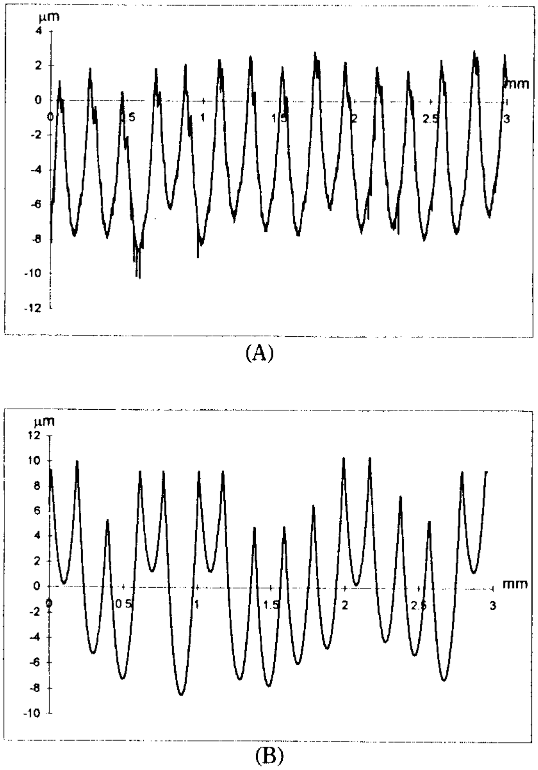
(B)

Fig. 6. Spatial frequency at feed=2 mm/rev, speed=210 rpm, depth of cut=127 mm (A) from measurement using surface profilometer (B) from in-process evaluation.

mm/rev, the high peaks of cutting vibrations might be covered by the overlaid shapes of tool edges in plotting of the subsequent cuttings. This effect might cause the R^{max} from in-process evaluations lower than those from measurements using the surface profilometer when the feed rate was 0.08 mm/rev. Although there were some exceptions, Table 1 showed this trend when the ratios of feed rate to tool nose radius were relatively low.

From the spectrum analysis done by Jang et al [9] and Sata et al [2], the roughness profiles of the machined components have specific frequency components of surface fluctuations. Whithout any unstable vibrations (chatter) during machining operations, the topography of a truned surface is largely governed by the tool geometry, tool/workpiece vibratory motion, the translatory montion of the tool (feed), and the rotary motion of the workipece during machining [8,10,11]. The characteristics of relative vibrations depended on the cutting conditions and the natural vibrational modes of the spindle-workpiece system. The structural vibrations of a machine tool determine the frequency components of the across-the-lay surface profiles [10]. When a specific machine tool and workpiece are selected, the cutting conditions determin the cutting forces which vibrate the machine tool [7,8]. Cutting vibrations are random and have a high spectrum intensity at a specific frequency of the machine tool structure even if there is no chatter during cutting operations.

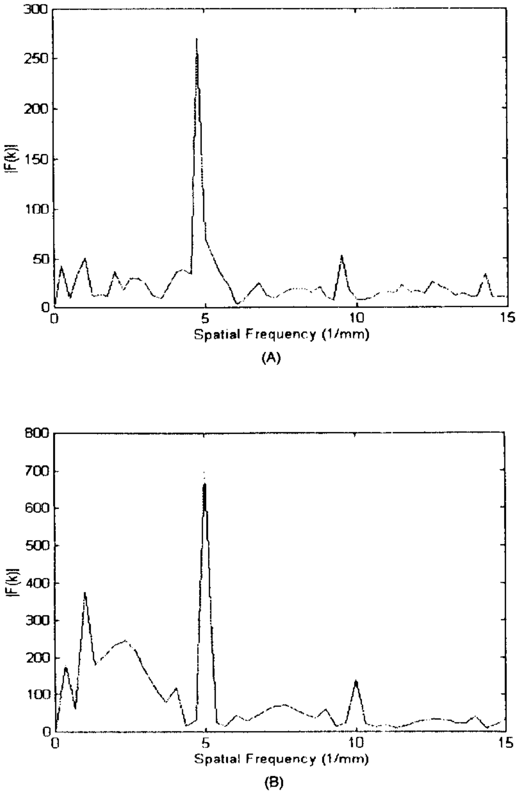
The present research was concentrated ion designing an in-process measuring technique of surface roughness in the across-the-lay direction of the machined surface. This research will be continued to develop on-line processing technique to plot three dimensional shapes of machined component considering tool wear. This present method requires an



(A)

(B)

Fig. 7. Surface profile at feed=2 mm/rev, speed=370 rpm, depth of cut=127 mm (A) from measurement using surface profilometer (B) from in-process evaluation.



(A)

(B)

Fig. 8. Spatial frequency at feed=2 mm/rev, speed= 370 rpm, depth of cut=127 mm (A) from measurement using surface profilometer (B) from in-process evaluation.

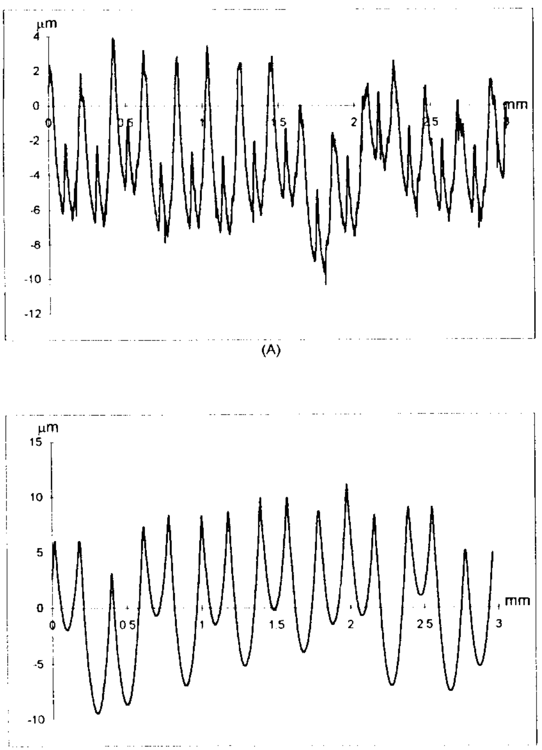


Fig. 9. Surface profile at feed=2 mm/rev, speed=700 rpm, depth of cut=127 mm (A) from measurement using surface profilometer (B) from in-process evaluation.

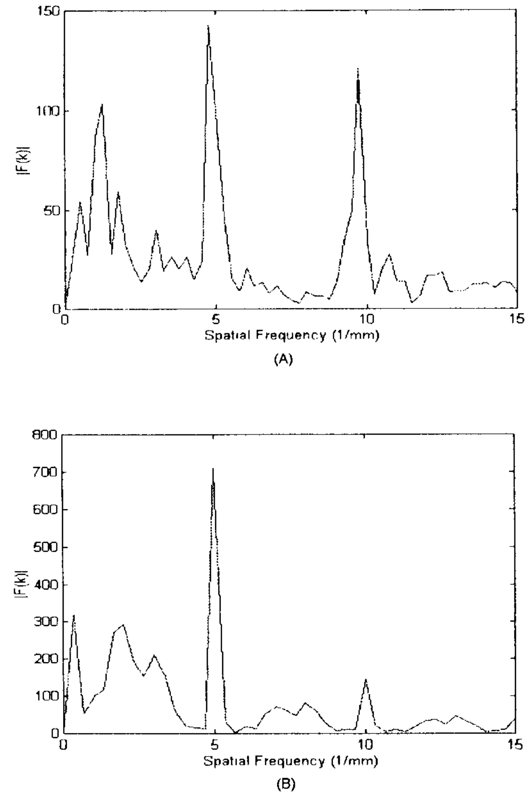


Fig. 10. Spatial frequency at feed=2 mm/rev, speed= 700 rpm, depth of cut=127 mm (A) from measurement using surface profilometer (B) from in-process evalution.

inductance pickup next to the cutting tool and a pressurized air line to avoid chips from obstructing the sensing area. The inductance pickup can be replaced by an accelerometer with a double integration for the more realistic situation of a harsh environment and small space such as those found in a Computer Numerically Controlled (CNC) machining center. This method can be also utilized to develop an automated production techniques in the labor-intensive machining such as ceramic machining for the automation and mass production. These devices can be also applied to the tribological experiments for the on-line measurements of wear and surface finish.

5. Conclusions

As a way of in-process evaluation of machined surface, a method to determin surface profiles and R^{max} during a turning process was proposed and cutting tests using an inductance pickup and a computer for data analysis were performed. Experimental results showed that the surface roughness along the workpiece without chatter were generally determined by the feed marks. Through superimposing the cutting vibrations to kinematic roughness values in a proper way, the surface profiles can be evaluated during cutting operation without interrupting the machine operation. A limitation of this technique is that the displacement pickup could be only used on ferrous materials. Further research will be needed to avert this problem and additional work is needed to investigate the possibillity of applying this method to cutting conditions with a lubricant.

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