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# Characterization of Grinding Wheels: An Annotated Bibliography

## Final Report

Robert W. McClung, Consultant

Ceramic Technology Project

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DEPARTMENT OF ENERGY

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# Characterization of Grinding Wheels: An Annotated Bibliography

Final Report

R. W. McClung, Consultant

Propulsion System Materials Program
Office of Transportation Technologies
Energy Efficiency and Renewable Energy
U.S. Department of Energy

December 1995

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# PREFACE

This work was performed in support of the Cost-Effective Ceramic Machining (CECM) effort which was begun at ORNL in 1991 as part of an initiative in low-cost ceramic manufacturing. This research project was sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the Ceramic Technology Project of the Propulsion System Materials Program, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

The grinding wheel is the heart of many abrasive machining processes, and it was deemed important to the goals of CECM to compile a survey of the open literature dealing with the methods of grinding wheel characterization. R. W. McClung, an expert in non-destructive testing methods and former Group Leader in the Metals and Ceramics Division, was asked to prepare this annotated bibliography. He spent over a year gathering and carefully reviewing the literature in the field. Papers from a number of countries are referenced in this report. After receiving and reviewing the compilation, I felt it would be useful to readers to have a subject index, and consequently prepared and appended one.

There still remain many challenges in developing low-cost structural ceramic machining processes and it is hoped that the information within this report will promote additional improvements in this area of advanced product engineering.

Peter J. Blau
Task Leader, Cost Effective Ceramic Machining
Metals and Ceramics Division
Oak Ridge National Laboratory

# CONTENTS

## Summary and Introduction

The characteristics of grinding wheels, after both fabrication and periods of operation, have a significant effect on the processed surface and the mechanical properties of advanced ceramics. An extensive literature survey and review has been conducted to determine and catalogue the various characterization methods that have been investigated and reported. Although many of the references have addressed the grinding of metals, the historical and technical merit justify their inclusion in this bibliography.

For convenience, the references have been subdivided into nine subheadings:

1. **Nondestructive Examination**
2. **Elasticity and Stiffness**
3. **Wheel Hardness**
4. **Topography and Profilometry**
5. **Observation of Texture of Wheel Surfaces**
6. **Wheel Wear**
7. **In-Process Monitoring of Grinding**
    - 7.1 Acoustic Emission
    - 7.2 Other
8. **Characteristics of Ground Surfaces**
9. **Miscellaneous**

There is obvious overlap in content of some of the subheadings as well as in individual references. The cited publications have been placed into the subheading that seems to provide the best overall fit. In some instances cross-references have been used to denote significant information under another subheading. References in each subheading are arranged in chronological order to preserve the historical development.

## Introduction

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# 1.0 NONDESTRUCTIVE EXAMINATION

(1) R. S. Hahn and R. L. Price (1968)
**"A Non-destructive Method of Measuring Local Hardness Variations in Grinding Wheels"**
*Annals of the C.I.R.P.*, Vol. XVI, pp. 19-30.

Observations made during grinding tests indicate that variations in the surface of the grinding wheel can induce various vibrations into the quill and spindle of a wheelhead which in turn can produce chatter in the part being ground. In addition it was observed that wheel surface variations can also cause workpiece roughness or local variations in the surface finish of the workpiece. Using a contact resonance method, an instrument was designed and built for measuring the local stiffness and local variations in stiffness of a grinding wheel. Tests were made on a group of wheels to prove out the instrument as well as to study the variations in the wheels. (Author)

Tests were performed to show variations in resonant frequency (local stiffness) around the circumference and lengthwise as functions of vibrator preload and dressing variables. (RWM supplement) (17 fig., 3 ref., 1 table, discussion)

(2) K. Umino and N. Shinozaki (1972)
**"New Gradetester of Grinding Wheel Using Ultrasonic Pulse Method - Study on Grading of Grinding Wheels by Ultrasonic Pulse Method (Part 5)"**
*J. Japan Soc. Pres. Eng.*, Vol. 38 No. 8, pp. 485-488.

Automatic computing gradetester of grinding wheels which based on ultrasonic pulse method is designed.

The characteristics of the new designed gradetester are as follows:
1. As it is a nondestructive method, it does not damage the surface of the measured grinding wheel.
2. Comparing with the mechanical methods, it has not the fault such as tool wear and has good accuracy.
3. Its operation is easy, because measured value is displayed in digital value and hence reading error is avoided.
4. It is also able to measure the homogeneity of the grinding wheel.
5. It can be applied to diamond wheels, fine grain size grinding wheels and so on. (Author)

The contact, through transmission, ultrasonic technique is applied using a frequency of 2MHz. The modulus is measured to ± 2% based on calculations with density and velocity. Measurements are made at 16 different radial positions and changes are plotted on a polar plot. (RWM supplement) (7 ref., 7 fig., Japanese text)

(3) R. Downer (1976)
**"Materials sounder to detect cracks in grinding wheels"**
*Tooling*, June, pp. 12-15.

A two-crystal ultrasonic technique (pitch-catch) was used with an increase in arrival time indicating the presence of a flaw on the flat surface of the wheel. A mechanical guide facilitated search unit placement at three 120° positions. Paste couplant (e.g. wallpaper) was used. For wheels over 1-in thick, both sides were checked. For 3-in thick wheels, the probe placement was also at 120° intervals on the grinding face. (RWM) (8 fig.)

(4) W. König, and H. Lauer-Schmaltz (1978)
**"Loading of the Grinding Wheel Phenomenon and Measurement"**
*Annals of the C.I.R.P.*, Vol. 27 No. 1, pp. 217-220.

In grinding, not only size, shape and distribution of the cutting edges but also the condition of the pores play an important role. Frequently, loading of the grinding wheel with chips occurs when ductile workpiece material is machined.

Recently, some measuring systems have been developed to determine the loading of grinding wheel pores.

An analysis of these existing systems has led to the lay-out and construction of a completely new type of sensor which works with self-inductance due to changes in the magnetic leakage field.

Initial investigations in which this sensor is applied show loading effects in grinding carburised steel C 15 with grinding wheels of great hardness and dense structure. (Author) (10 ref., 6 fig., 3 equations)

(5) C. M. Sayers and R. L. Smith (1982)
**"The propagation of ultrasound in porous media"**
*Ultrasonics*, September, pp. 201-205.

The equations of Ying and Truell, and Waterman and Truell, describing the propagation of ultrasound in two-phase materials are solved numerically for porous solids, and are found to give unphysical results for high porosity. A new self-consistent theory, which can be solved analytically, is presented and is shown to have reasonable behavior at high porosity. (Author) (17 ref., 4 fig., 27 equations)

See also Miscellaneous, Reference No. 86

(6) R. L. Smith (1986)
**"The Evaluation of NDT Techniques for Abrasive Wheels"**
*British Journal of Nondestructive Testing*, Vol. 28 No. 2, March, pp. 73-79.

A study into the techniques available for the non-destructive testing of abrasive wheels was carried out for the Health and Safety Executive. These included X-radiographic, ultrasonic and resonance techniques. A series of fracture studies was also carried out to estimate the typical critical crack sizes for abrasive wheels in use and the results used as an aid to assessing the applicability of each technique. Based on 3-point bend specimens fabricated with typical material (sintered with manufacturer's recommendations), cracks of 10mm must be detectable. X-radiographs detected oriented cracks (some using radio-opaque penetrant) with clear definition and is probably sensitive to a few mm length. Resonance techniques with Grindosonic was excellent at determining fundamental frequency but was not judged likely to find cracks in grinding wheels. Ultrasonic velocity measuring techniques could be used similar to resonance for grading wheels if density and Poisson's ratio are known. An optimum frequency is 0.5-1.0MHz. An ultrasonic pitch-catch technique was developed which can achieve the required resolution and is readily adaptable to practical situations. The pitch-catch technique (from the periphery to the center) saw localized variation in transmission (nonuniform structure of a good wheel) and detected a 3-mm long notch on the inner radius (bore). Surface waves, although slow, also found cracks. (Author and RWM) (9 ref., 1 table, 12 fig., 3 equations)

See also Miscellaneous, Reference No. 89

(7) R. W. Davidge (1989)
**"Defects in Ceramics - The Targets for NDT"**
*Br. Ceram. Trans. J.*, Vol. 88 No. 4, pp. 113-116.

This paper reviews briefly the defects commonly found in engineering ceramics that control the mechanical behavior. The nature and origin of the defects are indicated so that realistic targets for NDT techniques can be identified. Resin-bonded grinding wheels may be reinforced with layers of woven layers. Typical defects include irregular distribution of fibers and delamination faults between fiber layers. (Author and RWM) (14 fig.)

(8) V. Seiffert (1991)
"Zerstörungsfreie Messung der örtlichen Dichte an Sinterwerkstoffen - insbesondere bei Schleifscheiben"
*Keramische Zeitschirft*, 43 Jahrgang, Nr. 7, pp. 469-472.

**Non-Destructive Measuring of the Local Density of Sintered Materials - Especially of Grinding Wheels**

Non-destructive material testing is very critical in the case of grinding wheels. A decisive disadvantage of testing fired pieces is that defective wheels, although worth full production costs, have to be discarded. Density testing of unfired articles may be performed by penetrating the piece with gamma radiation, which is described. Additional information is given on the construction of the apparatus and the measuring accuracy, stating examples of application. (Author)

127Cs gamma radiation is applied to unfired grinding wheels to detect variations in density. A scintillator-photomultiplier detector is used with an X-Y scan. (RWM supplement) (9 fig.)

(9) C. Delebarre, C. Bruneel, R. Delwiche, and I. De Vos (1993)
**"Polycrystalline diamond cutting element control using high frequency C-scan image processing"**
*NDT & E International*, Vol. 26 No. 6, December, pp. 303-308.

A study of high-frequency (100 MHz) ultrasonic examination with C-scan image processing in polycrystalline diamond cutting elements in drilling tools. Three major types of defect are detected including diamond-layer debonding from the substrate, cracks, and thermal defects of the diamond layers. Good correlation is shown between ultrasonic measurements and abrasion resistance tests. Each kind of defect has an influence on one or more mechanical characteristics. (RWM) (11 ref.)

# 2.0 ELASTICITY AND STIFFNESS

(10) J. Peters, R. Snoeys, and A. Decneut (1968)
**"Sonic Testing of Grinding Wheels"**
Proc. 9th Int'l Machine Tool Design & Res. Conf., pp. 1113-1131.

The "grade or hardness" of a grinding wheel does not have a real physical definition. Grinding wheel hardness has a different meaning for the manufacturer and for the user. With this statement in mind, the modulus of elasticity of the grinding wheel material has been considered a physically defined grinding wheel criterion. The paper gives a detailed description of a precise and fast measuring method for the practical determination of the E-modulus by a sonic test.

It is shown that the E-modulus meets the manufacturers' as well as the users' needs. The "grade chart" relates the wheel composition with the empirically measured "hardness" and with the E-modulus value, on both vitrified and resinoid wheels.

Finally the E-modulus is related to the practical grinding work. (Author and RWM) (17 ref., 15 fig., 25 equations)

See also NONDESTRUCTIVE EXAMINATION, Reference No. 1

(11) R. Snoeys and I-Chih Wang (1968)
**"Analysis of the Static and Dynamic Stiffnesses of the Grinding Wheel Surface"**
9th Machine Tool Design & Res. Conf., pp. 1133-1148.

The stability of the grinding operation is greatly influenced by the elastic deformation of the grinding wheel-workpiece contact area. It has been found that a conservative stability-criterion for the grinding operation depends on the ratio of contact area stiffness to machine stiffness. This study is an attempt to correlate the stiffness of the grinding wheel surface to important parameters such as wheel surface roughness and grinding forces. In turn, this provides an explanation of the influence of grain size, dressing conditions, infeed rate, and stock removal upon the stability of the grinding operation.

The Hertzian theory of elastic contact between two smooth elastic bodies has been applied to investigation of the static and dynamic characteristics of the grinding wheel and the workpiece. It has been found that the Hertzian results are valid at high loads but, at lower loads, the theoretical results analysis predicts much larger values than are given by the experimental stiffness curve of the grinding wheel. This difference can be eliminated by considering the surface of the grinding wheel to be rough instead of smooth. (Author)

The test apparatus is described for measuring deformation of contact area. The model for contact stiffness includes stiffness of individual grains and grain-spacing distribution. (RWM supplement) (14 ref., 31 equations, 10 fig., appendix with 15 equations)

(12) K. Nakayama, J. Brecker, and M. C. Shaw (1971)
**"Grinding Wheel Elasticity"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 93, May, pp. 609-614.

The deflection of individual abrasive grains in the cutting surface of a vitrified grinding wheel has been postulated to explain many fine grinding results: however, the magnitude of the deflection has never been firmly established. Experiments conducted to measure the deflection associated with an individual grain showed it to be of the same order of magnitude as the undeformed chip thickness. A model of a grinding wheel which allows both the deflection of the center of an individual grain and the deformation in the contact zone between the grain and the work material to be evaluated was developed. Contact zone deformation was found to be approximately twice as great as the deflection of the center of the grain. (Author) (6 fig., 9 ref., 4 tables, 12 equations, discussion)

(13) R. Fukuda and T. Tokiwa (1974)
**"A Study on the Contact Stiffness between Grinding Wheel and Workpiece"**
*J. Japan. Soc. Pres. Eng.*, Vol. 40 No. 10, pp. 809-814.

In this paper the contact stiffness between grinding wheel and workpiece is experimentally investigated by dynamical method and formulated, in order to analyze the quantitative relation between frequency and amplitude of workpiece in external grinding in a system including contact stiffness. The contact stiffness is determined from the natural frequency measured by the impulse response of workpiece, which is pushed statically against grinding wheel with a preload. As a result of the investigation, it is found that the contact stiffness thus obtained can be formulated by the form of power function of normal contact force and further transformed into power function of equivalent elastic deformation in contact zone, and is proportional to contact width. The effect of contact length upon contact stiffness is also investigated and summarized with the calculated contact length under load, and then a method to estimate the contact stiffness under any contact length is described. Finally the vibration of workpiece, upon which the non-linear contact stiffness acts, is analyzed by energy method and the effect of amplitude on frequency is quantitatively discussed. (Author) (Japanese text) [5 ref. (English), 11 fig., 11 equations, 1 table (Japanese)]

(14) Y. Matsuno and H. Yamada (1982)
**"Elastic Moduli of Grinding Wheel Based on a Simplified Model"**
*Yogyo-Kyokai-Shi*, Vol. 90 No. 6, pp. 320-325.

The elastic modulus of grinding wheel is one of the very important mechanical properties on the grinding performance and theory of grinding. To obtain this value, the direct measurements on grinding wheels or the mathematical methods from the theoretical relation among volume fractions of grains, bonds and pores that are constituents of a grinding wheel and from each elastic moduli of the constituents are tried in the past. No simple and effective explanation was, however, established between the elastic modulus and composition of grinding wheel. In this paper, a simplified structure model was contrived and from this model, was induced the theoretical formula of the elastic modulus. The elastic modulus of grinding wheel is expressed as E, elastic moduli of grains and bonds as $E_g$ and $E_b$, volume fractions of abrasive grains and bonds in the grinding wheel as $V_g$ and $V_b$. Then, following relation is obtained:

$$E = \{1/V_g^{1/3}E_g + 3(1-V_g^{1/3})^2/V_bE_b\}-1$$

To verify this formula, test specimens of vitrified grinding wheel were trial-manufactured, based on the grain percentage : 43~51%, grade (hardness) : H~R, and grain size : # 46~# 120 of WA, # 60 and # 80 of GC, and the elastic moduli of specimens were measured by 3-point bending method.

The specimen size is 5 (thickness) x 12.8 (width) x 120 mm (length). The obtained values were compared with the calculated ones from the formula, and the results showed a good agreement in each combination of the volume fractions of grains and bonds, employing elastic modulus of WA grain $E_g$ : $35.7 \times 10^5$kgf/cm$^2$ and of vitrified bond $E_b$ : $6.31 \times 10^5$kgf/cm$^2$. The elastic moduli of specimens are in the range of $1 \sim 8 \times 10^5$kgm/cm$^2$. Therefore, the values of elastic moduli from the simplified model of grinding wheel are inferred to be reasonable. (Author) (11 ref., 6 fig., 2 tables, 3 equations, Japanese text)

(15) S. M. Pandit and G. Sathyanarayanan (1982)
**"A Model for Surface Grinding Based on Abrasive Geometry and Elasticity"**
*Journal of Engineering for Industry*, Vol. 104, pp. 349-357, November.

A model for a "characteristic grain" consisting of the superimposition of a large and a small wavelength has been introduced. The large wavelength representing the grain has been used in establishing the elastic deflection of the grain. Due to the elastic deflection, the small wavelength representing the cutting edges cuts a smaller "characteristic groove" on the surface, which provides a prediction of the rms value of the ground surface. Specific energy of grinding can also be predicted. The theoretical expressions for the deflection of the grain and for the rms values are developed from this model and found to agree very well with the values obtained by experiments. With an online measurement of the wheel profile, this approach has potential in computer control of grinding. (Author) (29 ref., 19 equations, 4 tables, 4 fig.)

(16) K. Umino, S. Tooe, and N. Shinozaki (1983)
**"Study on Irregularity of Wheel Grade (1st Report) - Irregularity of Wheel Grade and Grinding Phenomenon"**
*J. Japan. Soc. Pres. Eng.*, Vol. 49 No. 6, pp. 741-746.

In this paper, for a basic study to evaluate quantitatively the grinding ability of a grinding wheel which has irregularity of grade on its surface, grinding phenomenon that occurs during grinding process with such the wheel is considered. The results obtained are as follows: (1) Even if wheel balance is almost perfect, the wheel which has irregularity of grade on the surface influences its grinding ability. (2) Irregularity of grade on the wheel surface acts as one of the sources of forced vibration and influences grinding force and shape accuracy of a ground-workpiece. (3) For quantitative evaluation of grinding ability of a wheel, both the average grade and its irregularity must be considered. (4) Based on ultrasonic pulse method, both the average grade and its irregularity can be measured, and so this method gives us one of the effective procedure to evaluate grinding ability of a wheel. (Author)

Variations in elastic modulus are measured at different radial angles around circumference of wheel; some correlation is shown between elastic modulus and values from accelerometer attached to dresser. Distribution of cutting edges on wheel surface after dressing is illustrated with distribution of modulus around the wheel circumference. Waves of grinding force are observed with localized variations in modulus; also shape accuracy at workpiece is affected. (RWM supplement) [10 ref. (Japanese), 8 fig. (English), 14 equations, Japanese text]

(17) G. Spur and C. Stark (1984)
**"Methods for Testing Grinding Wheel Quality"**
Proc. 12th North American Man. of Res. Conf., pp. 339-346.

Additional test methods are required for grinding wheels to achieve optimal performance and to reduce variability in wheel classifications. Many variables in production processes (and between manufacturers) result in widely varying performance. For example, hardness (ability of grain to resist removal from bond) is dependent on density, grain size quality and distribution, wheel structure (proportions of bond and porosity) and manufacturing process (pressing and firing). Tests of most practical significance are elastic modulus (from natural frequency of vibration of the grinding wheel) and sand-blasting test (measurement of hole erosion). Other tests include density (data about porosity) and ceramography. Additional tests are needed. (RWM) (13 fig., 7 ref.)

(18) S. Tooe, K. Umino, and N. Shinozaki (1987)
**"Study on Grinding Characteristic of Grinding Wheel (1st Report) - Measurement of Grade Irregularity with Ultrasonic Pulse Method and Working States of Grinding Periphery"**
*Bull. Japan Soc. of Prec. Engg.*, Vol. 21 No. 4, December, pp. 245-250.

When high accuracy of the workpiece and the automation of the grinding work are considered, it is necessary to secure the reliability and the reproducibility for grinding wheel as a cutting tool. For the purpose, it is important to choose a grinding wheel of uniform grade. However, more or less grade irregularity could be unavoidable in the production of grinding wheels. As the irregularity of grade changes the grinding characteristic on the working periphery of a grinding wheel locally, it has a bad influence upon the dimensional accuracy of workpiece. It is considered to non-destructively measure the grade irregularity by applying the ultrasonic pulse method, the treatment of which is relatively simple. This method is capable of measuring the elastic modulus of a part of wheel. However, the elastic modulus measured is the mean value of the part which is placed between the emitter and the receiver near the working periphery of grinding wheel. In this study, the elastic modulus by ultrasonic pulse method is compared with the cutting edge density on working periphery and the contact stiffness between the grinding wheel and the workpiece for many kinds of grinding wheels. As the result, it is found that this method is applicable to measure the grade irregularity. (Author)

Comparison on vitrified grinding wheels of localized elastic modulus, stiffness of contact (related to the characteristic frequency after impact on grinding in pressure contact with work) and density of cutting edges [measured with typewriter carbon impressions (holes)]. Variables were grain size, wheel grade (breaking strength according to Ogoshi's grade testing method), structure and grade irregularity. (RWM supplement) (4 ref., 8 fig., 6 equations, 1 table)

## 3.0 WHEEL HARDNESS

(19) L. V. Colwell, R. O. Lane, and K. N. Soderlund (1962)
**"On Determining the Hardness of Grinding Wheels - I"**
*Journal of Engineering for Industry*, Vol. 84, February, pp. 113-128.

A new method for evaluating the hardness of grinding wheels has been developed. It involves crushing small amounts of abrasive from the surface of a grinding wheel while in rolling contact with a hard steel wheel. Measured reaction forces provide a sensitive indication of significant variations in the hardness as well as other important properties of bonded abrasives.

A laboratory analysis of the method demonstrates that the hardness values incorporate the same elastic constants which have been shown to be important in actual grinding. The analysis shows also that it is feasible to establish a universally applicable industrial standard for grinding wheel hardness.

The method is valuable also as a research tool and may be expected to aid in producing more uniform abrasive products and to yield information which will help improve practices in the manufacturing plant. (Author) (4 ref., 10 tables, 18 fig., 22 equations, discussion)

(20) J. Peklenik and H. Opitz (1962)
**"Testing of Grinding Wheels"**
Proc of the 3rd Int'l Machine Tool Design & Res. Conf., pp. 163-177.

Static hardness testing by use of chisel moving across wheel, tearing grains from bond bridges; measurement of bond forces; determines both strength of bond and distance between particles. Cutting edges are determined with a surface profilometer. Dynamic hardness determined on steel block containing a platinum wire; each abrasive grain cuts a small chip of platinum and steel forming a thermocouple with resultant thermal pulses recorded. A correlation is noted between bond force and the number of cutting edges. (RWM) (8 ref., 15 fig., 9 equations)

(21) L. V. Colwell (1963)
**"On Determining the Hardness of Grinding Wheels - II"**
*Journal of Engineering for Industry*, Vol. 85, February, pp. 27-32.

This second progress report on the crush grading of grinding wheels by means of force measurements takes up the question of the effect of variations in system rigidity on hardness ratings. Preliminary results with the consecutive infeed or single-pass procedure show no appreciable effect with a substantial reduction in rigidity. On the other hand, the two-pass or alternate infeed procedure is shown to be sensitive to system rigidity. This characteristic complicates the problem of devising a procedure for deriving a dimensionless hardness number. On the other hand, it offers a mechanism for isolating the effective rigidity of the grinding wheel itself. (Author) (2 ref., 13 fig., 1 table)

(22) W. D. Kingery, A. P. Sidhwa, and A. Waugh (1963)
**"Structure and Properties of Vitrified Bonded Abrasives"**
*Amer. Ceram . Soc. Bulletin,* Vol. 42 No. 5, pp. 297-303.

A simple model for the microstructure of a vitrified bonded abrasive product is described. Measured properties of commercial abrasive wheels are discussed in terms of this model microstructure. The relations necessary to describe the grade and structure of abrasive products are discussed and effects of microstructure on properties described. Analytical calculations are in satisfactory agreement with experimental measurements of strength and thermal conductivity. (Author) Hardness increases with ratio of bond to abrasive, bond strength and decreased porosity. Polished sections were examined in reflected light. Thermal conductivity and thermal expansion were measured. (RWM supplement) (9 ref., 13 fig., 7 equations, 3 tables)

(23) J. Peklenik, R. Lane, and M. C. Shaw (1964)
**"Comparison of Static and Dynamic Hardness of Grinding Wheels"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 86, August, pp. 294-298.

The values obtained by two new methods of measuring grinding-wheel hardness are critically compared for a variety of surface grinding wheels of different grain size and vitreous bond content. The two methods are found to agree quite well in their ability to distinguish wheels of different commercial hardness. One method is dynamic, using a rotating steel cutter, easily applied in the workshop, somewhat more complex to analyze. The other method is quasi-static, using a V-shaped tool to plow a groove, and capable of yielding a more complete picture in research studies of grinding-wheel hardness through statistical analysis of the results obtained. It would appear that both methods represent a distinct step forward in grinding-wheel technology and that each is of value in its own sphere of application. (Author and RWM) (11 fig., 4 ref., discussion)

See also ELASTICITY AND STIFFNESS, reference No. 17

## 4.0 TOPOGRAPHY AND PROFILOMETRY

(24) H. T. McAdams (1964)
**"The Role of Topography in the Cutting Performance of Abrasive Tools"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 86, February, pp. 75-81.

> Correlation and related statistical techniques are used to describe the cutting surfaces of grinding belts and wheels. The relation of these statistics to cutting performance is indicated. (Author) (10 fig., 1 table, 7 ref., 7 equations, discussion)

(25) H. T. McAdams (1964)
**"Markov Chain Models of Grinding Profiles"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 86 No. 4, November, pp. 383-388.

> Profiles of abrasive surfaces are analyzed by means of Markov chain theory. The Chapman-Kolmogorov equations, together with recurrent-event theory, are used to deduce theoretical distributions for such important statistics as the distances between effective cutting points and the lengths of lands on a worn grinding surface. Both first-order and second-order Markov chains are examined for their applicability to a stochastic model of the grinding process. (Author) (5 ref., 9 fig., 16 equations, discussion)

(26) R. W Story and E. J. Keyes (1969)
**"Profile Measurement of Coated Abrasive Surfaces"**
*Journal of Engineering for Industry*, Vol. 91, August, pp. 781-789.

> Coating variations which affect performance include grain weight (amount), grain distribution, grain orientation, and the level of the size coating applied after the grain is in place. The profile is a two-dimensional analog of the surface; a stylus is used to trace the contour determining the average level of high and low points. Discussion of equipment and analytical procedures for grade, grain distribution and density. (RWM) (16 fig., 5 ref., discussion)

(27) D. J. Grieve, H. Kaliszer, and G. W. Rowe (1970)
**"A 'Normal Wear' Process Examined by Measurements of Surface Topography"**
*Annals of the C.I.R.P.*, Vol. XVIII, pp. 585-592.

> The requirements of a technique to study a normal engineering wear process, usually characterized by the change of micro-geometry of the surface, are described.
>
> A stylus instrument used with a computer is employed to measure changes in surface topography that occur during wear. The technique of recording close parallel profiles to obtain a representation of a surface is developed to measure a variety of specimen shapes.
>
> Directional surface effects are examined by evaluating parameters describing the slopes in different directions; a series of results are included. (Author) (7 ref., 10 fig., appendix, discussion, 2 equations)

(28) S. J. Deutsch, S. M. Wu, and C. M. Straklowski (1973)
**"A New Irregular Surface Measuring System"**
*Int. J. Mach. Tool Des. Res.*, Vol. 13, pp. 29-42.

To measure and record highly irregular configurations, a new surface measuring system using an oscillating stylus is developed and coordinated with a data handling unit capable of direct interfacing with a computer. This on-line non-destructive measurement system is found to be accurate, capable of a comprehensive range of utilization and easily operated. Examples of measured grinding wheel profiles and tool craters are shown. (Author) (8 ref., 15 fig.)

(29) D. L. Thompson and S. Malkin (1974)
**"Grinding Wheel Topography and Undeformed Chip Shape"**
*Int'l Conf. on Production Engineering*, Part 1, Tokyo, pp. 727-732.

The topography of grinding wheels of various grain sizes was measured statically by an optical technique and dynamically by studying the scratches left on a smooth steel plate after lightly grinding a single pass. The optical method yielded good results with the coarser grained wheels. At a radial depth into the wheel equal to one grain diameter, the number of grains per unit area was found to approach the theoretical maximum number as calculated from packing considerations. The scratch method provided an effective means for measuring the fine scale topography of the wheel surface. With this method, the number of actual cutting points was found to be relatively insensitive to grain size. This is attributed to larger grains each having more cutting points than smaller ones. From the shapes of the scratches left on the steel plate, the undeformed chip was determined to have a trapezoidal cross-section with typically a 120 degree included angle between the sides and a 1-2 micron width at the bottom. (Author) (14 ref., 10 fig., 10 equations)

(30) Y. Matsuno, H. Yamada, et al (1975)
**"The Microtopography of the Grinding Wheel Surface with SEM"**
*Annals of the C.I.R.P.*, Vol. 24 No. 1, pp. 237-242.

Although a number of methods for the study of grinding wheel surface have been announced, observation with a scanning electron microscope is one of advantageous techniques. The vitrified grinding wheel is adopted as the test sepcimen in the cooperative work on grinding wheel topography in G-group of C.I.R.P. The photogrammetory method is also introduced into this experiment for quantitative measurement. The stereographing conditions used magnifications from 100 to 3000 and a stereographic angle 12°. The stereographs were mapped with a "Stereotop" plotter according to the parallax difference, and the relative height of contour lines ranged from 1 µm to 50 µm. The microtopographs representing cutting edges on a grinding wheel surface can be described by the contour lines. From the experiment on dressed and ground wheel surfaces, it was found that the microtopography is an appropriate method to express the states and numbers of cutting edges of a grinding wheel surface. (Author) (12 fig., 5 ref., 2 tables)

(31) W. König and W. Lortz (1976)

**"Three Dimensional Measurement of the Grinding Wheel Surface-Evaluation and Effect of Cutting Behavior"**

*Annals of the C.I.R.P.*, Vol. 25 No. 1, pp. 197-202.

In order to utilize the technological principles of grinding effectively, the relationship between grinding result and the geometry of the cutting area as well as the distribution of cutting edges should be well understood. A three-dimensional analysis of the structure of the cutting area will permit a comprehensive consideration of relevant influences better than a two-dimensional one.

The characterization of the cutting area is effected by tracing the grinding wheel with a stylus in transverse and circumferential direction. The evaluation of this measurement results in a density distribution of cutting edges. A mathematical formulation using statistical methods opens the way to a description of the three-dimensional cutting edge distribution depending on the kind of grinding wheel, the dressing conditions as well as geometrical and kinematic parameters. The latter are used in calculation to define dynamic cutting edges.

The results appear to be in good accordance with former investigations by other authors. Experiments demonstrate the change taking place in the cutting area after certain grinding times.

Considering important characteristics of the process, as surface finish and normal grinding force, it is intended to show a relation between the kind and the condition of the grinding wheel and its cutting action. (Author) (11 ref., 6 fig., 19 equations, 2 tables)

(32) J. Verkerk (1977)

**"Final report concerning C.I.R.P. Cooperative work on the characterization of grinding wheel topography."**

*Annals of the C.I.R.P.*, Vol. 26 No. 2, pp. 385-395.

In order to characterize the grinding wheel topography two wheels and a dresser have been sent to the cooperating laboratories of C.I.R.P. STC Abrasive Processes. Each experimenter applied its own measurement set-up and way of presentation. The measurements were performed by means of taperprint, microscopic, stylus, thermocouple, dynamometer, photo-electronic and scratch traces measuring methods.

Comparison of the results showed that the various measuring methods when properly interpreted lead to coherent quantitative results. The different measuring methods gave additional information that contributed to a better image of the wheelsurface. (Author) (8 ref., 24 fig., 4 equations, 27 papers in selected bibliography)

(33) M. C. Shaw and R. Komanduri (1977)

**"The Role of Stylus Curvature in Grinding Wheel Surface Characterization"**

*Annals of the C.I.R.P.*, Vol. 25 No. 1, pp. 139-141.

The stylus method of estimating the number of active abrasive grains in the surface of a grinding wheel is discussed. It is suggested that a chisel shaped stylus is preferable to one having a radius of curvature. It is also suggested that the density of active cutting points be expressed in terms of the area of wheel surface (C) instead of per unit length on the wheel face (C'), since the area measurement may be directly measured while the measurement in terms of length must be derived from the area measurement. It is concluded that measured dynamic values of C are about an order of magnitude less than values obtained using a tracer instrument, particularly if the tracer has a small radius of curvature. (Author) (8 ref., 3 fig., 5 equations)

(34) G. N. Shah, A. C. Bell, and S. Malkin (1977)
**"Quantitative Characterization of Abrasive Surfaces Using a New Profile Measuring System"**
*Wear*, 41, pp. 315-325.

An on-line computer-controlled profilometer is described for quantitative characterization of extremely rough surfaces such as grinding wheels and coated abrasives. Conventional profilometers offer difficulty in the characterization of such surfaces because of the tendency of the stylus to become stuck in the crevices. In this present system, the stylus oscillates while the surface below moves incrementally so that the surface is stationary when contacted by the stylus. Both stylus and wheel motion are controlled by a digital computer. Measurements of surface elevation are input to the computer for digital processing and various surface characteristics are computed. The use of the system is illustrated by showing the effects of grit size on coated abrasive topography, (Author) (14 ref., 11 fig.)

(35) P. Koshy, V. K. Jain, and G. K. Lal (1993)
**"A model for the topography of diamond grinding wheels"**
*Wear*, 169, pp. 237-242.

A mathematical model is presented to characterize the topography of a freshly dressed resin/metal bonded diamond grinding wheel. The planar grain density, the area due to exposed abrasives and the abrasive protrusion height distribution of a wheel are estimated with regard to the grit size and volumetric concentration of the abrasives. The model indicates that the protrusion height is approximately uniformly distributed and the percentage of area due to exposed abrasives on the wheel surface is independent of the abrasive grit size for a particular concentration. (Author) (21 ref., 8 fig., 11 equations)

## 5.0 OBSERVATION OF WHEEL SURFACE TEXTURE

(36) W. R. Backer, E. R. Marshall, and M. C. Shaw (1952)
**"The Size Effect in Metal Cutting"**
*Trans. ASDME,* Vol. 74, pp 61-72.

Cutting points are determined on the wheel surface from a trace produced by rolling the grinding wheel across a soot-covered glass plate. A thickness of 0.0001 in. of carbon black provides a replica with sufficient contrast for photographic enlargement using replica as negative. The points/in$^2$ are counted. The size of the cutting area is exaggerated. (RWM) (17 fig., 10 ref., 33 equations, 4 tables, discussion)

(37) K. E. Schwartz (1959)
**"A Film for Recording the Reactions in the Diamond Wheel Structure"**
*Industrial Diamond Review*, November, Vol. 19, pp. 214-218.

Flash-synchronized photographic observation of grinding wheel surface during operation. Observation of wear surfaces just after interaction on successive revolutions. (RWM) (4 ref., 11 fig.)

(38) S. G. Red'ko (1960)
**"The Active Grits on Grinding Wheels"**
*Machines and Tooling*, Vol. XXXI No. 12, pp 11-13.

Experiments on character of distribution and quantity of abrasive grains on the working surface of a grinding wheel: 1) By counting particles (with a microscope) with flat areas caused by wear; 2) By counting grains stained by turning wheel along a stained glass plate; 3) By counting thermal impulses in grinding small-diameter thermocouples. (RWM) (7 fig.)

(39) H. Grisbrook (1962)
**"Cutting Points on the Surface of a Grinding Wheel"**
Proceedings 3rd International Machine Tool Design and Research Conference, pp 155-161.

Examination of wheel surface on projection microscope shows multiple cutting points per grit particle and spacing. (RWM) (8 ref., 4 fig., 1 table)

(40) S. G. Red'ko and A. V. Korolev (1970)
**"Distribution of Abrasive Grains on Grinding-Wheel Faces"**
*Machines and Tooling*, Vol. XLI No. 5, pp. 64-65.

An experimental method of determining the depth of individual abrasive grain crests, relative to the periphery of the grinding wheel, is described. The method consists of a microscopic viewing at an angle to the wheel face ( in the plane of the wheel). The method is simple and convenient to use. A graph of abrasive-grain distribution over the surface of a type E9A4OSM2K wheel is given. The most accurate grain distribution is expressed by half depth of all grains measured. Different types of dressing are discussed. (Author and RWM) (3 fig.)

(41) A. M. Besuyen (1971)
**"The Measurement of the Grinding Wheel Wear with the Quantimet Image Analyzing Computer"**
*Annals of the C.I.R.P.*, Vol. XVIV, pp. 619-624.

In-process measurement of the wear land of the abrasive grains is needed for research on the mechanism of the grinding process. The measuring of the wear during the process of grinding, without interrupting the process, is in development at Delft. Many details of in-process measuring correspond with post-process measuring by means of the Quantimet Image Analyzing Computer. Therefore, this method has been chosen for preparatory study as a gauging method for in-process measuring.

The paper describes the study of the suitability of the Quantimet for determining the quantity of the wear land of the grains as a percentage of the working-face of the grinding wheel. An investigation has been made into the nature of the worn grain parts with the aid of the optical microscope and the electron-microscope. An enumeration of methods of measuring the wear land of the grains is given; their reliability is mentioned.

It follows from the study that the Quantimet is suitable for evaluation of photographs of the worn grain flats. It is possible to separate hazy images of grain-fractures, which are partly situated within the depths of focus of the microscope. A separate circuit detects the images on the principle of the definition. (Author) (8 ref., 2 tables, 7 fig.)

(42) C. P. Bhateja, A. W. J. Chisholm, and E. J. Pattinson (1971)
**"A Computer-Aided Study of the Texture of the Working Surfaces of Grinding Wheels"**
Proc 12th Annual Intl. MTDR Conf. Manchester, England, pp. 535-541.

A computer-aided technique for studying the surface texture of the working surfaces of grinding wheels has been developed. This has been used to investigate the effect of wheel dressing conditions on the behavior of the grinding wheel surface during use in grinding. It has been found that the total number of surface asperities on the working surface of a sharp wheel is virtually independent of the dressing feed, though with a degree of bunching of asperity peaks towards the outer region of the wheel surface. The degree of bunching of these asperity peaks decreases with increasing coarseness of dressing. The valleys in the surfaces, on the other hand, have a Gaussian-type frequency distribution. Significant changes in the forms of the frequency distributions of both asperity peaks and valleys on the working surface of the grinding wheel occur when the wheel becomes substantially worn. It is thought that the technique may be used in further studies of the wearing action of grinding wheels. ( Author) (8 ref., 2 tables, 8 fig., 2 equations, discussion)

(43) S. Malkin and N. H. Cook (1971)
**"The Wear of Grinding Wheels Part 1- Attritious Wear"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 93., November, pp. 1120-1128.

An investigation of attritious and fracture wear of grinding wheels in precision grinding is described in a two paper sequence. Attritious wear, the subject of this first paper, refers to the dulling of the abrasive grain due to rubbing against the workpiece surface. The amount of dulling, measured by the area of the wear flats on the surface of the wheel, is found to be directly related to the grinding forces. In general, both the vertical and horizontal grinding force components increase linearly with the wear flat area. This is explained by considering the grinding force as the sum of a cutting force due to chip formation and a sliding force due to rubbing between the wear flats and workpiece. Related studies of wheel dressing, surface finish, and workpiece burn are also presented. (Author) Wear flats were measured with a microscope with a vertical illuminator (flats appear bright). The number of active grains (those with flats/area) was determined. (RWM supplement) (20 ref., 21 fig., 3 tables, 13 equations)

(44) K. Nakayama (1973)
**"Taper Print Method for the Measurement of Grinding Wheel Surface"**
*Bull. Japan Soc. of Prec. Engg.*, Vol. 7 No. 2, June, pp. 59-60.

A technique is described for use of carbon paper and pressure to transfer information of wheel surface geometry onto paper record. (RWM) (4 ref., 4 fig.)

(45) R. Komanduri and M. C. Shaw (1974)
**"A Technique for Investigating the Surface Features of a Grinding Wheel"**
Annals at the C.I.R.P., Vol. 23 No. 1, pp. 95-96.

A technique is described for replication of surface details using cellulose acetate tape, subsequently viewed by SEM. To avoid tearing, thick [0.006 - 0.015 - in (0.015-0.0375 mm)] sheet is used. (RWM) (3 ref., 4 fig.)

(46) S. Malkin and T. Murray (1978)
**"Mechanics of Rotary Dressing of Grinding Wheels"**
*Journal of Engineering for Industry*, Vol. 100, February, pp 95-102.

An investigation is reported on the mechanics of the rotary dressing process for grinding wheels. Dressing forces were measured over a wide range of conditions, and SEM observations were made of the dressed wheel surfaces. It was found that the rotary dressing process is mainly controlled by the magnitude of the interference angle between the paths of the abrasive grains and the diamonds on the dresser surface. With a larger interference angle, there is a greater tendency for the abrasive to fracture rather than to plastically deform, thereby reducing the specific dressing energy and providing a sharper wheel with less flattened area on the grain tips. (Author) (14 ref. 10 equations, 15 fig., 1 table)

See Also TOPOGRAPHY AND PROFILOMETRY, Nos. 30 and 31
ELASTICITY AND STIFFNESS, No. 18

(47) P. Sathiamoorthy, V. Radharkrishnan, and J. F. Raman (1979)
**"Measurement and Analysis of Grinding Wheel Surfaces"**
*Precision Engineering*, Vol. 1, pp. 31-32.

Understanding of the mechanism of grinding is hampered by the difficulty of defining the effective cutting geometry. This paper describes a simple technique for the analysis of grinding wheel profiles. This study includes the random process analysis of the section and effective profiles of the wheel. (Author) (4 ref., 3 fig.)

(48) K. Syoji, L. Zhou, and S. Matsui (1990)
**"Studies on Truing and Dressing of Diamond Wheels (1st Report) - The Measurement of Protrusion Height of Abrasive Grains by Using a Stereo Pair and the Influence of Protrusion Height on Grinding Performance"**
*Bull. Japan Soc. of Prec. Engg.*, Vol. 24 No. 2, June, pp. 124-129.

The protrusion height of abrasive grain in a metal bonded diamond wheel plays an important role in grinding performance. Low protrusion height, for example, promotes the loading and increases grinding force markedly. A wheel with large protrusion height, on the contrary, has a problem of attrition wear and releasing of cutting edges. However the precise measuring method adapted to the protrusion height has not been developed so far. In this paper, a new 3-dimensional measuring technique [3D method] is proposed by using a SEM stereo pair. And the effect of magnitude of the protrusion height on a diamond wheel which is trued and dressed with a GC cup-truer is investigated experimentally on Si3N4 ceramic grinding. The main results obtained are as follows: (1) A typical cutting surface is structured after truing and dressing. Abrasive grains protrude over the flat base of metal bond and are followed with long bond-tails. (2) Grinding force grows monotonously along with the number of grinding passes and the increasing rate become lower when a larger protrusion height is applied. (3) The optimum protrusion height is discussed focusing on variations of grinding force, finished surface roughness and wheel wear. (Author) (3 ref., 12 fig., 1 table, 1 equation)

## 6.0 WHEEL WEAR

(49) H. Yoshikawa (1963)
**"Fracture Wear of Grinding Wheels"**
Prod. Engineering Res. Conf, ASME, pp. 209-217.

> Performance of grinding wheel should be interpreted in terms of microscopic structure of wheel surface and its changes during grinding; e.g., wear plateaus and new cutting edges due to mechanical fractures and tearing out of grains. (RWM) (30 ref., 10 fig., 21 equations)

> See Also TOPOGRAPHY AND PROFILOMETRY, No. 27
> OBSERVATION OF TEXTURE OF WHEEL SURFACES, Nos. 41 and 43

(50) S. Malkin and N. H. Cook (1971)
**"The Wear of Grinding Wheels - Part 2 - Fracture Wear"**
*Journal of Engineering for Industry* (Transaction of the ASME), Vol. 93, November, pp. 1129 - 1133.

> The nature and extent of grinding wheel wear in precision grinding were investigated directly from the wear particles removed from the wheel. A statistical analysis of the wear particle size distributions was developed to determine the relative amounts of bond fracture, grain fracture, and attritious wear. Most of the wear consists of grain and bond fracture particles with relatively more bond fracture occurring with softer wheels. The rate at which fracture wear occurs is directly related to the grinding forces and the amount of binder in the wheel. The attritious wear, although contributing insignificantly to the total, is the most important form of wear as it is directly related to the size of the wear flats, grinding forces, and workpiece burn, and therefore controls grain and bond fracture wear. (Author) (3 ref., 11 fig., 4 equations)

(51) T. J. Vickerstaff (1973)
**"Wheel Wear and Surface Roughness in Cross Feed Surface Grinding"**
*Int. J. Mach. Tool Des. Res.*, Vol. 13, pp. 183-198.

> A wheel wear mechanism is proposed for the cross feed surface grinding process which is consistent with that reported for other grinding processes. Test results are presented which confirm the proposed wear mechanism. The effects of cross feeding in both directions and using automatic feeding arrangements are discussed. The workpiece surface roughness is shown to be dependent on the ratio of wheel width to cross feed increment. The influence of a range of grinding conditions on both wheel wear and surface roughness is investigated. (Author) The wheel profile is checked by grinding a replica in the edge of a thin hardened steel blade. The blade was examined on a stylus surface-measuring instrument. (RWM supplement) (11 ref., 16 fig.)

(52) C. E. Davis (1974)
**"The Dependence of Grinding Wheel Performance on Dressing Procedure"**
*Int. J. Mach. Tool Des. Res.*, Vol. 14, pp. 33-52.

A number of techniques of pre-grinding preparation of a resin bond diamond abrasive grinding wheel have been investigated. The wheel condition after dressing was assessed by reciprocating plunge grinding of a fully annealed tool steel. The development of grinding force and the progression of wheel wear with time were measured and are discussed. (Author) (7 ref., 25 fig., 2 equations, 1 table)

(53) T. Yuhta, et al (1978)
**"On the Surface Nature of Diamond Wheel in the Process of Grinding Carbon Steel"**
*Annals of the C.I.R.P.*, Vol. 27 No. 1, pp. 255-259.

In this paper, in order to learn the relation between the surface nature of diamond wheel and the characteristics of grinding and wear of diamond wheel, experimental investigation on the change of surface nature of diamond wheel was carried out and using the results, a simulation which was designed for the grinding process with release and attrition wear of abrasive grain was carried out.

The experimental results show that there is a close relation between the grinding process and the surface nature of diamond wheel. For example, the number of effective abrasive grains increases with time in the transition of grinding process and become constant in the steady state. The distribution of abrasive grains toward bonding surface shows the same tendency . The results of the simulation prove that the decline of grinding efficiency in the transition is caused by attrition wear of abrasive grains. It is clear that the process of releasing Ni-clad diamond abrasive grains passes through loosing of bonding, rotation, rolling and movement of abrasive grains. It is suggested that the critical bonding force at loosening bonding decreases rapidly as a result that it is influenced by moment when projecting ratio abrasive grains is larger than about 0.5. (Author) (6 ref., 14 fig., 4 equations)

(54) J. Shibata, T. Goto, and M. Yamamoto (1982)
**"Characteristics of Air Flow Around a Grinding Wheel and Their Availability for Assessing the Wheel Wear"**
*Annals of the C.I.R.P.*, Vol. 31 No. 1, pp. 233-238.

In order to achieve unmanned as well as automated grinding systems, the development of in-process measuring devices for measuring wheel wear would be one of the most important factors. In this study, air flow characteristics around the grinding wheel were investigated experimentally and their availability for assessing wheel wear was discussed. The main points of the results obtained here are as follows:
(1) The layer of the peripheral air flow basically consists of two regions: central and outer.
(2) In order to assess the wheel wear from air flow characteristics, they should be measured in the central region, especially nearer to the wheel surface for detecting a decrease in the wheel radius and at a more distant position for detecting the variations in surface topography.
(3) The presence of a scraper plate can increase detection accuracy.
Furthermore, actual grinding tests were performed and it was confirmed that the method proposed here could be used for in-process measurement of the decrease in wheel radius. However, there still remain some problems for monitoring the wheel surface topography. (Author) (5 ref., 20 fig.)

# 7.0 IN - PROCESS MONITORING OF WHEEL OPERATION

## 7.1. Acoustic Emission (AE)

(55) D. Dornfeld and He Gao Cai (1984)
**"An Investigation of Grinding and Wheel Loading Using Acoustic Emission"**
*J. Eng. Industry* (Transactions of the ASME ), Vol. 106, February, pp. 28-33.

This paper investigates the potential for using acoustic emission signal analysis for a monitoring technique for process automation as well as a sensitive tool for investigation of grinding fundamentals. The acoustic emission generated during the grinding process is analyzed to determine its sensitivity to process efficiency and the condition of the grinding wheel. Acoustic emission from surface grinding is used to measure wear-related loading of the grinding wheel and sparkout (or loss of contact) between the wheel and the work surface. A discussion of energy dissipation in grinding and the generation of acoustic emission is included. This investigation showed that the acoustic emission energy, (RMS)2, increases with the combined effects of wheel wear and loading, the signal energy, (RMS)2, is a function of the undeformed chip thickness and that the signal accurately detects work-wheel contact and sparkout with a higher sensitivity than force measurement. (Author) (17 ref., 11 fig., 3 equations)

(56) Y. Kakino (1984)
**"Monitoring of Metal Cutting and Grinding Processes By Acoustic Emission"**
*Journal of Acoustic Emission*, Vol. 3 No. 3, pp. 108-116.

This paper reviews the present state of acoustic emission technology in Japan as applied to monitoring abnormalities in metal cutting and grinding processes. Successful monitoring is the key to promoting factory automation in metal working operation. Detection and processing of acoustic emission signals are examined. The importance of transducer locations and signal transmission paths for practical uses in machine tools is suggested. Means of reducing noise interference is discussed. Several practical examples are reviewed: 1) detection of cutting tool breakage, 2) breakage prevention and life time monitoring of small diameter tools, 3) detection of tool-workpiece contact, 4) detection of probe-workpiece contact, and 5) detection of thermal cracks of cutting tools. Finally, perspectives of acoustic emission technology are presented. (Author) (8 ref., 10 fig., 2 tables)

(57) H. Eda, K. Kishi, et al (1984)
**"In-Process Detection of Grinding Burn by Means of Utilizing Acoustic Emission"**
*Bull. Japan Soc. of Prec. Engg.*, Vol. 18 No. 4, December, pp. 299-304.

Grinding tests under abusive conditions have been performed in this study, with the aim of in-process detecting of grinding burn. Acoustic emission signals, which were detected during the progress of grinding burn, have been analyzed and compared with the signal before grinding burn occurred. The following results have been obtained: (1) Under a fixed grinding condition, the amplitude of AE signal increases with the number of grinding cycle and the progress of grinding burn. (2) AE around the frequency range of 10 kHz shows large power density when the abrasive grains are new and grinding burn has not yet taken place, but it decreases as the grains become worn and grinding burn proceeds.

(3) Frequency components of AE over 100 kHz increase with progress of grinding burn. (4) From the above facts, AE signal was led to two channels; one for the signal higher than 10 kHz (B), the other for the signal between 100 and 300 kHz (A). The ratio of the levels of these signals (A/B) showed good correspondence with the progress of grinding burn. By utilizing this relationship, it becomes possible to detect grinding burn in-process by means of acoustic emission. (Author) (4 ref., 13 fig.)

(58) I. Inasaki (1985)
**"Monitoring of Dressing and Grinding Processes with Acoustic Emission Signals"**
*Annals of the C.I.R.P.*, Vol. 4 No. 1, pp. 277-280.

The grinding process is affected by many factors. These include the selection of grinding wheel, the dressing condition and of course the grinding condition. In addition, the performance of the grinding wheel changes considerably during the grinding process. Therefore, it becomes important to monitor the dressing as well as the grinding process, so that the required result is achieved. In this study the acoustic emission (AE) signal is used to monitor these processes. The dressing process is monitored to produce a grinding wheel surface of constant quality. The tool life of the grinding wheel can be defined by monitoring the change of the amplitude and the frequency characteristic of the AE signal. Contact between the grinding wheel and the workpiece can be successfully detected with the AE signal, which means that this method is effective as a gap-eliminator. (Author) Sensors (1MHz) were mounted to the dresserholder and tailstock. Non-uniform wear of wheel was detected by AE. Grinding behavior was predicted by AE during dressing; during dressing the frequency of peak signals was relatable to mean separation of cutting edges on the wheel. AE was also used to detect initial contact of wheel with workpiece. (RWM supplement) (6 ref., 11 fig., 12 equations)

(59) H. Eda, Y. Kakino, et al (1985)
**"In-Process Detection of Grinding Cracks by the Use of Acoustic Emissions"**
*Bull. Japan Soc. of Prec. Engg.*, Vol. 19 No. 3, September, pp. 181-185.

In this study, grinding tests have been performed under abusive conditions to hardened steel, with the aim of detecting grinding cracks. In-process acoustic emission signals, which were detected during grinding, have been analyzed and compared with the signal produced before the grinding cracks were formed. Acoustic emissions between 600 - 800 kHz are detected when grinding cracks are formed, but are not detected when grinding cracks are not formed. By utilizing this relationship, it becomes possible to detect grinding cracks in-process. (Author) (4 ref., 13 fig.)

(60) T. Blum and D. A. Dornfeld (1990)
**"Grinding Process Feedback Using Acoustic Emission"**
SME Technical Paper MR90-525, 4th International Grinding Conference, October 9-11, Dearborn, Michigan.

This paper addresses new technologies for sensing the condition of the grinding wheel and for providing feedback on the efficiency of the grinding operation for process control. A review of sensing challenges in grinding is presented. This paper describes recent research in the application of acoustic emission sensing to grinding including: sparkout and contact detection, wheel loading, wheel dressing, and infeed control for plunge grinding. Results of experimental evaluation of these applications is presented. The results show that the acoustic emission signal is extremely sensitive to wheel/work contact, wheel condition and metal removal characteristics. Sensitivity to work surface burning is also demonstrated. The most promising application of this technology seems to be in precision grinding applications for which conventionally monitored parameters (such as wheel contact forces, low frequency vibration or spindle motor current) may be ineffective due to small metal removal rates. (Author) (23 ref., 17 fig., 2 equations)

(61) W. König and H. P. Meyen (1990)
**"AE in Grinding and Dressing: Accuracy and Process Reliability"**
SME Technical Paper MR90-526, 4th International Grinding Conference, October 9-11, Dearborn, Michigan, 20 pages.

Detection of the AE signal in the grinding and dressing processes is essentially determined by the characteristics of the specialized sensor employed and by the transmission behavior of the measuring chain. Adapted design of the complete signal processing system allows reliable compensation of thermal and dynamic displacements and detection of a variety of dressing faults during the conditioning process. Industrially tested applications demonstrate the accuracy and reliability of monitoring systems for the conditioning of CBN and conventional grinding wheels. (Author) (11 ref., 19 fig.)

(62) I. Inasaki (1991)
**"Monitoring and Optimization of Internal Grinding Process"**
*Annals of the C.I.R.P.*, Vol. 40 No. 1, pp 359-362.

The grinding process is influenced by many factors such as grinding wheel characteristics, dressing conditions and, of course, grinding conditions. Therefore, it is difficult to perform the grinding operation in an optimum state. In this study, in-process monitoring methods using power and acoustic emission sensors are proposed to detect malfunctions in the internal grinding process (AE). In addition, a new internal grinding cycle featuring rapid infeed is proposed to minimize the grinding cycle time. (Author) The AE is detected through the cutting fluid path. Monitoring the grinding power to calculate the time constant and dead time (delay between change in power and change in work piece dimensions) is effective to evaluate wheel surface characteristics. Sudden increase in grinding power occurs with grinding burn. Chatter vibrations are detected with AE. (RWM supplement) (6 ref., 15 ref.)

(63) Y. P. Chang, A. E. Diniz, and D. A. Dornfeld ( 1992)
**"Monitoring The Grinding Process Through Acoustic Emission Using A Squirter"**
Japan/USA Symposium on Flexible Automation - Vol. 1, ASME.

An acoustic emission (AE) squirter type sensor has been developed and investigated for monitoring cylindrical grinding process. Experiments have been conducted to evaluate the influence of grinding variable changes on the sensor signals. The mean AErms is used as the primary sensor signal and shows satisfactory sensitivity to the variations in the grinding variables. The sensor was attached to the cutting fluid supply line. Signals related to coolant flow condition are also studied. The frequency spectra of the signals illustrate that the AE signals from grinding are only contained in a high frequency range (220 - 450 kHz.). A high pass filter has been adapted in an attempt to eliminate noise. (Author and RWM) (19 ref., 13 fig.)

(64) D. Dornfeld (1992)
**"Application of acoustic emission techniques in manufacturing"**
*NDT International*, Vol. 25 No. 6, pp. 259-269.

This paper reviews applications of acoustic emission sensing techniques in manufacturing processes. Acoustic emission (AE) has seen a tremendous growth in use in process monitoring and quality control in manufacturing processes since its discovery in the early 1950s in Germany. Originally applied to the destructive testing of structures (especially storage and pressure vessels) it has also become a monitoring technique in manufacturing due to its sensitivity to process parameters. This paper gives some background on the sensing needs in manufacturing for machine diagnostics as well as process monitoring, reviews the potential for AE application in manufacturing and illustrates some of the existing applications dating back to the first process monitoring in the 1970s. Special emphasis is on machining and tool condition monitoring. (Author) Success was noted in AE of grinding with objectives for monitoring contact and sparkout, wheel dressing and wheel wear and the detection of chatter or deterioration of surface finish. (RWM supplement) (60 ref., 8 fig., 3 tables)

## 7.2 Other Methods

See Also: WHEEL HARDNESS, No. 20

(65) H. Tsuwa (1964)
**"An Investigation of Grinding Wheel Cutting Edges"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 86, November, pp. 371-382.

A new apparatus for tangential and angle-viewing microscopic observation and tracing of cutting edges of a wheel has been developed. An electro-optical system is used for recording. The use of this apparatus allows us to visually witness the behavior of abrasive grains during the grinding operation. A phase-contrast microscope, as well as an electron microscope has been used with the new apparatus in this investigation. A method of calculating effective grain spacing to show distribution of cutting edges, as well as the cutting edge ratio to known worn conditions of grains has been completed. These aforementioned values for various grinding wheels have been studied in grinding operations and the changing aspects of them have been noted. Through these experiments, we have had helpful suggestions about grinding mechanisms; there is no self-dressing action of grains in the usual grinding work; sliding of the cutting edges takes place in the grinding, and wear of the grinding is increased by this action. (Author and RWM) (35 fig., 10 ref., 9 equations)

(66) H. Makino, T. Surro, and E. Fukushima (1966)
**"An Experimental Investigation of the Grinding Process"**
*Journal of Mechanical Laboratory of Japan*, Vol. 12 No. 1, pp. 17-25.

In the process of precision grinding of hardened steel, roughness of ground surface shows a characteristic variation according to the operational condition. At the beginning of the grinding process the roughness of ground surface is subjected to the effect of dressing for wheel. As the grinding goes on, however, surface roughness eventually approaches a final value which is determined by the rate of stock removal and specification of wheel.

From these facts it is considered that the micro-structure of wheel face such as topography by which the profile of ground surface is generated usually varies accompanied with the progress of wheel wear. While there are many ways to express the micro-structure of wheel face, the thermo-couple method has a feature that the successive cutting point spacing of wheel face in grinding is able to be obtained.

The paper deals with the precise experiments for measuring successive cutting point spacing using a device based on the thermo-couple method, and also the relation between the active cutting point in grinding and the geometrical state of workpiece surface. (Author) (3 ref., 15 fig., 6 equations)

(67) T. Suto (1968)
**"A New Apparatus for Measurement of Cutting Edges on Grinding Wheel"**
*J. Soc. Precision Mechanics*, Japan, Vol. 34, pp. 606-611.

The present paper deals with a new method of high speed measurement of active cutting edges, which is an effective in-process measurement and has a possibility to application as a sensor for adaptive control grinding. An apparatus composed of microscope, photomultiplier tube, electric circuit, and electronic counters has been developed to measure the number and area of worn flank surfaces of active cutting edges and successive cutting edge spacing. Relation between the area of wear land of the cutting edge and its photo-electrical pulse is examined. It is verified that the height of the pulses is practically considered to be in proportion to the area of wear lands, if an adequate condition of the time constant of the electric circuit is selected. As the result, a new method that treats the height of the pulse is introduced to realize speedy and in-process measurement. For example, it takes only one second to measure a circumference of wheel with 300mm diameter. Experiments with this apparatus are performed upon GC #46 wheel used to grind a high speed steel. The distribution and average of the area of worn flank surfaces of active cutting edges, and how they change during the grinding process are also investigated. (Author) (Japanese text) [6 ref. (1 German text), 11 fig.]

(68) J. K. Banerjee and M. J. Hillier (1969)
**"Wheel Wear Pattern in Surface Grinding"**
*Tool and Manufacturing Engineering*, February, pp. 59-61.

Grinding force measurements were made on a freshly-dressed wheel. In early passes the edge of the wheel crumbled rapidly and grinding forces are not sensitive to thermal growth of workpiece. The latter becomes more effective after wear land settles to table geometry. (RWM) (3 ref., 6 fig., 8 equations)

(69) T. Suto, T. Waida, and T. Sata (1969)
**"In-Process Measurement of Wheel Surface in Grinding Operations"**
10th Machine Tool Design Res. Conf., pp. 171-180

A new method for in-process measurement of active cutting edges on the grinding wheel is proposed. The light which is projected on the wheel surface and reflected is received by a photomultiplier through a slit. Then the output of the photomultiplier is amplified and modulated in square wave form to give the position and worn area of active cutting edges on the wheel surface. Growth of worn area, tearing out, fracturing and new exposure of active cutting edges are examined with this equipment. Under various grinding conditions these behaviors of active grains are investigated. (Author) Other calculations of total number of active grains, total length of wear land, and ratio of different kinds of grain. Changes in number of active grains with different grinding parameters are shown. The effect of dressing on development of worn areas is addressed. Grain survival increases with grinding speed or work speed. (RWM supplement) (8 fig., 4 ref., 4 equations)

(70) J. N. Brecker and M. C. Shaw (1974)
**"Measurement of the Effective Number of Cutting Points in the Surface of a Grinding Wheel"**
International Conf. on Production Engineering, Part 1, Tokyo, pp. 740-745.

A new method of determining the active number of cutting points in the surface of a grinding wheel is described that includes elastic and dynamic effects. The method employs a workpiece that is so thin that only one grain is in contact at a time, thus enabling the number of chips produced in a given time to be determined by measuring the number of force peaks using a piezoelectric dynamometer of very high frequency response. (Author) Dressing conditions play a major role in determining the active number of cutting points. The active number of cutting points varies appreciably for grinding conditions that involve very small chips (sparkout, fine grain size, fine dressing conditions). (RWM supplement) (8 ref., 11 fig., 7 equations)

(71) T. Suto, H. Inoue, et al (1976)
**"A Newly Developed In-Process Sensor for Detecting Active Grain Wear in Grinding Operation"**
*Annals of the C.I.R.P.*, Vol. 25 No. 1, pp. 229-234.

A photo-electronic sensor has been newly developed for the real time detection of the collective behaviors of the active grain wear even at 60 m/sec wheel speed. With this sensor, the growth of the spacially periodic wear of active grains has been experimentally investigated. When the initial wear land caused uniformly over the wheel working surface grows to a certain level, it changes into a striped pattern consisting of fractured and worn grains arranged alternately, inducing chatter vibration. The stripes decrease in number to a certain value with the progress of grinding, increasing the pitch. However, all pitches are not equal even on the same wheel circumference, but are distributed into several different lengths. Through the simultaneous observations of the grain wear and the chatter vibration, the coincidence of their growth and period has been found. Thus, the possibility to identify the wheel surface conditions for the purpose of adaptive control of grinding process has been verified. (Author) (8 ref., 13 fig., 1 equation)

(72) W. Radhakrishnan and J. Fazlur Rahman (1977)
**"A Preliminary Investigation on the Condition of the Grinding Wheel Surface by Air Flow Measurements"**
*Annals of the C.I.R.P.*, Vol. 25 No. 1, pp. 147-150.

Rotating bodies cause air to flow around them. When the surface of the rotating body is having marked irregularities these may cause variations in the nature of flow. A grinding wheel rotating at high speeds is a typical example for this. In this paper, a preliminary study of the grinding wheel surface condition based on the air flow around it, is reported. The air flow measurements were those with a pitot tube and a hot wire anemometer, for different wheels and at different conditions. The results showed a clear change in the flow pattern depending on the grinding wheel surface condition. This measurement is of practical significance as it may indicate the stage at which a redressing of the grinding wheel becomes necessary. (Author) (9 ref., 14 fig., 7 equations)

(73) L. Tigerstrom (1981)
**"Dynamic Measuring of Number of Grinding Edges and Determination of Chip Parameters"**
*Manufacturing Engineering Trans.*, SME, pp. 1-7.

A measuring equipment incorporating a piezoelectric dynamometer in the workpiece is presented with which the active edge density is measured as a function of the "injection angle" of the workpiece material flow into the grinding wheel. The results obtained make possible a determination of the active edge density for different grinding processes and grinding data. The contact arc of the individual active edge in relation to the real contact arc can be determined, as well as the maximum area of the undeformed chip section of the individual edges. Because the measurement is made continuously during several wheel revolutions, the dynamic behavior of the wheel can be studied. (Author and RWM) (14 fig., 10 ref., 14 equations)

(74) M. Higuchi and A. Yano (1981)
**"Characteristics of Sound Radiation of Grinding Wheel - Study on the Grinding Sound (1st Report)"**
*Bull. Japan Soc. of Prec. Engg.*, Vol. 15 No. 4, December, pp. 243-248.

It is universally admitted that the grinding sound is of considerable utility as the informational medium of grinding phenomenon.

The sound radiation of the grinding wheel, which is one of the sound sources in the grinding process, has not yet been clarified although it caused a lively concern. In the present paper, the discussion of the characteristics of sound radiation from the grinding wheel is based on its acoustic constant. The experimental results obtained are as follows. (1) The grinding sound pressure level tends to increase with the product Lc.tmax and level off when the mean cutting force is equal to the strength of bond bridge. (2) The highly peaked constant bandwidth spectra of the grinding sound appear at the frequencies which agree very well with the natural frequencies of the grinding wheel. (3) The highly peaked spectrum levels also increase with the product Lc.tmax, especially the effect of increased undeformed chip thickness tmax is larger than the effect of increased undeformed chip length Lc. (Author) (6 ref., 10 fig., 2 equations)

See also WHEEL WEAR, No. 54

(75) V. Radharkrishnan and B. T. Achyutha (1985)
**"In-Process Monitoring of Corner Wear in Cylindrical Plunge Grinding for Possible Adaptive Control Applications"**
Milton C. Shaw Grinding Symposium PED 16 ASME, N.Y.

Corner wear in plunge grinding is critical since this affects the tolerance specified on the plunged corner radius on the component. Grinding of crankshaft is illustrative of this requirement. This paper deals with the nature and geometry of the corner wear and its continuous monitoring using the fluctuations in the airflow velocity around the grinding wheel. The changes in the airflow due to the corner wear could be used as a feed back signal for adaptive control of the grinding process. (Author) This is not for continuous monitoring due to effects of swarf and coolant. Transducers other than the pitot tube could be unaffected by coolant, allowing continuous monitoring. (RWM supplement) (11 ref., 20 fig.)

## 8.0 CHARACTERIZATION OF GROUND SURFACES

See Also: WHEEL WEAR, No. 51

(76) C. P. Bhateja (1975)
**"The Intrinsic Characteristics of Ground Surfaces"**
Proceedings: Thirteenth Annual International Technical Conference, Chicago, Illinois, May 4-6, American Society for Abrasive Methods, pp. 11-18.

This paper describes an anatomical study of ground surfaces. The complex nature of the ground surface texture is unfolded with the help of the scanning electron microscope, the computer assisted analysis of surface profiles and the taper sectioning techniques.

Several inherent features of the ground surface texture are identified with their origins. The influences of the grinding wheel characteristics, the diamond dressing process and the various grinding variables have been discussed. The study has revealed that the various mechanisms of grinding wheel wear, namely, grit fracture, attrition and bond failure type dislocation of grits, have their signature effects on the ground workpiece.

It is proposed that the ground surface texture is the combined result of the processes of ideal cutting, ploughing with side displacement and back transfer of work material. In spite of the fact that these processes are influenced considerably by the numerous grinding variables, both controlled and uncontrolled, it is interesting to find that the gross features of the ground surface microtexture do follow certain predictable patterns. (Author) (8 ref., 11 fig., 1 table)

(77) T. Busch (1968)
**"Let's clean up - The Mess in Surface Measurement"**
*The Tool and Manufacturing Engineer*, Vol. 60 No. 1, January, pp. 54-59.

Clarifies misconceptions of surface measurement and profiles using both mean-line methods and area systems. (RWM) (8 ref., 8 fig.)

(78) T. J. Vickerstaff (1970)
**"Diamond dressing - its effect on work surface roughness"**
*Ind. Diamond Review*, Vol. 30, pp. 260-269.

A research programme has been undertaken to establish the parameters of the dressing process - using single-point diamond tools - which are significant in relation to the work surface roughness produced. The wheel profile and the work surface have been investigated to determine the relationship between them. (Author) (16 ref., 7 fig., 5 tables)

(79) H. Kaliszer and G. Trmal (1974)
**"Factors Influencing the Topography of Ground Surfaces"**
Intl'l Conf. on Production Engineering, Part 1, Tokyo, pp. 689-694.

The paper analyzes the types and the formation of macro and micro geometry generated on the workpiece periphery as a result of conventional plunge grinding operation.

The paper also contains general guidance for Industry including practical examples based upon the optimisation of grinding conditions.

Special consideration is given to the effect of wheel unbalance by considering the apparent run-out of the wheel periphery and the superposition of waves generated on the surface periphery of the ground components. (Author) (6 ref., 9 fig., 1 table, 5 equations)

# 9.0 MISCELLANEOUS

(80) E. J. Krabacher (1959)
**"Factors Influencing the Performance of Grinding Wheels"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 81, August, pp. 187-200.

Optimum utilization of grinding wheels can best be achieved if the nature of their performance and wear characteristics, and the factors that affect these characteristics, are understood and applied. As reported in this paper, a comprehensive, continuing, grinding-research program has contributed to such an understanding.

A study of the nature of grinding-wheel wear indicates that the grinding-wheel wear curve is similar to those of other cutting tools. It demonstrates further that the type of grinding operation significantly affects the nature of wheel wear. A unique technique has been developed for very accurately measuring grinding-wheel wear. This measured wear may be translated into terms of "grinding ratio," which is the generally accepted parameter for measuring wheel wear. It is the ratio of the volume of metal removed per unit volume of wheel worn away.

Extensive studies have been carried out to determine the effect of mechanical variables on grinding ratio, power required in metal removal, and on surface finish. Experimental findings indicate that grinding ratio decreases with increased metal-removal rate and increases with workpiece diameter, decreased chip load, and increased concentration of grinding fluid. Power is found to increase with both the metal-removal rate and the amount of metal removed. It increases slightly with workpiece diameter and is affected little by work-material hardness. Surface finish is found to improve with decreased metal-removal rate and decreased chip load. It also is affected little by work diameter or work-material hardness.

Fundamental research in the mechanics of wheel wear is supplying much additional information in the study of grinding-wheel wear. The measurement of grinding forces employing a cylindrical grinding dynamometer provides the opportunity for relating the wear of grinding wheels to the basic mechanics of the process through such fundamental quantities as grinding forces, specific energy, and grinding friction.

Two additional experimental techniques for the study of chip formation in grinding have also proved to be most useful research tools. A "quick-stop" apparatus is used to freeze the grinding action by accelerating a tiny workpiece almost instantaneously to grinding-wheel speed. Another technique permits the comparison of the shape of the grinding grit and that of the contour of its path through the workpiece by a unique replicating method. (Author) (5 ref., 23 fig., 1 table, discussion)

(81) J. Crisp, J. R. Seidel, and W. F. Stokey (1968)
**"Measurement of Forces During Cutting With a Single Abrasive Grain"**
*International Journal of Production Research*, Vol. 7 No. 2, pp. 159-171.

The forces that occur between a single grain and a workpiece during the cutting process have been measured by two methods. In one, a dynamometer which utilizes piezoelectric elements measures both the tangential and normal components of force, a small workpiece on the dynamometer being subjected to single grain cutting. In the other method, a single abrasive grain is mounted on a rotating member, the change of angular speed of which is measured during the cutting process. This speed change can be related to the average tangential force between the abrasive gain and the workpiece during the cutting process, although, in the present work, it is used directly to find the work of cutting.

To determine the response of the dynamometer, and to calibrate it, small steel balls have been bounced off the workpiece, and the output of the dynamometer compared with the pulse shape that has been determined analytically.

Included are oscilloscope traces showing the response of the dynamometer during the bouncing ball calibration, and during cutting. Results include values of energy expended in cutting as determined by both procedures. (Author) (4 ref., 7 fig., 3 tables, 3 equations, appendix with 2 fig., 4 equations)

(82) R. Snoeys and D. Brown (1969)
**"Dominating Parameters in Grinding Wheel - and Workpiece Regenerative Chatter"**
10th Machine Tool Design Reg. Conf., pp. 325-348.

The grinding parameters, which are shown to be important from the theoretical analysis, are discussed in terms of their effect on grinding process stability. Some important cases of instability, which can occur in practice, are discussed in a theoretical manner.

It is shown that the theoretical derivation of the formulated stability requirements are an extension and a generalization of the classical single tool cutting stability criterium. A set of chatter tests was performed in order to verify these theoretical predictions. The theoretical correlation between the machine characteristic, the workspeed, the compliance of the grinding wheel-workpiece contact area and the appearance of work generation or wheel regeneration has been checked.

Some recommendations yielding an improvement of the grinding stability are formulated. (Author) Addressed are wheel features and attributes such as the wear pattern on the grinding wheel, shape of wheel, cutting stiffness (a function of wheel speed and work speed) and wear resistance. The contact stiffness is influenced by grinding wheel composition (stiffness of grains, grain species, diameter, etc), dressing conditions, wheel and workpiece diameters, etc.). (RWM supplement) (11 ref., 11 fig., 5 tables, 18 equations, appendix w/15 equations)

(83) S. Kannappan and S. Malkin (1972)
**"Effects of Grain Size and Operating Parameters on the Mechanics of Grinding"**
*Journal of Engineering for Industry* (Transactions of the ASME), Vol. 94, August, pp. 833-842.

An investigation is described of the effects of grain size and operating parameters on the mechanics of grinding. Results indicate that the specific energy in grinding, which is the total specific grinding energy minus the specific energy due to sliding between the wear flats and the workpiece, is independent of grain size and decreases with increasing table speed and downfeed. It is postulated that the specific cutting energy consists of chip forming energy which is independent of table speed and downfeed, and plowing energy which decreases with increasing table speed and downfeed. Results for G-ratio, surface finish, and burning conditions are also presented. Of particular interest are the effects of grain size on burning conditions. With finer grain size, burning occurs at larger wear flat area and energy input per unit area ground, but the G-ratio and grinding wheel tool life are less. This is related to increased attritious wear with finer grains. (Author) (23 ref., 21 fig., 4 equations)

(84) J. Verkerk (1975)
**"The real contact length in cylindrical plunge grinding"**
*Annals of the C.I.R.P.*, Vol. 24 No. 1, pp. 259-264.

The difference between the real and the geometric contactlength as a result of the elastic deformation of wheel and workpiece was investigated for cylindrical plunge grinding. The real contactlength, which is of great importance for the analysis of the grinding process, was measured in-process by means of a small thermocouple in the workpiece surface. The effect of grainsize, wheelhardness and real contactlength appeared to be considerably longer than the geometrical length, at small depth of cut and high workspeed. Taking the ratio of the equivalent deformed and undeformed radii as a measure for the deformation of the wheel, the density of active grains shows a conformity with the deformation. An analysis of the results shows that the deformed wheel radius obtains an opposite curvature in the interference zone at large deformations. Special attention has been payed to the evaluation of the measured signals and the effect of the dressprofile on the real contactlength-measurements. (Author) (9 ref., 12 fig., 1 table, 12 equations)

(85) R. L. Allor and R. R. Baker
**"Effect of Grinding Variables on Strength of Hot Pressed Silicon Nitride"**
ASME Paper 83-GT-203, 5 pages.

An experimental study was conducted to evaluate the effect of several grinding variables on the room temperature strength of Norton NC-132 hot pressed silicon nitride. The grinding variables studied included diamond grit size, diamond concentration, type of diamond bond, downfeed rate and type of cut. Significant effects on strength were noted for all variables except diamond concentration. (Author) (14 ref., 6 tables, 4 fig.)

(86) D. B. Marshall, A. G. Evans, B. T. Khuri Yakub, J. W. Tiens, and G. S. Kino (1983)
**"The Nature of Machining Damage in Brittle Materials"**
*Proc. R. Soc. Lond*, A. 385, 461-475.

The micromechanics of failure emanating from machining-induced cracks in brittle materials is investigated. In situ monitoring of crack response during breaking tests (with use of acoustic wave scattering), strength measurements and post-failure fractography all indicate that the crack response is dominated by residual stresses. Two components of residual stress have been identified: a crack-wedging force due to the plastic zone beneath the strength-controlling machining groove, and a compressive surface layer due to adjacent grooves. The wedging force dominates and causes stable equilibrium crack extension during a breaking test. The implications of the results for non-destructive evaluation of surface damage by acoustic wave scattering is discussed. (Author) (25 ref., 10 fig., 2 tables, 7 equations)

(87) S. A. Haywood (1984)
**"Mechanical Design Safety of Vitrified Grinding Wheels"**
*British Ceramic Trans.*, Vol. 83 No. 5, pp. 134-137.

Vitrified grinding wheels are brittle. Wheels in use have a primary centrifugal stress at steady speed. Lower stresses are due to grinding forces, acceleration and retardation, out-of-balance, and thermal conditions. (RWM) (6 fig., 2 tables)

(88) T. Nakagawa, K. Suzuki, T. Uematsu, and M. Kimura (1988)
**"Development of a New Turning Center for Grinding Ceramic Materials"**
*Annals of the C.I.R.P.*, Vol. 37 No. 1, pp 313-322.

A grinding center based on an NC turning center has been developed for efficient external, internal or cam grinding of ceramic mechanical parts. The grinding center is provided with not only various grinding wheels, but also an ultrasonic grinding attachment for reducing grinding force during coring or expanding holes. The grinding center is also equipped with an on-machine wire electro-discharge truing/dressing unit for metal bond diamond wheels. All the other revisions necessary for grinding ceramic materials have been made on the turning center. The developed grinding center was confirmed to have expected abilities in efficient grinding and form grinding. (Author) (2 ref., 11 fig., 2 tables)

(89) E. Brinksmeier, H. Siemer, and H. G. Wobker (1988)
**"Requirements on Nondestructive Testing Methods after Machining of Ceramics"**
Proceedings of the 3rd International Symposium, Nondestructive Characterization of Materials, Saarbrücken FRG, October 3-6, pp. 36-45.

Grinding of tool ceramics introduces microcracks and stresses into the surface layers. The intensity of the surface damage depends on the material removal mechanism in grinding. Especially very small surface damages influence the function of tool ceramics. Therefore nondestructive testing methods with high resolution and high reliability are needed. (Author) (13 ref., 10 fig.)

(90) M. Weck and J. Alldieck (1989)
**"The Originating Mechanism of Wheel Regenerative Grinding Vibration"**
*Annals of the C.I.R.P.*,Vol. 38 No. 1, pp. 381-384.

The article deals with the origins of self excited vibrations in cylindrical grinding machines. Proceeding from the simulation of the dynamics interactions between the grinding wheel and workpiece to the resulting dynamic cutting forces, the mechanisms that lead to the self excited vibrations during grinding are described. Theoretical considerations are explained based on computer simulations that take into account the dynamic compliance of the grinding machine. Corresponding measurements, that were taken during the course of machine investigations are also presented. (Author) (9 ref., 11 fig.)

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