Fundamentals for Vibration Diagnosis by Ground Surface Marks*

Yi HAN** and Tetsutaro HOSHI***

Ground surface imperfections are often attributed to periodical marks caused by vibration in grinding. According to the mechanism by which the marks were formed, there are various characteristics which can be important clues to diagnosing the type of grinding vibration and making appropriate counterplans. By classifying the marks due to each type of grinding vibration experimentally as well as theoretically, they can be divided into two categories depending on whether the marks were formed chiefly by a shape error or by a roughness variation. In addition, the relationship between the presence of the marks and the speed ratio, and the marks' inclination to the wheel axis are generalized to correspond with the different grinding processes and types of grinding vibration. The generalized relationships make it possible to narrow down the possible causes to a few types of vibration. Also, an optical method which is necessary for the diagnosis is proposed for measuring the characteristics of the marks. Together with the principal counterplans for each type of grinding vibration, a system of knowledge for vibration diagnosis has been obtained.

Key Words: Vibration Diagnosis, Grinding Marks, Shape Error, Roughness Variation, Optical Measurement

1. Introduction

There are different types of vibration that may occur in the grinding process. Some of them occurs more and less persistently and presumably is hard to eliminate from grinding. Vibration becomes a problem when it grows rapidly, or even a little surface imperfection on a ground surface is intolerable. Techniques by which such a problem can be diagnosed and solved correctly and quickly are needed. Renker(1), and Hahn(2),(3) classified grinding marks into categories for the benefit of identifying types of vibration and the causal mechanisms. These classifications are principally based upon the inclination of the grinding marks. However depending on the mechanisms by which the grinding marks are formed, they may have various characteristics which will be important clues to diagnosing the vibration and making appropriate counterplans. The purpose of this paper is to generalize the grinding marks from different types of vibration and to provide a method for vibration diagnosis. In the present study, initially the marks resulting from each type of vibration are created experimentally in order to obtain the necessary knowledge for the vibration diagnosis. Then for analyzing the light reflectivity variation of the marks, an optical means will be proposed which is considered necessary for investigating the characteristics of the marks.

* Received 29th July, 1991. Paper No. 90-0029B

** Department of Productin Engineering Development, Koyo Seiko Co., Ltd., 24-1 Kokubuhiganjyo-cho, Kashiwara-shi, Osaka-fu 582, Japan

*** Department of Production Systems Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku-cho, Toyohashi-shi 441, Japan

2. Types of Grinding Vibration and Their Phenomena

2.1 Characteristics of grinding marks

The term grinding marks will refer to the periodic pattern apparent on a ground surface. They can be formed due to local and periodic variations of the roughness, or periodic shape errors of the surface. Generally such marks correspond to some vibration that has occurred during grinding. According to the mechanism by which the marks are formed, they have various characteristics. For example, as shown in Fig. 1, when there is the relative displacement X_d between the wheel and workpiece, it will correspond to a component of the grinding marks d_1 in a shape error on the ground surface. Otherwise, when there is some periodic variation of roughness or wear around the wheel working surface, it will be reproduced onto the ground surface in a form of roughness variation during grinding. This kind of component d_2 of grinding marks, produced due to the surface imperfections of the grinding wheel, can be detected by means of light reflectivity variation measurement; however, it can hardly be detected through shape error measurement by a roundness instrument. Therefore, depending on the mechanism by which the grinding marks were formed, they can be classified into shape error marks and roughness variation marks. This characteristic of the grinding marks is referred to as the mark form hereafter.

In the case where the grinding marks are produced with the same harmonic period as that of wheel rotation, such as the surface imperfections of the wheel (as shown in the Fig. 1, where the number of wheel surface alternations is designated by N), or wheel runout (the frequency F_w equals that of wheel rotation speed N_g) and so on, the components of the marks (d_1 or d_2) have integer multiple relationships with the speed ratio of the wheel and workpiece used (hereafter referred as to speed ratio). Otherwise, there will be no such relationships.

Moreover, the grinding marks can appear parallel or slanted to the wheel axis according to the grinding process (traverse-cut or plunge-cut), characteristics of vibration (regenerative or forced) or the inclination of marks existing on the wheel working surface. The inclination of grinding marks can be axial, slanted or undisciplined with respect to the wheel axis.

In respect to the vibration diagnosis by the grinding marks produced during grinding, the more that is understood about the characteristics connected to various types of vibration, the easier it is to diagnose the type of vibration causing the problem.

2.2 Types of vibration and their phenomena

When diagnosing the type of vibration, initially the marks produced due to the vibration should be differentiated as shape error marks or roughness variation marks. Based upon this differentiation, causal types of grinding vibration can be divided into the following two categories according to the theoretical and experimental studies.

1 Shape error marks (detectable with shape error measurement)
   a) Workpiece Regeneration (as shown in Fig. 2)
   b) General Forced Vibration (including wheel runout)
2 Roughness variation marks (detectable with light reflectivity variation measurement)
   a) Wheel Regeneration (as shown in Fig. 2)
   b) Vibration in dressing or marks due to the dressing process

The knowledge about the relationships between the types of grinding vibration and their phenomena has been generalized into a table. The following explanation is according to this table.

2.2.1 Shape error marks Three types of vibration which will cause the shape error marks on a ground surface are taken up in the following, together with the phenomena concerning each.

1) Workpiece Regeneration: In proportion to the increase of the workpiece speed, the transfer factor[9] concerning regenerative effect on the workpiece surface becomes larger. As a result, the grinding system will become unstable and vibration of workpiece regeneration happens. Marks produced under this condition are parallel to the wheel axis in the plunge-cut process, and slanted to the wheel axis in the traverse-cut process because of the regenerative effect.

Principal counterplan: slow down workpiece speed[4].

2) General Forced Vibration: When there exists some forced vibration inside or outside of the grinding system, it will have an effect on grinding so that the marks, straight and parallel to the wheel axis, will appear in the plunged-cut process. In the traverse-cut process, if there is not a harmonic proportion between the period of vibration and the feed rate of the table

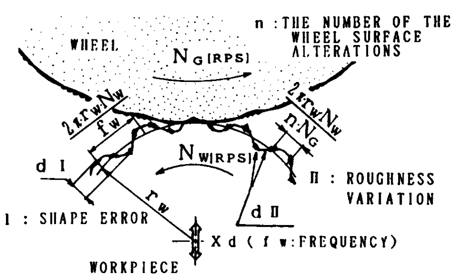


Fig. 1 Illustration of the mechanism by which grinding marks are formed

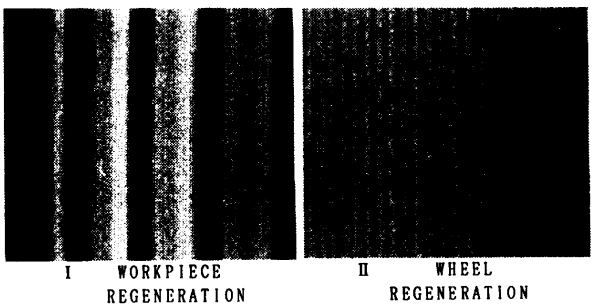


Fig. 2 Examples of two types of grinding marks produced in plunge-cut process

Table 1 Types of grinding vibration and phenomena concerning them

CAUSE	PLUNGE-CUT	TRAVERSE-CUT	COUNTER PLAN
I SHAPE ERROR MARKS			
WORKPIECE REGENERATION	1.UNRELATED 2.AXIAL	1.UNRELATED 2.SLANTED	REDUCE THE WORKPIECE SPEED
GENERAL FORCED VIBRATION	1.INTEGER MULTIPLES OR UNRELATED 2.AXIAL	1.INTEGER MULTIPLES OR UNRELATED 2.AXIAL OR SLANTED	SUPPRESS THE IDLE VIBRATION
WHEEL RUNOUT	1.EQUAL 2.AXIAL	1.EQUAL 2.AXIAL OR SLANTED	BALANCE THE WHEEL AND THE WHEEL SPINDLE
II ROUGHNESS VARIATION MARKS			
WHEEL REGENERATION	1.INTEGER MULTIPLES 2.AXIAL	1.INTEGER MULTIPLES 2.AXIAL OR SLANTED	SHORTEN THE DRESSING INTERVAL
REGENERATION IN DRESSING	1.INTEGER MULTIPLES 2.SLANTED	1.INTEGER MULTIPLES 2.SLANTED	REDUCE THE INFEED OF DRESSER
BACK AND FORTH DRESSING	1.TWICE 2.SLANTED OR AXIAL	1.TWICE 2.SLANTED OR AXIAL	DRESS IN ONE DIRECTION
FORCED VIBRATION IN DRESSING	1.INTEGER MULTIPLES 2.AXIAL	1.INTEGER MULTIPLES 2.AXIAL OR SLANTED	SUPPRESS THE VIBRATION IN DRESSING

1.THE RELATIONSHIP BETWEEN THE PRESENCE OF MARKS AND THE SPEED RATIO
2.THE INCLINATION OF MARKS WITH REFERENCE TO THE WHEEL AXIS

with respect to the workpiece speed, marks slanted to the wheel axis appear on the ground surface. Furthermore, depending on whether the vibration frequency has a harmonic proportion to that of wheel rotation or not, the relationship between the presence of marks and the speed ratio will or will not be integer multiples. In the case when the frequency of a forced vibration is in the vicinity of a natural frequency of the grinding system, a kind of composite vibration[9] may grow or subside in an irregular pattern. This type of vibration is classified as general forced vibration here.

Principal counterplan: discover forced vibration in idling and control or separate it from the grinding system.

3) Wheel Runout: Due to an out-of-balance grinding wheel and wheel axis, a grinding machine may vibrate at the same frequency as the wheel rotation during grinding. This will result in a relative displacement between the wheel and the workpiece in each wheel cycle. Therefore, the component of the marks due to this type of vibration will equal those of the speed ratio. The marks will be slanted to the wheel axis in the traverse-cut process because of the different feed rate of the table, as mentioned above. This type of vibration is also considered as a special of the general forced vibration when the forced vibration frequency equals that of wheel rotation.

Principal counterplan: balance wheel and wheel axis[5], and use a speed ratio controller (for example, adjust the speed ratio to 0.3) to erase the undulation[6].

2.2.2 Roughness variation marks Four types of grinding vibration which will cause roughness variation marks are listed below.

1) Wheel Regeneration: There is no wheel wear at the initial stage of the grinding test using a newly dressed wheel. When static grinding force remains constant for a certain period of time, among the many higher harmonics of the frequency of wheel rotation a certain frequency component is selectively amplified and develops into wheel regeneration. This particular mechanism causes the wheel to wear gradually developing regularly spaced alterations around its working surface and therefore regeneratively increases vibration until the periodic pattern produced on the ground surface becomes intolerable. In this case, the component of the marks has an integer multiple relationship with the speed ratio. It produces marks parallel to the wheel axis; however, slanted marks may occasionally appear in the traverse-cut process due to the different feed rate of the table.

Principal counterplan: shorten the dressing interval, balance the wheel[7], and use a method of alternating wheel speed grinding[8].

2) Regeneration in dressing: Regenerative chatter that may occur in the dressing process is actually damage done to the wheel surface by the dresser. In this case, because of the regenerative effect, marks slanted to the wheel axis appear around the wheel working surface and will be reproduced onto the workpiece surface with integer multiples of the speed ratio used during grinding.

Principal counterplan: reduce the infeed of the dresser[9].

3) Back-and-forth dressing: When dressing is conducted with bidirectional traverse feed, it will form two cycles of roughness variations around the wheel working surface. In grinding with the wheel, the marks which have a component of twice the speed ratio will appear on the ground surface. The marks will be parallel to the wheel axis only if the back-and-forth traverse feed rates are equal.

Principal counterplan: dress in only one direction.

4) Forced vibration in dressing: Wavy patterns may be formed around the wheel working surface due to some forced vibration outside or inside of the grinding system during dressing. In grinding with the wheel, marks corresponding to the waviness will be reproduced onto a ground surface in an integer multiple of the speed ratio used. The marks may be parallel to

the wheel axis in the plunge-cut process, and parallel or slanted to the wheel axis in the traverse-cut process because of the different feed rate of the table, as expressed in section 2.2.1 on General Forced Vibration.

Principal counterplan: find forced vibration in dressing, control or separate it from the grinding system.

3. Measurement and Analysis of Light Reflectivity Variation

By analyzing the topography of a ground surface, the necessary information to be obtained about the characteristics of grinding marks is: 1) mark form, 2) relationship between the presence of marks and the speed ratio used, and 3) inclination of marks with reference to the wheel axis. Variables 2) and 3) can be determined by illuminating the surface of a workpiece with a He-Ne laser beam, detecting the intensity variation of the reflected ray and processing it into the Fourier spectra of the frequency components and a curve of secondary degree[10],[11]. The shape error marks, however, can be measured with shape error measurements such as a roundness instrument. As a practical method for the vibration diagnosis it is desirable that the three characteristics of the grinding marks can be investigated with a same apparatus.

3.1 Measurement and analysis

Regrarding the light reflectivity variation of a ground surface both, shape and roughness can be detected by illuminating the surface with a light beam of a certain diameter and analyzing the intensity variation of the reflected ray from it. Actually it is normal to find two such kinds of variation on the same ground surface. When measuring the light reflectivity variation, it is necessary to differentiate the frequency components of the reflection intensity variation to determine that each component chiefly corresponds to shape error marks or roughness variation marks. By changing the diameter of the light beam expander, it has been known that the reflectivity variation due to a shape error will become more sensitively detectable when the diameter of the light beam expander is narrowed down. Based upon this, by turning the diameter from the maximum to the minimum and comparing the intensity variation of the reflected ray, the frequency components can be divided into those which are due to a shape error of the surface and those which are due to roughness variation of the surface, so that it is possible to provide information about the characteristic of mark form for vibration diagnosis.

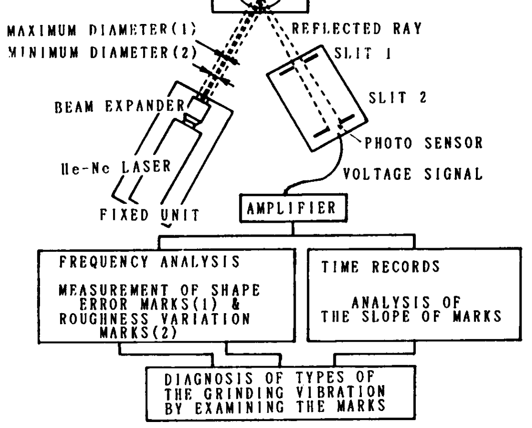
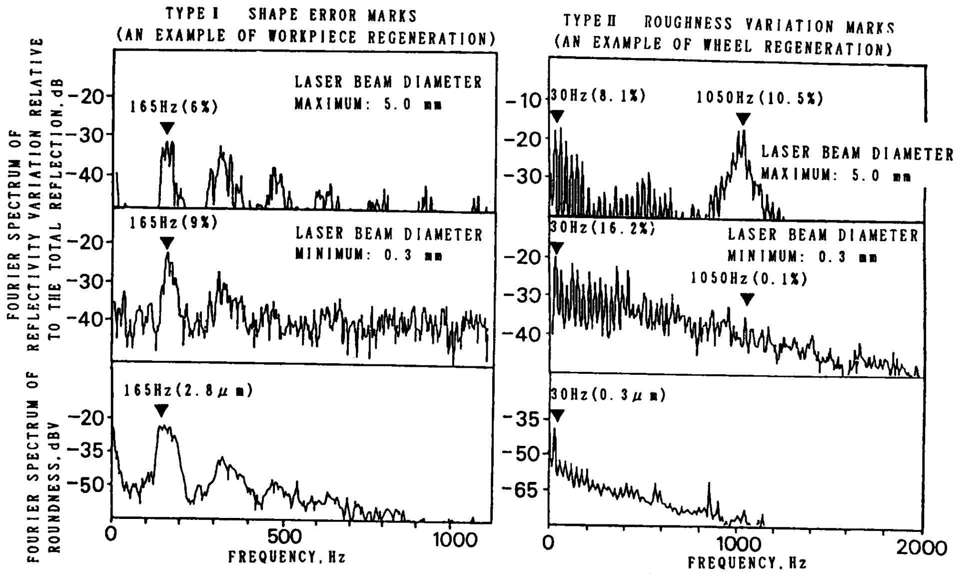


Fig. 3 Outline of measurement and analysis of light reflectivity variation for grinding marks

Figure 3 shows an outline of measurement and analysis of the light reflectivity variation of grinding marks. A He-Ne laser with an adjustable diameter of a beam expander is used. In order to obtain a reflected ray, holders of the laser and a photosensor which can be used to pick up the reflected ray are made to be adjusted vertically, horizontally, and rotationally. The moving unit for the specimen has two kinds of motion, straight line for a plane surface and rotational for a cylindrical surface. The reflection is detected through two narrow slits by the photosensor. In practice, the frequency analysis of the reflection intensity variation is conducted separately with both the maximum and the minimum diameter of the beam expander, and the voltage signal from the photosensor is amplified and used for analyzing the slope of the marks. The reflection intensity variation is also expressed in a power spectrum ratio of the noted frequency to the total power summed up across the measured frequency range except the DC component. By comparing the power spectrum ratios obtained separately, those frequency components obtained by the minimum diameter which have larger power spectra ratios than those obtained from the maximum diameter are judged as shape error marks, while others are due to roughness variation. In this way, the three kinds of characteristics which are necessary for diagnosing grinding vibration can be determined.

3.2 Examples of shape error marks and roughness variation marks

Figure 4 compares the results of the measurement and the analysis of the reflection intensity variation obtained by investigating two kinds of grinding marks due to workpiece regeneration and wheel regeneration, and the results of shape error measurement with a roundness instrument. The vertical axis for the reflectivity variation measurement expresses the Fourier spectra of each frequency component under the condition that the DC component is considered as



Here the percent values in the parentheses indicate power spectrum ratio of the noted frequency component to all components below 1 000 Hz (left) and below 2 000 Hz (right)

Fig. 4 Measurement results of two types of grinding marks

zero dB. As it can seen on the left, the 165 Hz frequency component of the reflectivity variation is detected when the beam diameter is at both maximum and minimum. However, when the diameter is at minimum, the component shares 9 % of the total power of the reflection intensity variation and is more sensitive than the 6 % when the beam diameter is at maximum, as in the middle of the figure. Therefore the component is due to shape error marks of a ground surface. At the same time, this component can also be measured with a roundness instrument, as shown at the bottom. On the other hand, the 1 050 Hz frequency component of the reflectivity variation on the right is detected only when the beam diameter is at maximum and the component shares 10.5 % of the total power of the reflection intensity variation. When the beam diameter is at minimum, this component only shares 0.1 % and can hardly be detected, as shown in the middle of the figure. Therefore the component is due to the roughness variation marks of a ground surface. At the same time, there is no such a component that can be measured with a roundness instrument as shown at the bottom of the figure. Incidentally, the power ratio of the 30 Hz component is growing from 8.1 % to 16.2 % in correspondence with the maximum and the minimum beam diameter. This component of shape error is also confirmed by the result of the roundness measurement shown at the bottom.

4. Vibration Diagnostics

The purpose of vibration diagnosis is to identify the type of vibration involved and make appropriate counter plans. By using the generalized relationships between the types of vibration and the characteristics of grinding marks and counter plans it is possible to narrow down the possible types of vibration with respect to a certain grinding process when diagnosing a vibration problem. For vibration diagnostics, initially it should be determined whether the marks were formed due to shape error or roughness variation. Based upon this, it is possible to center the attention to the upper part or the lower part of the table as shown in the section 2.2. Then depending on the relationship between the presence of marks and the speed ratio used, and the inclination of marks with reference to the wheel axis, one or more possible types of vibration can be addressed. Use of a counter plan may confirm or disprove the diagnosis. If disproven, the diagnosis may be made again by using the results. With generalized knowledge about grinding marks, the number of procedures performed to achieve a diagnosis will decrease. For this purpose, it will be effective to produce a production system that can quickly and effectively perform these diagnoses by using knowledge engineering and incremental inductive learning technology. The learning function is intended to allow the system to improve its own performance and adapt to new situations[12].

5. Conclusions

Grinding experiments have been conducted to observe the grinding marks due to various types of grinding vibration. By analyzing the mechanisms by which the marks were formed, a basic method for vibration diagnosis has been proposed. The types of grinding vibration have been classified into two categories based upon whether the marks produced were formed due to shape error or roughness variation. Together with the other characteristics of the marks such as the relationship between the presence of marks and the speed ratio used, and the inclination of marks with reference to the wheel axis, a system of knowledge useful for diagnosing the grinding vibration has been obtained with respect to different grinding processes. Moreover, a practical means of light reflectivity variation measurement for the marks has been provided.

We express our thanks to Yasuhiko Osada, who studied for his master's degree at Toyohashi University of Technology, for his cooperation in making the optical instrument. We also thank our friend Ellen McClung for her comments on translating this paper.

References

(1) Renker, H., The Identification of Grinding Fault from the Appearance of the Ground Surface, Proc. 16th Int. Machine Tool Design and Research (MTDR) Conf., Manchester G. B. (1975), p. 367.

(2) Hahn, R. S., Grinding Chatter-Causes and Cures, The Tool and Manufacturing Engineer, (September 1963), p. 74.

(3) Hahn, R. S., Grinding Chatter in Precision Grinding Operations—Causes and Cures—, SEM Technical Paper MR 78-331, (1978), p. 1.

(4) Sugihara, K., Inasaki, I. and Yonetsu, S., Stability Limit of Regenerative Chatter in Cylindrical Plunge Grinding —A Proposal of the Practical Stability Limit Equation—, J. of Japan Society for Precision Engineering, (in Japanese) Vol. 46, No. 2 (1980), p. 61.

(5) Horiuchi, O. and Kojima, H., A New Liquid-injection Type Automatic Balancer for the Grinding Wheel, J. of Japan Society for Precision Engineering, (in Japanese) Vol. 52, No. 4, (1986), p. 713.

(6) Horiuchi, O., Techniques for Improved Roundness in Cylindrical Grinding, ASME Grinding Symposium Miami (1985), p. 237.

(7) Han, Y. and Hoshi, T., Role of Process Nonlinearity in Wheel Regenerative Grinding Vibration, Annals of the CIRP Vol. 39/1/1990, p. 367.

(8) Hoshi, T., Mitsui, S. and Horiuchi, O., A Method for Controlling Vibration in Plunge-Cut Cylindrical Grinding, J. of Japan Society for Precision Engineering, (in Japanese) Vol. 53, No. 6, (1987), p. 940.

(9) Hoshi, T., Machining Chatter, Kogyo-Chosa-Kai, (1977), (in Japanese).

(10) Osada, Y. and Hoshi, T., Reflectivity Variation Analysis of Ground Surface, 19th Graduation Research Meeting Papers of Tokai Student Conference, Prepr. of Jpn. Soc. Mech. Eng., 1988. 3 (in Japanese).

(11) Onoda, R. and Hoshi, T., Reflectivity Variation Measurement of Cylindrical Ground Surface, 17th Graduation Research Meeting Papers of Tokai Student Conference, Prepr. of Jpn. Soc. Mech. Eng., 1986. 3 (in Japanese).

(12) Han, Y. and Hoshi, T., A Self-learning Expert System for Grinding Vibration Diagnosis, Proceedings of Pacific Rim International Conference on Artificial Intelligence '90, p. 146-151.