통합절삭 시뮬레이션 시스템용 선삭표면조도 시뮬레이션 알고리즘의 설계

Design of an Algorithm to Simulate Surface Roughness in a Turning for an Integrated Machining Simulation System

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Abstract

The fundamental issues to evaluate machine tools performance through simulation pertain to the physical models of the machine tool itself and of process while the practical problems are related to the development of the modular software structure. It allows the composition of arbitrary machine/process models along with the development of programs to evaluate each state of machining process. Surface roughness is one of the fundamental factors to evaluate machining process and performance of machine tool, but it is not easy to evaluate surface roughness due to its tribological complexity. This paper presents an algorithm to calculate surface roughness considering cutting geometry, cutting parameters, and contact dynamics of cutting between tool and workpiece as well as tool wear in turning process. This proposed algorithm could be used in the designed virtual machining system. The system can be used to evaluate the surface integrity of a turned surface during the design and process planning phase for the design for manufacturability analysis of the concurrent engineering.

Key Words : Computer Simulation, Surface Roughness, Machining, Tool Wear

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1. INTRODUCTION

Due to the increasing demand for the better quality and a great variety of products, manufacturing engineers are facing with a difficult problem of increasing productivity without compromising quality. In machining processes, surface characteristics of machined parts have been recognized as important factors of the quality control in production. Fine finished surface not only provides customer satisfaction for product appearance, but also assures the functionality and reliability of the product. One of the important quality factors to evaluate surface finish is surface roughness, which plays an important role in all areas of tribology. Relative motions between cutting tool and workpiece surface generate surface roughness during machining operation [1-3].

Landis [4] generated the surface profile based on feed rate and the radius of a round nosed tool. Perfect cutting tool condition (no tool wear) was assumed in the simulation. In his model, the surface profile was simply a function of feed rate and tool radius. Fathailal [5] illustrated the surface profile considered the wear in the nose and minor flank of cutting tool. Due to the wear effect, he concluded that the tool nose was like egg shape instead of perfect round shape. Solaja [6] predicted the surface profile of the workpiece by assuming uniform flank wear on the cutting zone and a single notch formed at the end of cutting edge. In his research, the surface roughness could be obtained from the feed rate, original tool nose radius, and the size of the wear. All three models did not consider the effect of induced relative cutting vibration.

Under ideal cutting conditions, the surface profile of a turned workpiece is formed by the repetition of the cutting tool tip geometry at intervals of the feed. However, it is well known that actual surface profiles contain components arising due to sources other than the process geometry. For example, the induced relative cutting vibration (the relative displacement between cutting tool tip and workpiece surface) will disrupt this ideal pattern. According to Jang [1,8], this relative cutting vibration will actually generate the surface profile based on the tool geometry during machining process. To develop an adequate surface texture prediction model, the model must incorporate the effects of the cutting process and its dynamics on the surface.

Tool wear is another important factor, which needs to be considered in the surface formation process. In the metal cutting process, the relative motion between cutting tool and workpiece surface is strongly affected by tool wear and the surface roughness will be changed [2,9,10]. Tool wear, once formed, not only changes the shape of the tool tip, but also increases the relative cutting vibrations between cutting tool and workpiece surface. In general, the combined effects of the tool tip shape change due to wear and the increase of the relative cutting vibration cause the surface roughness to increase. This paper presents algorithms that can be applied to simulation of surface generation in turning process. The algorithms can be utilized to develop computer simulation and on-line monitoring technique of turning operation.

2. SURFACE GENERATION MODEL WITHOUT TOOL WEAR

Relative motions between tool and workpiece generate a machined surface during machining operation. Basically, the tool geometry and the feed rate determine the surface profile along the axial direction of the workpiece. Under ideal cutting condition, that is, without vibration or 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 that case, the surface profile of the machined surface should only be a function of the geometry of the tool and the manner in which the tool is fed across the surface.

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. Cutting parameters (*i.e.*, speed, depth of cut and feed rate, chip loads and chip formations, dynamic characteristics of the tool-spindle structure, and non-homogeneous hardness distribution in the workpiece) are generally considered to be major factors affecting this random relative vibration between the tool and workpiece [1,8]. This cutting vibration reflects the dynamic response of the machine tool structures under cutting forces and in turn affects the surface of workpiece. Therefore, it is significant to analyze the cutting surface formation with vibration together. Due to vibration, the profile of workpiece surface is not merely depending on tool's geometry and the relative motions between tool and workpiece but becomes complex because of the repeated cutting by the tool's minor cutting edge [11]. Fig. 1 below shows the ideal surface profile without any vibration affects and the surface profile with cutting vibration effects.

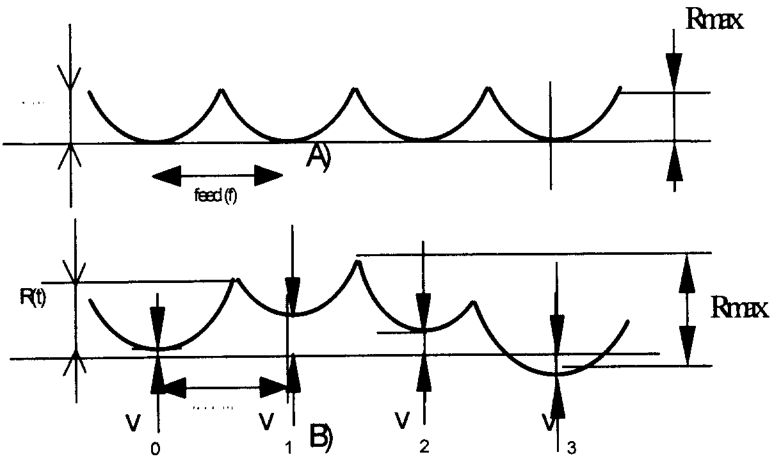


Fig. 1 Vibration effect on surface generation

A) Ideal surface without vibration
B) Surface profile with vibrations

As we can see in Fig. 1, the vibrations, expressed by V_i, are considered as random signals due to the dynamic responses of turning process. In addition, the adjacent two vibrations can be considered to have a time period, T, equal to the time needed for one revolution in the turning process. Under vibrations, the surface profile is different from the ideal case. The surface roughness is also increased depending on the significance of the random vibration.

Based on the mechanism of the formation of cutting marks, we can derive mathematical expressions for the surface profiles of axial sections of the workpiece. In order to build a mathematical model for the turning process, first we must consider a cylinder turned by a single point tool which has a nose radius equal to r. The cutting vibration signals can be recorded at regular time intervals such as $v_1(t)$, $v_2(t+T)$, $v_3(t+2T)$, ... $v_i(t+(i-1)T)$, where T is the time needed for one revolution of the workpiece, assuming only the nose radius of the tool generates the new surface. Therefore, the nose radius of the cutting tool and relative vibrations in the radial direction of the workpiece are considered to be responsible for the finished surface geometry. Fig. 2 shows us the surface generation mechanism in i-th and (i+1)-th revolutions. As we can see, we can image two cross circles, which have radii equal to r, to form surface and the actual surface profile can be defined by solving two circles' cross points.

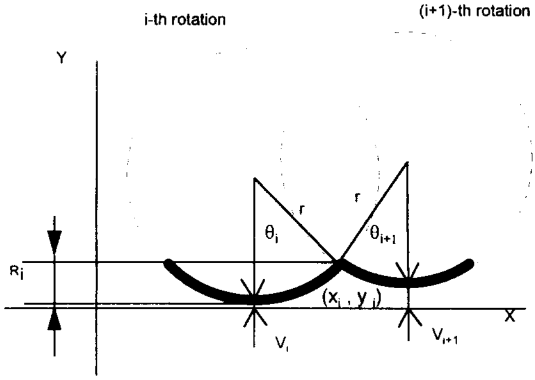


Fig. 2 Surface generation mechanism

The equation of the surface profile of the i-th rotation can be expressed by:

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

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

where θ_i is the half angle between the two adjacent crossing points, i is the number of the revolution, $x_i(t, x)$ is only a function of the number of the revolution, and $y_i(t, x)$ is a time function and is sampled with sampling period $T = 60/n$ (T is the time needed for one revolution of the workpiece). In order to find out the value of θ_i, we need to solve the cross points first. Assume (x_i, y_i) is the cross point in i-th and $(i+1)$-th revolution. We can define (x_i, y_i) by solving the equations of the two circles. Let (x_c, y_c) be the center coordinate of i-th circle (revolution) and $(x_c + f, y_c')$ is the center coordinate of $(i+1)$-th circle. Where y_c is depending on vibration $v_i(t+iT)$ and y_c' are depending on vibration $v_{i+1}(t+(i+1)T)$. Through the computer simulation, we can simulate the surface profile during the cutting process.

3. SURFACE GENERATION MODEL WITH TOOL WEAR

It is well know that the surface roughness is influenced significantly by tool wear. Among the well-known types of tool wear, flank wear and crater wear are often considered as the wear types which lead to tool failure first. However, minor flank wear (nose wear) and notch at the minor cutting edge are recognized as being more important in determining the tool life because of their greater influence on the dimensional accuracy and surface quality of the finished product. In order to understand the interrelationships between tool wear progression and shape changes of the cutting tool, the tool wear must be expressed by using a mathematical function considering tribological factors such as friction, cutting heat, material properties and geometry of workpiece and tool, and lubricant. Based on the interrelationships between tool wear and shape changes of the cutting tool, the surface texture can be generated.

As shown in Fig. 3, flank wear can be broken up into three regions. They are major flank wear which develops on the flank of the main cutting edge over the length that equals to the chip width, nose flank wear which develops on the flank of the tool tip, and minor flank wear which develops on the minor cutting edge.

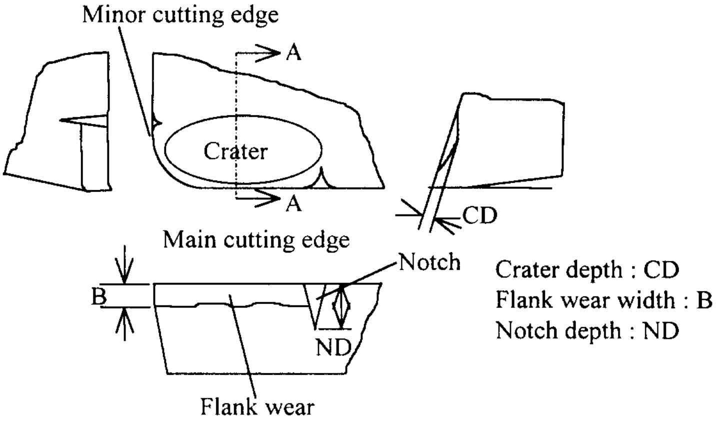


Fig. 3 Tool wear features

Flank wear is considered as the A.S.A standard measures for the determination of tool life. In fact, increasing flank wear will cause reducing the cutting tool tip radius. Crater wear is another major type wear. Usually, crater wear does not affect the change of tool shape, unless it grows too big and the tool breakage occurs. Notch is formed in a very complicate way and may not show clear in all cutting processes.

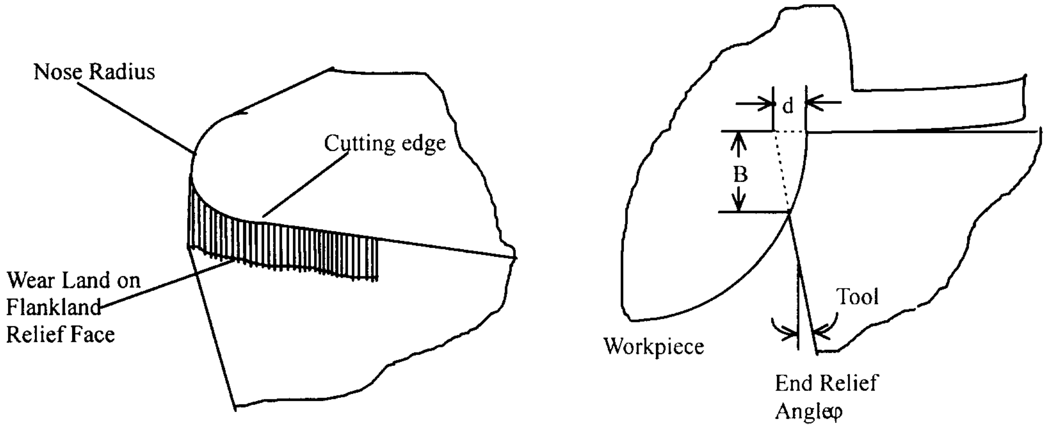


Fig. 4 Geometry of tool wear

Assuming flank wear is formed along the contact area and the wear land has a uniform width at a particular instant, the initial tool nose radius r_0 decreases to r and the peak-to-valley surface roughness will increase. The relationship between the flank wear width and the radius change can be defined from the cutting tool geometry. The flank wear, which has a width of B, will actually reduce the tool nose radius by the amount of d. Based on the tool tip geometry, d can be expressed as follows,

$$d = B \tan\varphi + R - \sqrt{R^2 - B^2} \qquad (3)$$

where R is the radius of workpiece.

Notch is another major type of wear. It has been found that when a very soft metal such as iron ingot is cut by using a tungsten carbide tool, notches is frequently formed at the free edge of the chip. These notches do not generally shorten tool life or lead to tool breakage when cutting such soft metals. Machining harder steels do not tend to form notches. However, when machining superalloys and refractory metal, notch formation is extremely fast and often determines tool life. Quantitative index of notch measurement is the notch depth. Solaja [6] established a model for a sharp notch formed in the trailing edge, as shown in Fig. 5. Based on his experimental results, he also concluded that the flank wear width was about 75 % of notch depth. According to the geometry in Fig. 5, the peak-to-valley surface roughness for a worn tool with one notch on the trailing edge can be given as follows:

$$h_{\max} = (B_1 - B)\tan(\gamma) + (B_1^2 - B^2)/D + (f - 0.065 B_1 r_0 / f)^2 / 8(r_0 - B\tan(\gamma)) \quad (4)$$

where B is flank wear width, B_1 is notch depth that is 4/3 B, γ is clearance angle, and D is the diameter of workpiece.

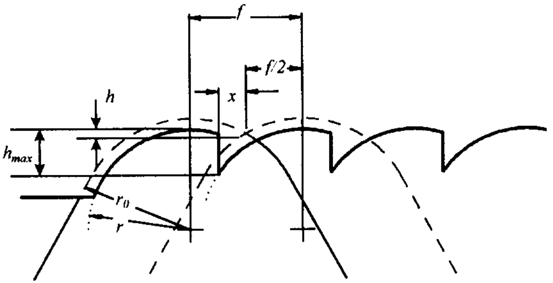


Fig. 5 Ideal case of rounded tool subject to a single notch on the trailing edge and concentrated wear

In stead of using sharp notch, notch may have round shape as shown in Fig. 6.

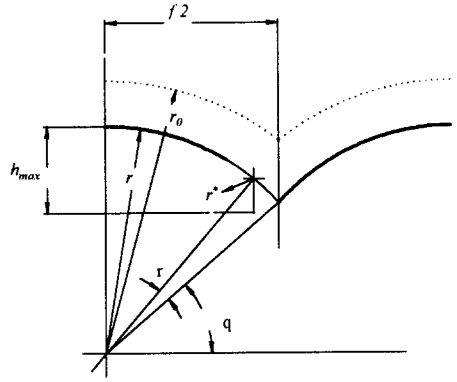


Fig. 6 Ideal case of rounded tool subject to a single round shape notch

The peak-to-valley roughness h_{max} is simply the maximum roughness and can be defined as follows:

$$h_{max} = r - r\cos(\theta + \rho) + r^* \qquad (5)$$

where r is worn tool radius, θ is the angle of the two cusp intersection point, ρ is the small angle between notch center and infersection point and can be found as follows:

$$\rho = \tan^{-1}(r^*/r) \qquad (6)$$

Finally, r^* is the notch radius and can be defined from tool geometry:

$$r^* = B_l \tan\gamma \qquad (7)$$

where B_l is notch depth and γ is the side clearance angle.

Considered a single sharp notch formed on the trailing edge with cutting vibration effect. Due to the vibration effect, the cross point of two adjacent cusps is no longer the same. The notch is tended to be formed at the location where contacts with the chip edge occur most frequently. Once the notch initiated, it will propagate due to the effect of stress concentration around the notch. Fig. 7 illustrates the workpiece surface profile caused by a single round shape notch on the trailing edge and concentrated flank wear under vibration effect.

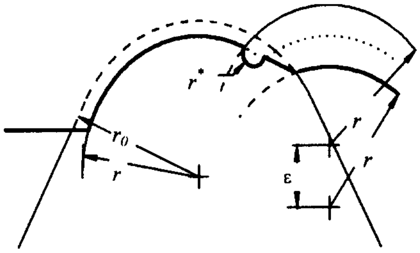


Fig. 7 Vibration effect on rounded tool subject to a single round shape notch on the trailing edge and concentrated wear

4. RESULTS AND DISCUSSIONS

In order to verify the effectiveness of the proposed models and to simulate the surface profile under the tool wear situation, computer program was designed according to the proposed algorithm. 0.4 mm was assumed for the tool radius and 0.15 mm/rev for the feed rate in the simulation. Two tool wear conditions with different amplitudes were applied to show the correlation between tool wear and surface roughness. Fig. 8 shows the ideal surface profile (no vibration effect) subjected to flank wear with 6 μm width and a single notch on trailing edge with 8 μm depth as well as perfect surface profile. Similarly, Fig. 9 shows the surface profile subjected to flank wear with 9 μm width and a single notch on trailing edge with 12 μm depth.

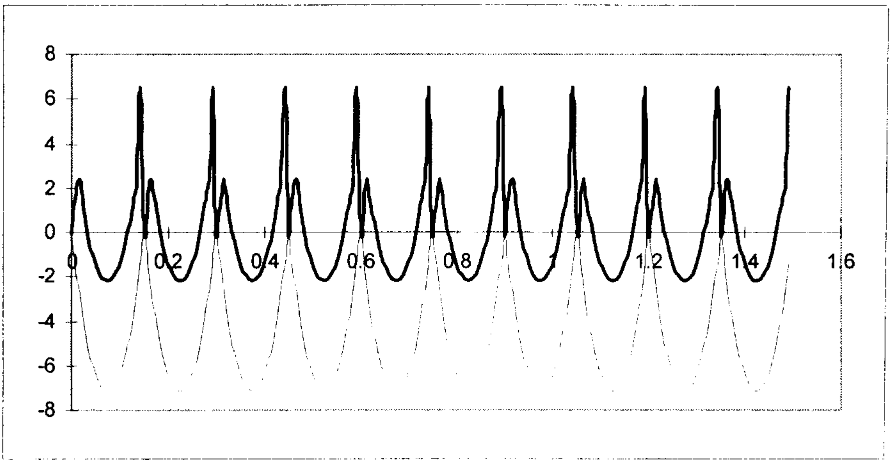


Fig. 8 Surface Profile Under Flank Wear = 6 μm, Notch = 8 μm

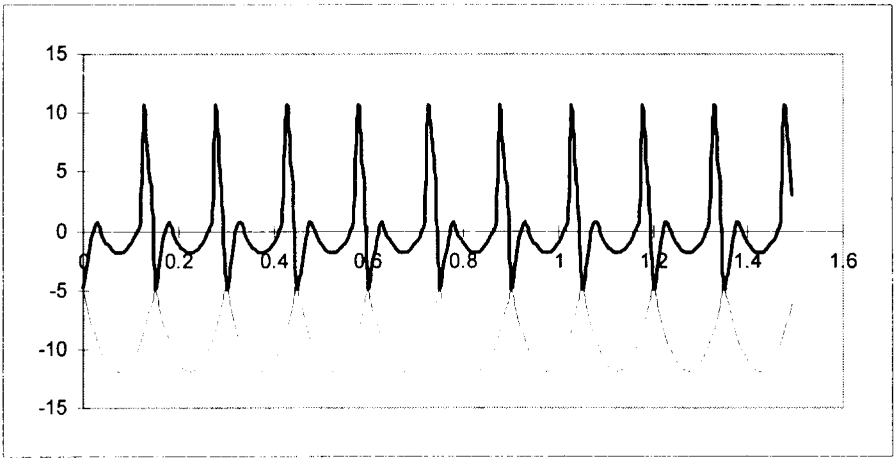


Fig. 9 Surface Profile Under Flank Wear = 9 μm, Notch = 12 μm

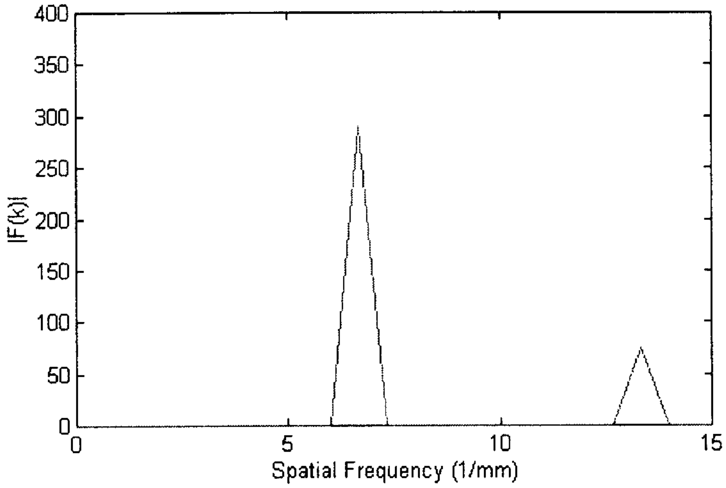
The light line is the surface profile without tool wear and the bolt line is the profile affected by the tool wear. The tool was assumed to move from left to right. It has been observed that the peak-to-valley surface roughness was increased from 7.18 μm to 8.71 μm for the first case as well as from 11.85 μm to 15.29 μm for the second case. It was clear that tool wear caused increase of the surface roughness. In order to understand tool wear effects on the surface finish clearly, the spatial frequency analysis was also applied to surface profiles formed using new tool and worn tool. The spatial frequency is defined as the number of cycles per unit length (mm) as follows:

$$\textit{Spatial Frequency} = \frac{\text{Time Frequency}}{2f_{nyq}f}$$

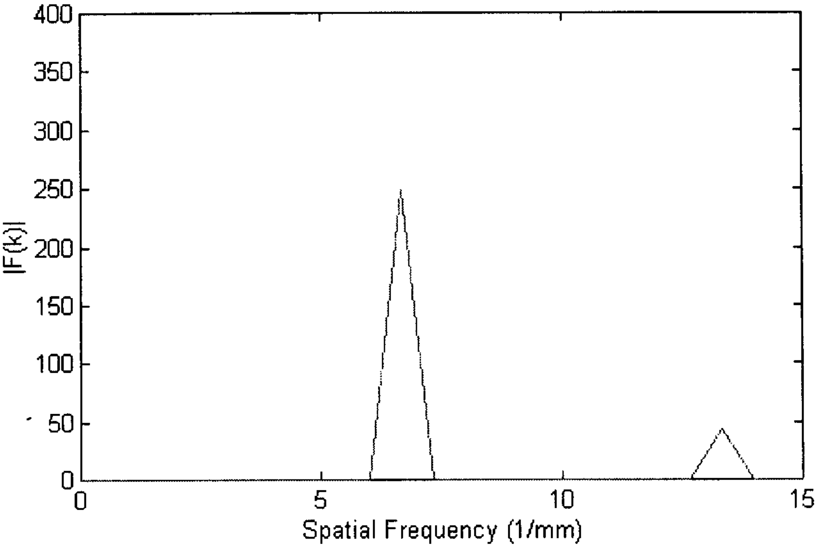
$$\text{where } f_{nyq} \text{ is Nyquist frequency } = \frac{\text{sampling frequency}}{2} \tag{8}$$

$$f \text{ is feed rate}$$

Sampling frequency is equal to number of samples per second, equal to the lathe spindle speed. The spatial frequency response for the tool with and without wear are shown in Figs. 10 and 11.

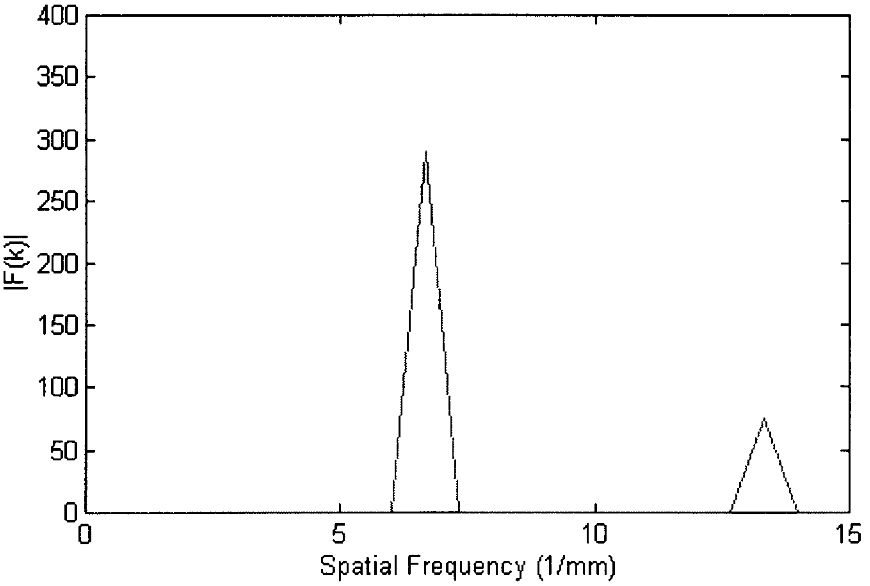


(a) without tool wear

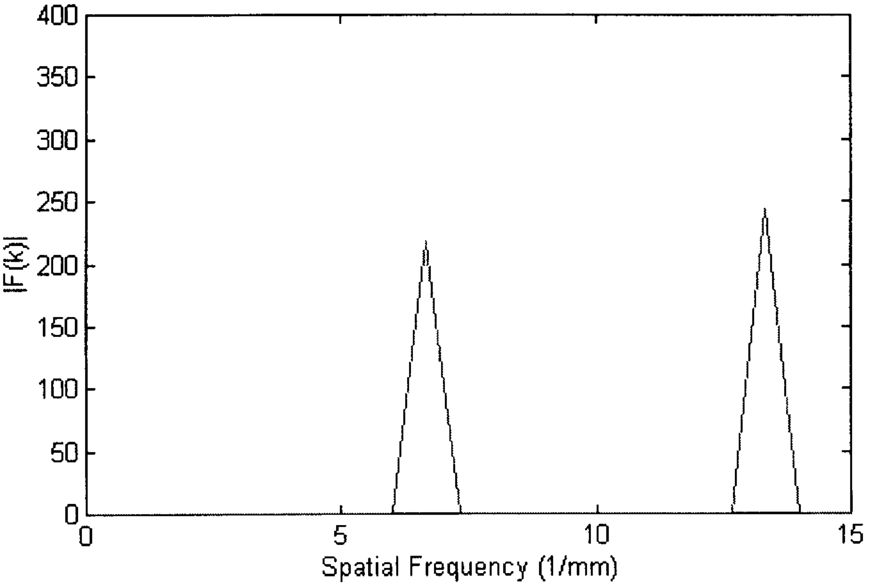


(b) with flank wear = 6 μm, notch = 8 μm

Fig. 10 Spatial Frequency Response of Fig. 8



(a) without tool wear



(b) with flank wear = 9 μm, notch = 12 μm

Fig. 11 Spatial Frequency Response for Fig. 9

In order to see the vibration effect on surface generation, the vibration was considered in the computer simulation. Fig. 12 shows the surface profile subjected to random vibration with amplitude of 5 μm and flank wear with 6 μm width and a single notch on trailing edge with 8 μm. Fig. 13 shows the surface profile subjected to random vibration with amplitude of 5 μm and flank wear with 9 μm width and a single notch on trailing edge with 12 μm.

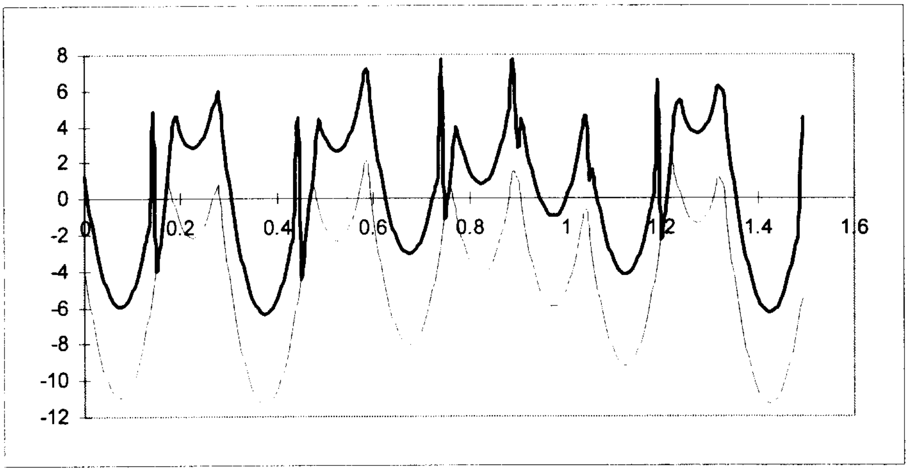


Fig. 12 Surface Profile Under Flank Wear = 6 μm, Notch = 8 μm With Vibration Effect

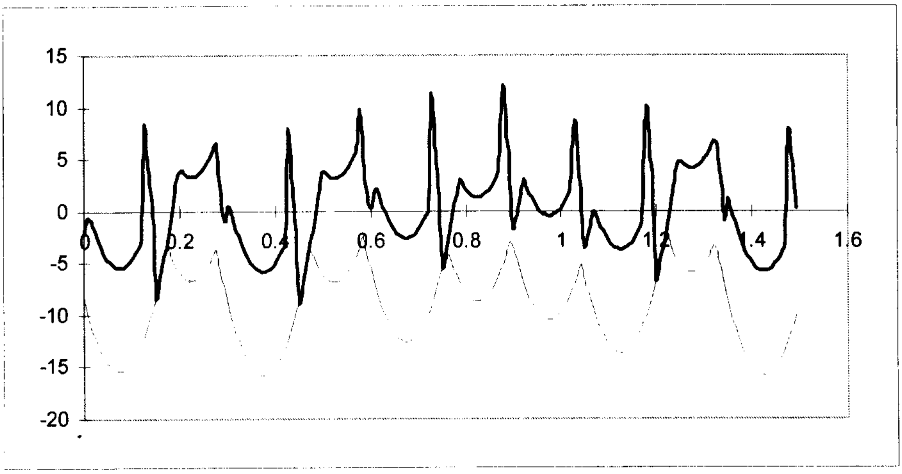
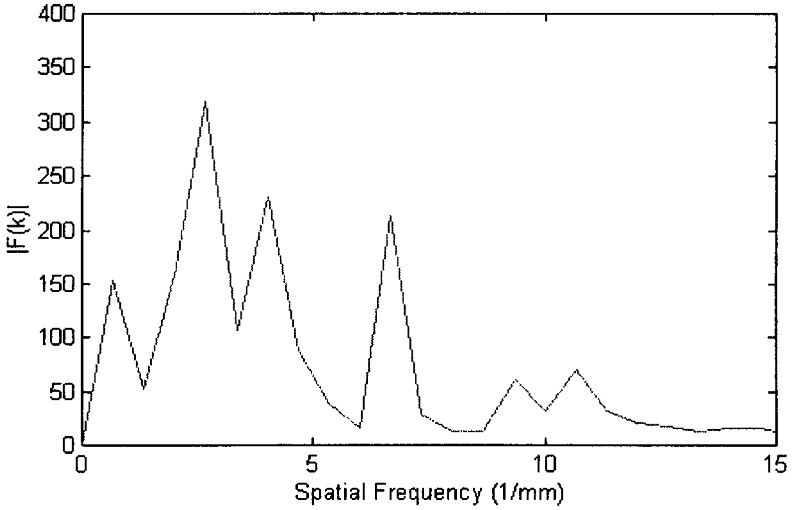


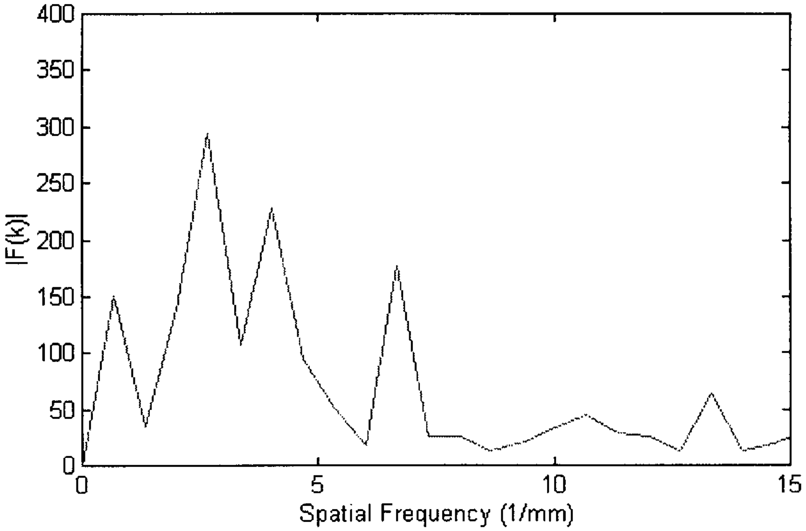
Fig. 13 Surface Profile Under Flank Wear = 9 μm, Notch = 12 μm With Vibration Effect

As a result, the surface roughness was increased from 13.5 μm to 14.1 μm for the first case and from 15.85 μm to 20.65 μm for the second case.

The spatial frequency response for Figs. 12 and 13 are given in Figs. 14 and 15.

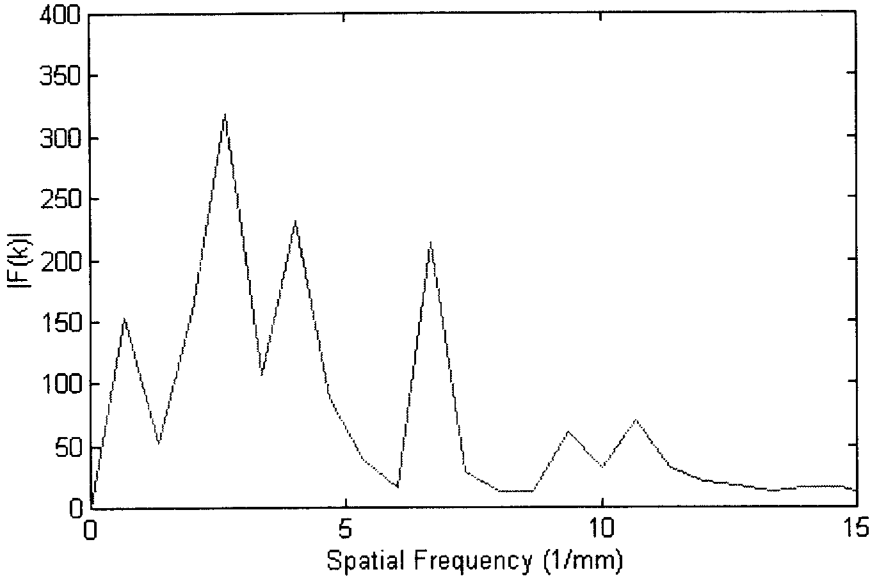


(a) without tool wear

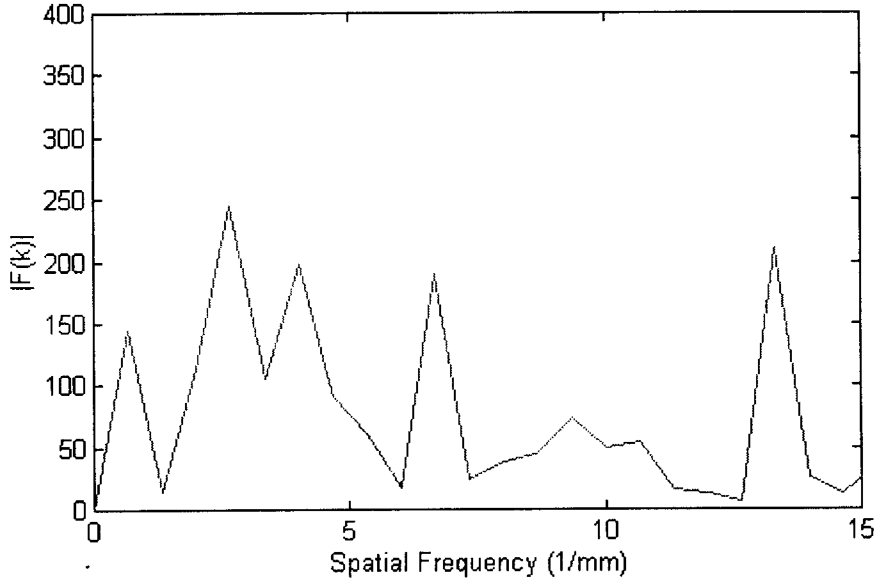


(b) with flank wear = 6 μm, notch = 8 μm

Fig. 14 Spatial Frequency Response for Fig. 12



(a) without tool wear



(b) with flank wear = 9 μm, notch = 12 μm

Fig. 15 Spatial Frequency Response for Fig. 13

Compared with the cases without vibration, the vibration actually raised the surface roughness and tool wear also raised the surface roughness. Under bigger tool wear, the surface profile becomes different from the original shapes of surface roughness because the arc shape of tool edge is changed sue to the notch. Therefore, the smaller feed rate may not provide the better surface finish because the notch causes to deteriorate the arc shape that makes the surface finish worse.

5. CONCLUSIONS

Algorithm for the design of computer simulation program to predict surface finish in a turning was developed. The algorithm considered tool geometry, cutting mechanism, and tool wear. Since the relative cutting vibration and tool wear are the most important factors to cause the surface roughness variations, the algorithm considered these factors in surface roughness generation. Tool wear and its effect on variation of tool tip profile were considered in the formulation. The surface profiles varied due to tool wear could be generated by superposition tool tip profiles and relative vibration signals. This pc-based computer simulation program can display results from each model and be utilized to provide a global understanding of surface generations so that the engineers can make decisions without conducting cutting tests.

6. ACKNOWLEDGEMENT

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