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A Ground Surface Roughness Model Considering Grit and Vibration Variances

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Keywords： grinding, surface roughness, spindle vibration, grit kinematic effect, process variance

ABSTRACT

By combining the kinematic grit and spindle vibration effects, an analytical ground surface roughness model representing their individual effects on the ground surface was developed. In this model, the surface profile is treated as the superposition of variances of the kinematic grit and vibration profiles. By summing the variance of the two profiles, the root-mean-square ground surface roughness can be estimated. The transmitting factor, which defines the amount of power transmitted from spindle vibration to the ground surface, was derived from the dynamic grinding system and is related to the stiffness of the process, namely the workpiece cutting stiffness and wheel contact stiffness. An experimental procedure for identifying the stiffness in the process was also developed. Due to its analytical nature, the model estimates the ground surface roughness as well as allowing for the analysis of the contribution and effects of the grinding conditions, machine vibration and stiffness within the process. Procedures for identifying the process parameters were developed and a series of experiments with varying parameters were performed in order to validate the model. Discussions regarding the grinding conditions for the surface roughness based on experimental and model analysis results are presented. The model predictions and experimental results support the finding that a greater grinding depth and width increases the grinding force and hence deteriorates the ground surface. Furthermore, although a greater feed of the workpiece results in a larger grinding force and spindle vibrations, it also increases the cutting stiffness and thus reduces the transmitting factor of the spindle vibration, diminishing its adverse effects on the ground surface roughness.

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INTRODUCTION

Grinding is usually applied as the final phase in the production of components requiring good surfaces and fine tolerance. Quality of the products which incorporate such components is often directly affected by the ground surface. Industrial experience suggests that the use of finer grit size, lower feed or grinding depth leads to a finer surface. However, a mathematical model for the ground surface may be more useful to analyze the effects of the grinding conditions and machine characteristics, allowing for the determination of appropriate conditions or machinery.

The nature of a ground surface is determined by the relative motion between the engaging grits and the workpiece, as well as the material side flow on the workpiece and the built up edge on the grinding wheel surface. The process is called “clean cutting” when only the relative motion of grits and the workpiece is considered. There are two main effects leading to the relative motion, namely the grit kinematic effect and machine vibration. The kinematic effect is a result of wheel rotation and the feed of the work. Many researchers have concentrated on the grinding kinematic effect and presented predictive methods to estimate the ground surface roughness. Nakayama and Shaw presented an analytical model for the peak to valley roughness of a ground surface with varying active grit densities and radial grinding depths. Without considering the machine vibration, wheel built up edge or material side flow, the predictive result is approximately 70% that obtained from experiments. Other research groups have used the topography of the wheel surface in conjunction with computational methods to establish the ground surface topography and roughness. Due to a lack of analytical capabilities, such methods require grinding conditions to be altered and the entire simulation repeated in order to study their effects. Based on experimental methodology and results, some have developed surface roughness models with empirical constants, but somewhat elaborate experiments are required to obtain the necessary constants for the model.

The above models and methods relating to surface roughness have either not considered or not clarified the effects of grinding vibration. The two main sources of grinding vibration are self-excited chatter and forced vibration. The former is generated by an unstable grinding condition, while the latter arises from forcing sources such as the dynamic grinding force and unbalanced wheel rotation. Although both the effects of kinematic grit and machine vibration in the grinding process have been widely studied, the extent that a certain level of vibration will contribute to the composition of surface roughness has rarely been analytically investigated. To account for this, in this paper the variance analysis of the kinematic grit profile and machine vibration signal is applied in order to establish their combined effects as well as represent their explicit effects on the ground surface. Nakayama and Shaw's model is directly employed in calculating the kinematic surface roughness and as such is not directly derived in the present paper. The effect of machine vibration, specifically the spindle vibration, was found to be related to the cutting stiffness and wheel contact stiffness. To obtain these parameters for every experiment, the procedure required to identify these parameters was also developed. A series of experiments was carried out to validate the model and discussions about the effect of grinding conditions on the surface roughness were made based on the experimental results and analysis of our model.

ROOT MEAN SQUARE SURFACE ROUGHNESS MODEL IN THE LONGITUDINAL DIRECTION

The composition of kinematic grit and machine vibration effects on the ground surface

The ground surface is generated by the relative motion of engaging grits and the work surface due to kinematic grit and vibration effects. The profile of the ground surface along the lay direction, x, is assumed to consist of two profiles, as shown in Fig. 1. The lay profile of a ground surface, $r(x)$, can be expressed as

$$r(x) = k(x) + d_g(x) \tag{1}$$

where k is the ground profile due to the kinematic grit effect and d_g is the vibration profile of engaging grits, created by the combined vibration effect of all engaging grits. The machine vibration is transmitted to the wheel engaging surface, resulting in the vibration of the engaging grit. After a grit leaves the ground surface, the next grit engages the work surface immediately and machine vibration continues to influence this engaging grit. The following engaging grits will have likewise been influenced, showing that machine vibration is continuously transmitted to the vibration profile of engaging grits.

A connection exists between d_g and machine vibration. The wheel contact stiffness k_c, work cutting stiffness k_w, and the wheel wear stiffness k_s, are the dominating parameters between the engaging surface of the wheel and machine dynamics, as shown in Fig. 2. In an ordinary grinding operation, k_s is always larger than the other two parameters by about 2 – 4

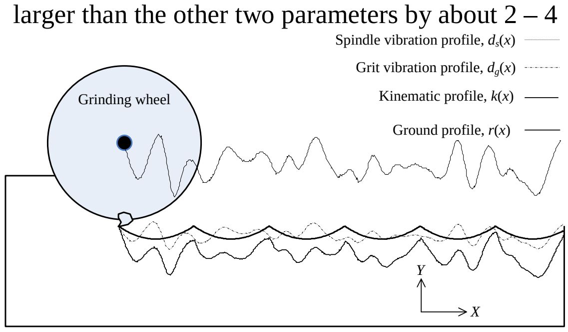

Fig. 1. The combination of ground surface profiles

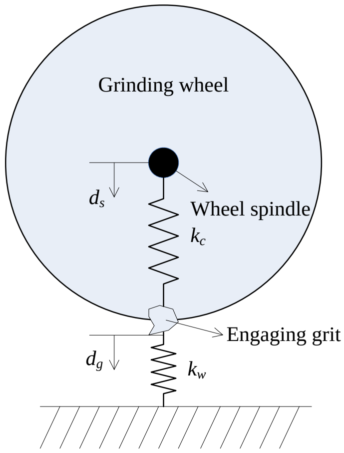

Fig. 2. The grinding process dynamics between the wheel spindle and engaging grit

orders of magnitude. Ignoring the effect of k_s, the relation between d_g and the machine vibration signal, d_s, can be expressed as

$$d_g = \frac{k_c}{k_w + k_c} d_s \tag{2}$$

By substituting equation (2) into (1), the profile of a ground surface in the lay direction can be expressed as

$$r(x) = k(x) + \frac{k_c}{k_w + k_c} d_s(x) \tag{3}$$

The root mean square surface roughness of the ground surface in the lay direction

The root mean square (rms) surface roughness, R_q, is defined as the variance of the surface texture. To calculate the R_q of a ground surface, the variance analysis for (3) can be denoted as

$$R_q{}^2 = E\left[r(x)^2\right] \tag{4}$$

Substituting (4) into (3), the derivation of the rms roughness can be shown as

$$R_q^{\ 2} = E\left[\left(k + \frac{k_c}{k_c + k_w} d_s\right)^2\right]$$

$$= E\left[k^2 + \frac{2k_c}{k_c + k_w} d_s k + \left(\frac{k_c}{k_c + k_w} d_s\right)^2\right]$$

$$= E\left[k^2\right] + \left(\frac{k_c}{k_c + k_w}\right)^2 E\left[d_s^{\ 2}\right] + \frac{2k_c}{k_c + k_w} E\left[d_s k\right]$$

$$= r_k^{\ 2} + \left(\frac{k_c}{k_c + k_w}\right)^2 r_{ds}^{\ 2} + \frac{2k_c}{k_c + k_w} \rho_{ds,k} r_k r_{ds} \tag{5}$$

where r_k is the kinematic roughness, r_{ds} is the variance of the machine vibration signal and $\rho_{ds,k}$ is the correlation coefficient between kinematic and machine vibration effects. Due to the differing origin of the two effects, they can be assumed to be stochastically independent of each other. This means that $\rho_{ds,k}$ is zero and (5) can be reduced to

$$R_q^{\ 2} = r_k^{\ 2} + \left(\frac{k_c}{k_c + k_w}\right)^2 r_{ds}^{\ 2} \tag{6}$$

The above equation for rms roughness can be interpreted as the root sum square of varying sources with given transmitting factors. The physical significance of the transmitting factor is the partition of the variance (or power) of a signal transmitted to the combined variance (or power). As shown in (6), the transmitting factor for the kinematic effect is 1, which can be explained by the fact that the kinematic mark is completely produced on the engaging surface. For machine vibration which does not happen on the engaging surface, the factor is $\frac{k_c}{k_c + k_w}$, which indicates that a larger k_c or a smaller k_w increases the effect on the ground surface roughness. In the case where an ideal rigid wheel is used, $k_c >> k_w$, resulting in the transmitting factor approaching 1 and d_g being almost equal to d_s. This means that the machine vibration profile is completely transmitted to and remains on the ground surface. In the case where $k_c << k_w$, the ground surface is not significantly influenced by vibration.

Kinematic surface roughness model

The kinematic surface roughness model presented in is directly employed, that is

$$h = \frac{h_0}{2}\left[1 + \sqrt{1 + \frac{2v}{VAh_0^{\ 2}\sqrt{2\rho D}}}\right] \tag{7}$$

where v is the work table speed, V is the wheel peripheral speed, D is the wheel diameter and ρ is average grit diameter, while A and h_0 are the wheel parameters. The relation between the active grit density C and maximum surface roughness h was linearized in, where A is the slope of C and h, while h_0 is the maximum surface roughness at C = 0. For a common surface grinding process, the maximum surface roughness is about 4 times that of the average surface roughness and the root mean square roughness is about 1.3 times that of the average surface roughness. As a result, r_k can be estimated to be one third of h and expressed as

$$r_k = \frac{h_0}{6}\left[1 + \sqrt{1 + \frac{2v}{VAh_0^{\ 2}\sqrt{2\rho D}}}\right] \tag{8}$$

For the wheel (WA60H90I) used in our experiments, A = 457 mm^{-3}，h_0 = 1.4 μm and ρ= 137.5 μm. By incorporating the grinding conditions, the kinematic root mean square roughness can be calculated using equation (8).

Identification of work cutting and wheel contact stiffness

The work cutting and wheel contact stiffness varies with grinding conditions, even for the same work and wheel. To obtain these varying parameters, a method of identifying them is required. The work cutting stiffness is defined as the radial grinding force for per unit grinding width and is therefore expressed as

$$k_w = \frac{f_r}{d} \tag{9}$$

where f_r is the average radial grinding force and d is the true ground depth which is obtained by scanning the transverse profile of the ground groove using a surface profilometer, as illustrated in Fig. 3. The difference between the nominal grinding depth, d_f, and d is the summation of machine and wheel deflections. The relation between the deflections and the machine stiffness k_m, k_c and k_w can be expressed as

$$\frac{1}{k_m} + \frac{1}{k_c} = \frac{d_f - d}{f_r} \tag{10}$$

By rearranging (10), the wheel contact stiffness can be written as

$$k_c = \frac{f_r k_m}{\left(d_f - d\right)k_m - f_r} \tag{11}$$

To calculate k_c using (11), k_m must first be known. It is reasonable to ignore the deflection of the work table since its dynamic flexibility in the grinder (Chevlier FSG-2A818) is smaller than the spindle by 1 to 2 orders of magnitude, as illustrated in Fig. 4. Hence, only the spindle stiffness is considered for the estimation of k_m in this paper. To measure the spindle's stiffness, a static contact method is presented in Fig. 5, where the static contact force f is measured by a dynamometer and the nominal feed of the shaft, d_f, and the wheel deflection, d_c, are measured by capacitive displacement gauges (Accumeasure ASP-10-CTA).

The contact force and wheel and spindle deflection remains zero until the wheel makes contacts with the work surface, as illustrated in Fig. 5(a). The spindle then keeps down-feeding without rotating, as illustrated in Fig. 5(b); the contact force increases, resulting in the spindle deflections d_m and d_c. The difference between d_f and d_c is d_m and the spindle stiffness can then be calculated using the ratio of f to d_m:

$$k_m = \frac{f}{d_m} = \frac{f}{d_f - d_c} \tag{12}$$

This result is illustrated in Fig. 6, which indicates a spindle stiffness of about 13.5 N/μm for the machine under various contact forces. In the following analysis, k_m is assumed to remain constant for different grinding experiments.

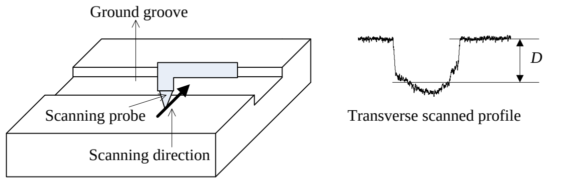

Fig. 3. Measurement of the true ground depth

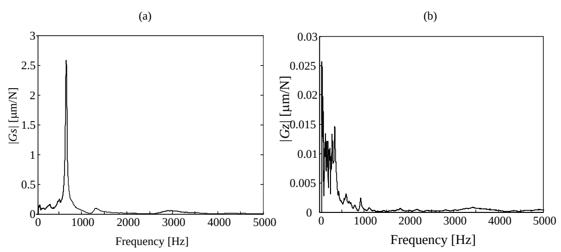

Fig. 4. Dynamic flexibility of (a) the spindle and (b) work table

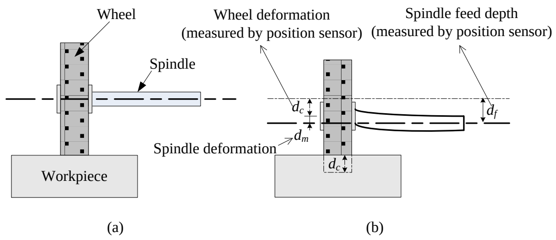

Fig. 5. The spindle stiffness test, (a) before and (b) after static loading

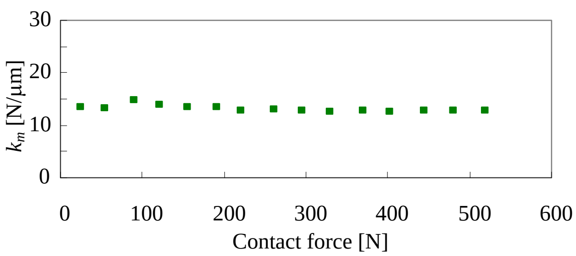

Fig. 6. Spindle stiffness under different contact forces

EXPERIMENTAL VERIFICATION AND DISCUSSION

Experimental setup and method

A series of experiments listed in Table 1, utilizing differing grinding depths, work table speeds and grinding widths were conducted to investigate the effects of process parameters and to validate the model. Grinding was performed with a SKD11 (HRc 60) on a surface grinder (Chevalier FSG2A818). A datum surface for the work is carefully prepared before proceeding with the experiments. The grinding conditions listed in Table 1 were used and the wheel was down-fed to the nominal grinding depth relative to the datum surface. Only a single stroke of the work table was carried out for each grinding experiment without any spark-out or cross-feed processes.

The machine vibration is measured by accelerometers, but only the spindle vibration is considered since its dynamic flexibility is much higher than that of the work table, as illustrated in Fig. 4. Due to the rotation of the wheel, the spindle vibration is difficult to measure. To overcome this, an indirect method is applied. As illustrated in Fig. 7, when the spindle was not rotating, two accelerometers were attached to the spindle head and the housing of the spindle, represented by positions 1 and 2 respectively. An impulse response test was then performed on the spindle head. The results at the two positions, *G1(S)* and *G2(S)*, and their ratio, *H(S) = G1(S)/G2(S)*, are shown in Fig. 8. The vibration signal at position 2 was measured and then the spindle vibration was estimated by multiplying the measured signal in the frequency domain with *H(S)*.

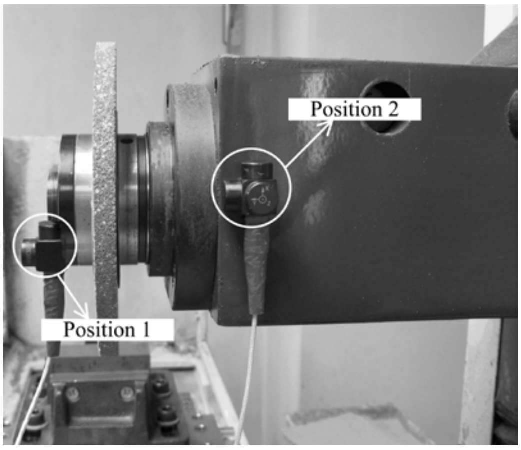

Fig. 7. Experimental setup for measuring the gain of impulse response between positions 1 and 2

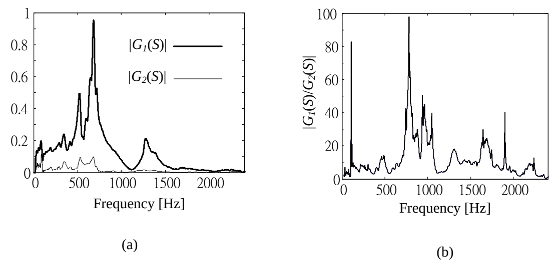

Fig. 8. Impulse response for (a) positions 1 and 2 and

(b) $|G_1(S)|/ |G_2(S)|$

Table 1. Experimental conditions and results

	Grinding conditions			Measured values	
No.	V_w	d_f	W	f_r	D
	[m/min]	[μm]	[mm]	[N]	[mm]
1	0.10	10.00	10.00	46.0	3.7
2	0.10	10.00	20.00	70.6	2.7
3	0.10	20.00	10.00	88.1	9.1
4	0.10	20.00	20.00	135.5	6.7
5	0.20	10.00	10.00	57.8	2.6
6	0.20	10.00	20.00	79.4	1.9
7	0.20	20.00	10.00	116.7	6.6
8	0.20	20.00	20.00	163.0	4.9
	Identified values			Calculated results	
No.	k_w	k_c	$k_c/(k_w+k_c)$	r_k	r_d
1	[N/μm]	[N/μm]		[μm]	[μm]
2	12.4	15.9	0.56	0.556	0.60
3	26.5	33.5	0.56	0.556	0.90
4	9.7	20.1	0.67	0.556	1.05
5	20.1	42.1	0.68	0.556	1.30
6	22.3	18.5	0.45	0.627	0.71
7	42.6	35.3	0.45	0.627	0.96
8	17.6	24.7	0.58	0.627	1.21

Result of the grinding experiments

The roughness along the lay direction in 20 arbitrary locations on the ground surface was measured with a cutoff of 0.8 mm in each experiment. The results are summarized in Table 1 and shown in Fig. 9. The thin line in Fig. 9 represents the range deviation of these 20 measured rms roughness while the circles represent the average value of the measured data. The predicted value is shown in the bar charts next to the thin lines, where the white component is the variance of the grit vibration signal and the shaded component is the square of the kinematic surface roughness. As can be seen in Fig. 9, the predicted data is about 80-95% of the measured value and both follow the same trend under different grinding conditions. This consistent difference between the measured and predicted values might be explained by the many other contributing factors not considered in the surface roughness model, including the material side flow, BUE and vibration of work table, etc.

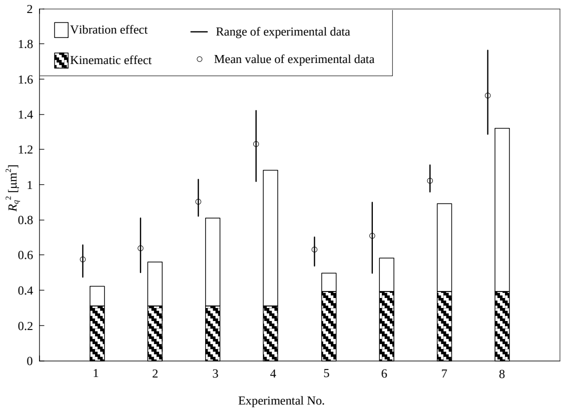

Fig. 9. Experimental and predicted root mean square surface roughness

Discussion

The effects of kinematic grit and spindle vibration on the ground surface can be calculated separately using the model in equation (6). This allows their individual effects to be established. The variance of the engaging surface vibration effect on the surface roughness, shown in the white component of the bar chart, is determined by the spindle vibration and transmitting factor. In the following discussion, the effects of grinding conditions on the ground surface can be analyzed based on both the model and the experimental results.

Effect of grinding depth

The transmitting factor is determined by the ratio of k_c to k_w, which indicates that a larger k_c/k_w increases the transmitting factor. As can be seen in Table 1, k_c is increased with grinding depth due to a larger contacting length between the wheel and the work engaging surface. k_w is found to decrease with increasing depth, which means a larger chip thickness is usually accompanied by a lower the specific grinding energy. Furthermore, a greater grinding depth will increase the grinding force, which results in larger spindle vibration and, consequently, a poorer ground surface, as noted when comparing the results of experiments No. 1 and 3. Similar phenomena can also be found when comparing the pair of results from experiments No. 2 and 4, 5 and 7, as well as 6 and 8.

The Effect of grinding width

k_w and k_c is almost proportional to the grinding width, as shown in Table 1. The transmitting factor is not affected by the conditions of different grinding width. However, the grinding width increases the grinding force, causing larger spindle vibration, and consequently increases the surface roughness. As a result, the vibration variance in experiment No. 1 is more significant than that of experiment No. 2. This effect can also be found when comparing the results of experiments No. 3 and 4, 5 and 6 as well as No. 7

and 8. It was also found that the range deviation of the measured surface roughness increases with the grinding width as a result of the increasing variation of grit conditions.

The effect of work table speed

In experiment No. 6, a higher table speed was used than in experiment No. 2. The grinding force and spindle vibration was found to be larger in experiment No. 6, as shown in Table 1. However, the variance of grit vibration is smaller in experiment No. 6 than in experiment No. 2, as can be seen in Fig. 9. Similar results are noted when comparing experiments No. 1 and 5, 3 and 7 as well as 4 and 8. These results can be explained by the smaller transmitting factor in experiment No. 6; according to the definition of work cutting stiffness, k_w is theoretically proportional to the table speed. This leads to a smaller transmitting factor and reduces the effect of spindle vibration on the ground surface.

Conclusion

An analytical roughness model for a ground surface in the lay direction that combines the kinematic grit and spindle vibration mechanisms was presented. Explicit combined effects of both mechanisms and grinding conditions were incorporated in the presented model, where the kinematic grit effect was adapted from an existing model, while the spindle vibration was obtained by an indirect measurement. The effect of spindle vibration was shown to be determined by its magnitude as well as by the process' transmitting factor, which is defined to be the ratio of the wheel contact stiffness to the work cutting stiffness. A larger ratio will lead to more significant spindle vibration effect on the ground surface. A series of experiments were carried out to characterize the effects of both mechanisms and grinding parameters. The model is validated and the effects of the grinding parameters on the ground surface are discussed based on the experimental and predictive results. The effects of grinding parameters can be summarized as below:

1. The grinding depth increases both the spindle vibration and the transmitting factor, thus deteriorating the ground surface to a greater extent than the grinding width and table speed.
2. A larger grinding width does not affect the transmission factor, it increases the grinding force and spindle vibration, and consequently raises the surface roughness.
3. The table feed speed increases the grinding force and spindle vibration. But, due to the resulting greater work cutting stiffness, the transmitting factor is decreased, making spindle vibration a less significant factor on the ground surface roughness.

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NOMENCLATURE

C active grit density

D true grinding depth

d_f, d_c, d_m nominal grinding depth, wheel deflection and spindle deflection, respectively

d_s, d_g vibration signals of the spindle and the engaging surface, respectively

D wheel diameter

F radial grinding force

$G_1(S)$, $G_2(S)$ dynamic flexibility for position 1 and 2

H peak to valley surface roughness of kinematic effect

$H(S)$ $G_1(S)/G_2(S)$

K profile of grit kinematic effect on ground surface

k_w, k_c cutting stiffness for workpiece and wheel contact stiffness, respectively

k_m machine static stiffness

R total profile of a ground surface

r_k, r_{ds} rms surface roughness of kinematic effect and rms value of spindle vibration, respectively

R_q root mean square surface roughness

v, V workpiece velocity and wheel speed respectively

ρ average grit diameter

考慮磨粒與振動變異效應之表面粗糙度模式建立

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摘 要

通過結合磨粒運動和主軸振動效應，建立了反應磨粒與主軸震動對表面粗糙影響的解析模型。在考慮振動效應之磨削表面粗糙度模式中，均方根表粗度之平方可表示為磨粒隨砂輪轉動及振動之軌跡變異數相加。從動態磨削系統得出的傳遞因子定義了從主軸振動傳遞到表面的功率，與製程剛性有關，即工件的切削剛性和砂輪的接觸剛性。由於本模型的分析性質，本模型可用於估計表面粗糙度，並分析磨削條件、機床振動和加工過程中剛性的貢獻和影響。本文建立一參數識別程序，並進行了一系列參數變化的實驗，以驗證模型，根據實驗和模型分析結果，討論表面粗糙度的磨削條件。模型預測和實驗結果表明，磨削深度和磨削寬度越大，磨削力越大，磨削質量越差。此外，雖然較大的工件進給會導致較大的磨削力和主軸振動，但也會增加切削剛性，從而降低主軸振動的傳遞因子，減少其對表面粗糙度的不利影響。