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A Study on the Simulation Model of the Surface Roughness for Turning Process

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Abstract

In this paper, a surface generation model is presented to simulate surface roughness profile in turning operation. The simulation model takes into account the effect of tool geometry, process parameters, rotational errors of spindle, and the relative vibration between the cutting tool and workpiece. The surface roughness profiles are simulated based on the surface-shaping system. The model has been verified by comparing the experimental values with the simulation values. It is shown that the surface simulation model can properly predict the surface roughness profile.

Key words: Surface roughness, Surface-shaping system, Process parameter, Rotational error of spindle, Vibration.

1. Introduction

The understanding of the characteristics of the surface generation is crucial in establishing the relationship between surface topography and the functional behavior of the machined surface. The first requirement for the adequate resolution of this issue is the availability of suitable modeling techniques for the prediction of the outcome of surface generation processes.[1]

Recently, many attempts have been made to develope numerical simulation methods for manufacturing processes. A computer model[2] has been developed, which took into account the geometry and the kinematics of the motions of the milling cutter including a superimposed tertiary spindle motion onto the conventional milling process. A methodology to dynamically generate the surface topography was presented under the random excitation environment through computer simulation in boring process.[3] An exploratory attempt was made to study the grinding process with respect to the surface topography and nature of surface interactions in terms of grain distributions and kinematic conditions.[4] A generalized model of surface generation was introduced to provide a general mathematical basis for the prediction of the surface characteristics of metal removal manufacturing processes.[5]

In this paper, surface generation model has been presented by considering the effect of tool geometry, process parameters, rotational error of spindle, and the relative vibration between the cutting tool and workpiece. The surface roughness profiles are simulated based on the surface-shaping system. The results between experiment and simulation have been compared and analyzed.

2. Mechanism of Surface Roughness Generation in Turning Operation

There are many factors which influence the surface roughness of the machined workpieces. Among various factors, the dominant factors are tool geometry, feed rate, rotational errors of the spindle (spindle runouts), machining vibration. Figure 1 shows the mechanism of the surface generation.

2.1 The effect of the tool geometry and feed rate

Under ideal conditions, the surface roughness profile is generated by the repetition of the tool tip profile at intervals of feed per revolution. The surface roughness profile along the feed direction is determined by the tool geometry and the feed rate. It is well known that the theoretical surface roughness is primarily a function of the feed for a given nose radius and varies as the square of the feed, $R_a = 0.0321 f^2 / r$.[6] From the expression, the surface roughness improves with the increase in nose radius of cutting tool. This has been confirmed by many experimental studies. The ideal surface roughness profile is shown as Figure 1. Where f is feed rate and r_ε is nose radius of the cutting tool.

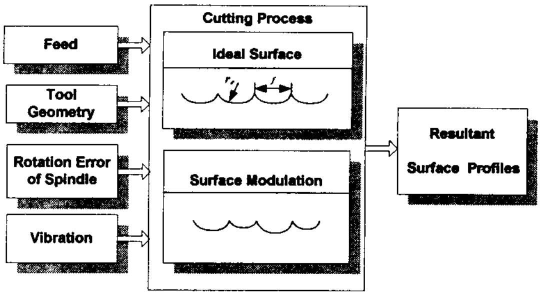


Fig. 1 Mechanism of the surface generation

2.2 The effect of the rotational errors of spindle

The rotational errors of spindle in machine tool can be classified as three kinds, namely, the radial direction error, axial direction error and tilt. These errors arise because of the inaccuracy of the spindle bearings. When there are the spindle rotational errors, which cause a relative displacement between the tool and the workpiece, these errors lead to a modification of the surface roughness profile. Since the radial direction is a sensitive direction of error, the rotational error of spindle, in this paper, is only considered as random radial direction error. The maximum magnitude of the random rotational error is assumed to be 0.005mm.

2.3 The effect of the vibration

In general, the vibration between the cutting tool and the workpiece arises in three directions, namely, radial, axial, tangential direction of the workpiece. However, the vibration in the radial direction is considered in this paper because it has the most important effect on the surface roughness of the machined workpiece. A dynamic system can be modeled as a single degree-of-freedom system as shown Figure 2. The mathematical form of the model is given by

$$m\ddot{x} + c\dot{x} + kx = P_x(t) \qquad (1)$$

where m is equivalent mass of the tool holder, c is damping coefficient, and k is static stiffness. In order to obtain the value of these parameters, experiments were conducted to measure the frequency response of the tool holder. A dynamic signal analyzer (B&K) was used to monitor the performance of the tool holder in the experiment.

The relative motion between the tool and workpiece in the radial direction is assumed to be harmonic motion. The radial force generated by the cutting process can be expressed by a sinusoidal function.

$$P_x(t) = P\sin\omega t \qquad (2)$$

where P is cutting force in the radial direction, which can be found in machining handbook. ω is frequency, which is assumed to be 15 Hz based on analysis of the surface profile.

3. Surface Generation by The Surface-Shaping System for Turning

Surface-shaping system will be used to designate a system model which includes the machine tool's kinematics and the geometry of the cutting tools and workpieces and derives the relationship between the surface-shaping points on the cutting tool and workpieces with the aim to predict the texture of the resulting machined surface.[5] The system includes not only nominal motion between tool and workpieces but also tool runout, spindle rotation error, elastic-plastic deformation, vibration, higher order motion, and complex geometries of the cutting edges. The model of the surface-shaping system can be expressed as follows:

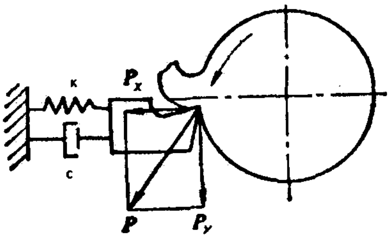


Fig. 2 Dynamic model of turning process

$$r_0 = B_{0,n} B_T e^4 \qquad (3)$$

The model links the coordinates of the surface-shaping points of the tool with the coordinates of the workpiece. Figure 3 shows the traditional turning process with a single-point tool. The radius vector r_0 of the surface-shaping points p_k on the cutting edge *in the reference frame* {S_0} *is derived as* follows:

$$r_0 = B_{0,5} r_5$$

$$= {}^N A^6(\theta)\,{}^N A^1(x)\,{}^N A^2(y)\,{}^N A^3(z)\,{}^E A^1(e_{v_x})\, r_5 \qquad (4)$$

where ${}^{N}A^{6}(\theta)$ represents the nominal rotation of the frame {S₁} about the Z-axis and ${}^{N}A^{1}(x)$, ${}^{N}A^{2}(y)$, and ${}^{N}A^{3}(z)$ are the nominal translations x, y, and z of the different frames in the X, Y, and Z directions with respect to frame {S₀}, respectively. ${}^{E}A^{1}(e_{v_x})$ represents the machining vibration. r_5 is the radius vector of the surface-shaping points of the tool in frame{S₅} which can be written as:

$$r_5 = {}^{N}A^{5}(\psi)\,{}^{N}A^{1}(\rho)\,{}^{N}A^{2}(p_{yk})e^{4} \tag{6}$$

where ${}^{N}A^{5}(\psi)$ is the nominal rotation of the radius vector r_5 about the Y-axis and ${}^{N}A^{1}(\rho)$ and ${}^{N}A^{2}(p_{yk})$ are the nominal translations ρ and p_{yk} of the radius vector r_5 in the direction of the X and Y axes with respect to frame {S₅}, respectively.

4. Simulation and Experimental Results

Based on the surface-shaping system, computer simulation for the surface roughness profiles is carried out using the parameters tabulated in Table 1. Figure 4 shows the methodology to simulate a machined surface. Figure 5 shows the comparison of the results of simulation with Boothroyed's expression. It can be found that these results are very approximative. Figure 6a and 6b show the simulated surface under the ideal conditions and with random radial direction error, respectively. Apparently, the two figures show different surfaces. The average values of the surface roughness, S_a, are 1.6 μm and 2.09 μm, respectively.

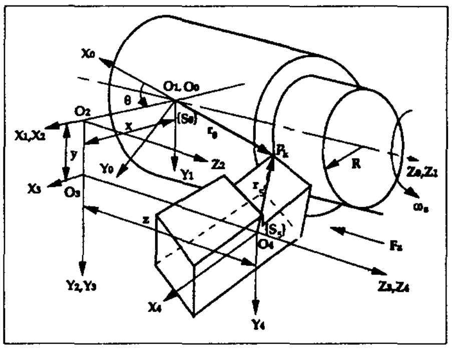


Fig. 3 Surface-shaping system of the turning process

Table 1. Simulation parameters

Spindle Speed (rpm)	500
Feed (mm/rev)	0.2
Depth of Cut (mm)	2
Nose Radius (mm)	0.8
Equivalent Mass of Tool Holder (kg)	0.725
Damping Coefficient (N-s/m)	142
Stiffness (N/m)	2.9×10^{7}
Workpiece Material	SM45

In order to verify the results of the simulation, an experiment was conducted in the lathe. The cutting parameters of the experiment was selected as same as those of the simulation shown in Table 1. Figure 7a and 7b show resultant surface profiles of the simulated and experimental results, respectively. The surface roughness average R_a is 1.89 μm for the simulated surface, and 1.61 μm for the experiment. From the figure, the simulated surface profile is approximatively agreement with the result of the experiment.

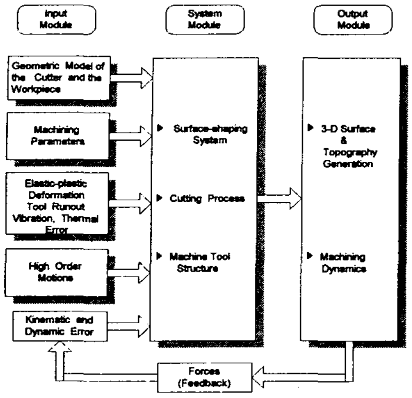


Fig. 4 Methodology to simulate a machined surface

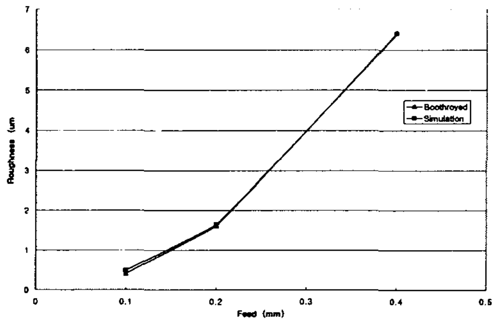
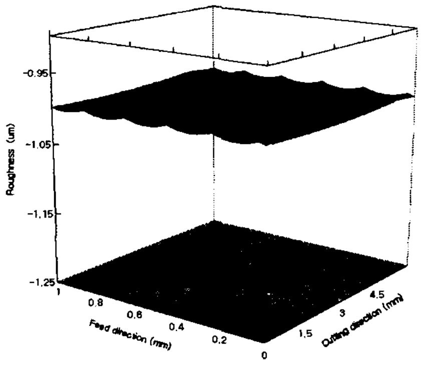
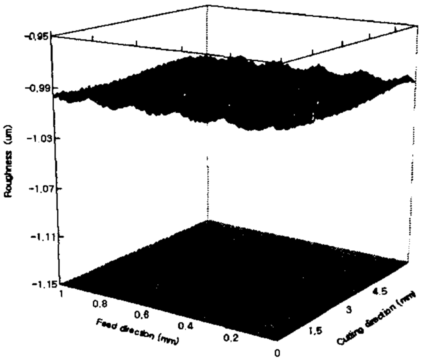


Fig. 5 Comparison of the simulation results with Boothroyed's expression



(a) Ideal surface



(b) With random radial direction error

Fig. 6 Simulated surface based on the surface-shaping system

5. Conclusions

In this paper, a surface generation model is established to simulate the surface roughness profile in turning operation. The model is based on surface-shaping system which takes into account the effects of the tool geometry, cutting parameter, rotational error of spindle, and relative motion between the cutting tool and the workpiece. The following conclusions are made based on this study:

1. Ideal surface roughness profiles dependent on the feed rate and nose radius of the cutting tool.
2. The rotational error of spindle and relative vibration leads to a modification of the surface roughness profile.
3. It is shown that the surface generation model proposed in the paper can properly predict the

surface roughness profile.

4. The surface-shaping system can be applied to predict the surface roughness profile not only in the turning process, but also in other operation, such as milling, grind process.

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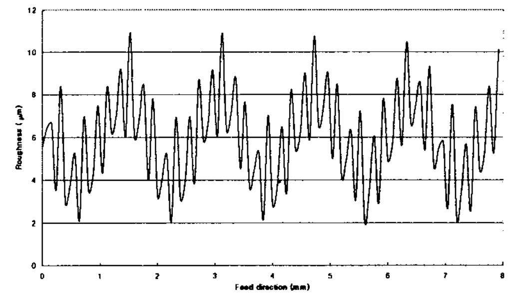
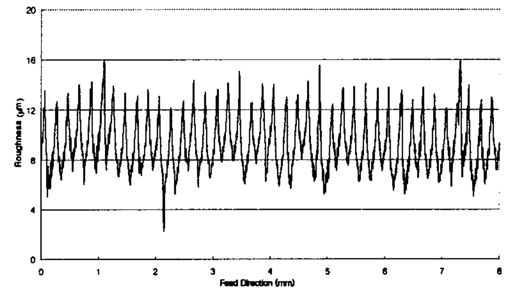


(a) Simulate surface profile



(b) Experimental surface profile

Fig. 7 Comparison of the simulated surface profile with the experiment result