MANUFACTURING PERSPECTIVE

An Overview of Applied Mechanics in Grinding

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Grinding has been a major manufacturing process for many decades, but it is still known throughout industry as a skill-controlled, not-highly-automated process. Published technical papers do not directly provide useful grinding methods, so that industry experts usually prefer to use their own empirical or semi-empirical methods to design particular processes. For that matter, the results published in technical papers are sometimes in conflict with practical observations. However, the rapid development of high technology, especially associated with the application of advanced materials, creates greater requirements for grinding processes. Thus, empirical methods become powerless in solving grinding application problems. What is needed is increased reliability, greater economy, higher performance, and the design of fully automatic grinding production lines. Attaining these objectives requires more research into grinding processes to reveal their mechanisms and to provide practical guidelines for industry.

With these goals in mind, this article critically reviews the main problems of mechanics in grinding processes, discusses the importance of mechanics analysis in the improvement of grinding technology, and emphasizes some new and unconventional research approaches for the automation of grinding operations. The authors attempt to explain the profoundness of various problems in very simple terms, so that even nonexpert readers can easily understand the problems and take them as starting points for further research.

INTRODUCTION

Grinding is one of the most versatile methods of machining for providing precise geometry. Although it was used mainly as a finishing process just a decade ago, a bulk removal grinding process (e.g., [1, 2]) has been developed that combines the advantages of a large material removal rate — characteristic of cutting processes — with high precision and surface quality—characteristics of grinding. It appears evident that in the near future increasing proportions of total material removal will be accomplished by grinding, thereby increasing the importance of grinding in the overall manufacturing scheme.

Of all the conventional machining processes, grinding is usually the most expensive per unit volume of bulk removal. In the manufacture of precision components, grinding alone may constitute a significant portion of total cost (e.g., typically 25 to 50 percent for rolling element bearings). However, rapid developments in various areas of high technology, such as space, optics, atomic power, and electronics, create further requirements for the quality of ground elements. Besides low roughness and high accuracy, the traditional requirements for grinding, these technologies need further guarantees of optimal residual stress distribution and reasonable microstructures of the surface material. This, in turn, demands greater productivity, higher quality, and lower costs from grinding processes. Hence, manufacturers must know the principle factors affecting the surface quality of the workpiece as well as the proper setting of grinding parameters. Unfortunately, grinding processes are so complex and difficult to study that their governing parameters are difficult to define. For instance, it has long been known that residual stress in machined surfaces, caused by thermal cycling, mechanical deformation, and microstructural transformation of the surface layers, plays an important role in surface integrity and the working life of a workpiece. To study this problem, however, many significant factors must be involved: grain sizes, grain type, number of active grains per unit area, feed rate, depth of cut, length of contact arc, properties of the work material, geometric structure and grade of the wheel, coolant chemistry, coolant supply conditions, and so on. Simply put, the dominant variables are difficult to determine. Practical grinding processes are still being performed empirically or semi-empirically, and are known through industry as Black Art [3]. This occurs because technical papers published on grinding research usually do not directly provide useful methods for grinding engineers. In fact, their results are sometimes in conflict with practical observations. However, empirical and conventional methods become powerless in solving complicated grinding problems. A new approach must be found to meet the imperative needs of higher performance, greater economy, and reliability.

With these objectives in mind, it is the goal of this article to critically review the main problems of mechanics in grinding processes and to emphasize the importance of mechanics analysis in the improvement of grinding technology. Based on a careful discussion, the article proposes some new and unconventional approaches for further research on the automation of grinding processes. The authors try to explain the profoundness of various grinding problems in very simple terms, so that even nonexpert readers can easily understand the problems presented and use them to develop future research strategies.

UNDERSTANDING GRINDING AND MECHANICS

Some Grinding Basics

A grinding wheel essentially consists of a large number of abrasive particles, called *grains*, held together by a suitable agent, called *bond*, as shown in Fig. 1. The cutting process of a grinding wheel may be regarded as a multipoint cutting tool with a cutting action similar to that of a milling cutter except that the cutting points on the grinding wheel are irregularly shaped and are randomly distributed over the active face of the wheel.

Those grains at the surface of the wheel that actually perform the cutting operation are called *active grains*. The percentage of active grains relative to the bonding agent significantly influences grinding efficiency. Take peripheral grinding as an example, as shown in Fig. 2a. Each active grain removes a short chip of gradually increasing thickness regulated by the relative feed rate of the workpiece. Because of the irregular shape of the grains, however, there is considerable interference between each active grain and the new work surface. The interference results in progressive wear, causing the formation of worn areas, thus increasing friction, leading to an increase in the force acting on the grain. Eventually, this force becomes large enough either to tear the worn grain from the bonding agent, thus exposing a new unworn grain or to fracture the worn grain producing new cutting edges. From the angle of the work material under grinding, as shown in Fig. 2b, horizontal force leads to severe plastic shear deformation and forms a chip (e.g., in a cutting process). Therefore, vertical force is necessary to keep the depth of cut of the grain. Unlike tool cutting, the deformation of a chip is unpredictable. Before it tears or wears away, a chip may bend, break, or cram into the gap between neighboring grains. For ductile work materials, if the grinding wheel is not dressed in a timely manner, such a cram will result in a sharp change of interface forces and lead to instability of the grinding process.

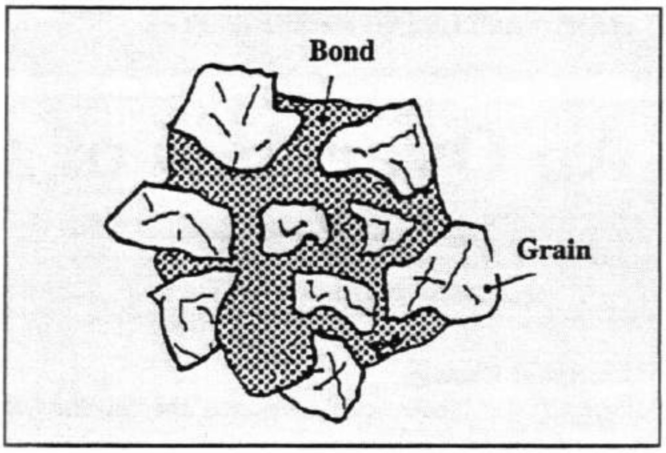

FIG. 1. Grains and bond

In steady grinding, when the interface tangential and normal grinding forces F_t and F_n have reached their equilibrium value, the elastic deformation rate of the wheel–workpiece system must become zero. Thus for a steady state, if only the grinding interface is examined, the elastic deformation of the grinding machine does not need to be considered, as in the deflection of a wheel spindle.

Correlation of Mechanics with Grinding

Mechanics analysis is predominantly involved in two aspects of a grinding system, grinding wheel selection and surface integrity of ground components. Figure 3 summarizes the

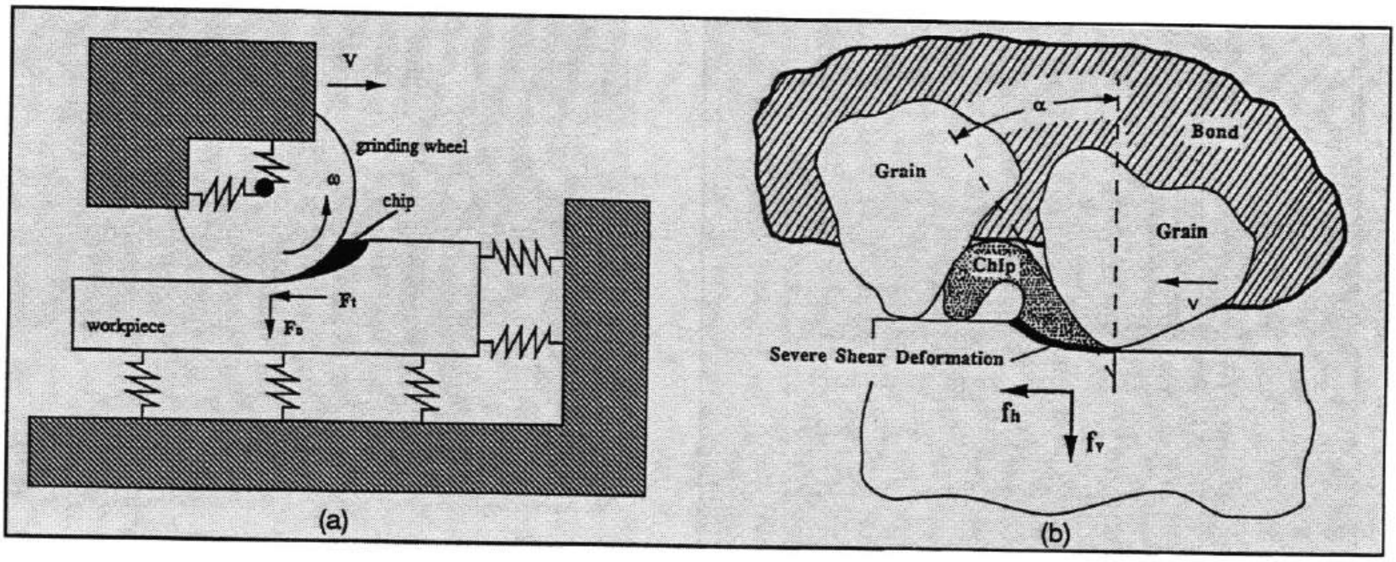

FIG. 2. a) A schematic diagram of grinding and b) deformation of a chip

relationship between mechanics analysis and the principal factors in grinding processes: the thick lines indicate strong correlation and dependence, while the thin lines imply relatively weak connections. The figure shows that a grinding process is influenced by many factors. Among these, heat, interface forces, surface cracking, residual stress, and the properties of the work material are the five most important factors related to surface integrity and the selection of wheels. Obviously, it is unrealistic to take all of the factors into account at the same time. Therefore, for convenience, the investigations into wheel selection and the surface integrity of workpieces are performed individually. Interactions between them are simplified into comprehensive effects under certain acceptable assumptions.

Findings in stresses and strains are the main direct outputs from mechanics analysis. Specifically, wheel deformation, wheel—workpiece interaction, (residual) stress prediction, and the stability of a grinding operation are the objectives of mechanics research. Usually, the complexity of analyzing a process depends on how many factors are involved. To predict residual stresses in a ground component, for instance, the total strain in governing equations of mechanics (e.g., [4, 5]) should be a summation of different parts from various sources: mechanical deformation, thermal deformation, and phase transformation.

Numerous technical papers and monographs regarding grinding have been published in the last 40 years. The literature search performed for this article showed that the number of papers that discuss grinding recorded in the Engineering Index from January 1970–April 1991 is 15,604. Of these, 161 investigated residual stresses (with explicit keywords), while only a small number studied grinding from the angle of mechanics. This dearth of research on the mechanics of grinding has resulted because the process is too complicated for theoretical modeling, and primary empirical data must be accumulated from actual processing — which is difficult and expensive to accomplish — to understand grinding empirically.

RESEARCH PROGRESS, METHODS, AND COMMENTS

There are many open questions in every branch of the flow chart shown in Fig. 3. However, only those that are important and dependent on mechanics analysis will be discussed individually.

Interaction Between a Grinding Wheel and A Workpiece

Interaction between an Individual Grain and A Workpiece

An abrasive cutting process is closely related to the interaction of negative rake tools with a workpiece. These interactions are also closely related to the mechanics of indentation and work hardening of material in the theory of plasticity.

Geometric Models of Grains

Abrasive grains embedded on bonded abrasive wheels have irregular profiles. In order to develop a model of the cutting process for a grain, it is essential to simulate the grain with a simple geometric shape that will approximately but reasonably reflect its real characteristics. In the literature, a cone, sphere, and a pyramid with or without a pointed tip have been applied. Usually, one would choose a specifically shaped grain to investigate specific effects, such as rake angle effect, truncation effect, and so on.

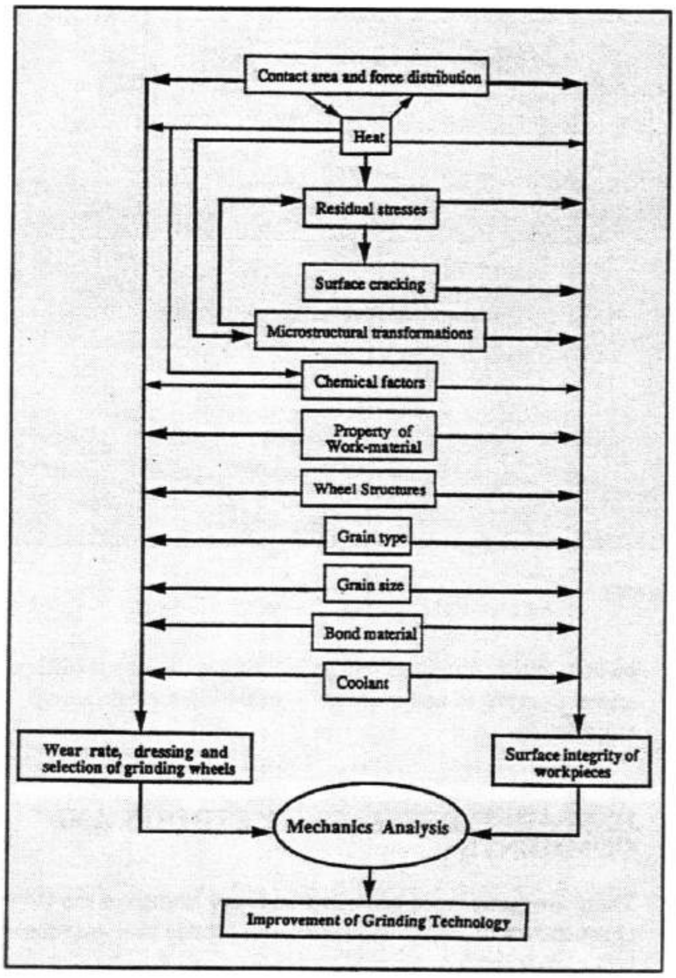

FIG. 3. Relationship between mechanics and grinding

A Machining Model of Grains

Experiments have indicated that an abrasive grain performs three distinct processes on a workpiece in grinding metals (e.g., [6, 7]): 1) rubbing, in which the grain rubs on the workpiece causing elastic and plastic deformation without material removal; 2) ploughing, in which the grain causes plastic flow in the material and extruded material is thrown up and broken off along the sides of the groove resulting in low rates of bulk removal; and 3) cutting, in which a fracture takes place in the plastically stressed zone just ahead of the rubbing grain, causing formation of a chip, resulting in fairly rapid stock removal rates. Generally, cutting and ploughing, or a combination of these elements are the dominant type of materials flows. In some cases, it may not be unrealistic to concentrate attention purely on cutting or ploughing. For example, based on the available results, Malkin discussed certain behaviors of an individual grain in the machining process and its relationship with grinding energy (power), and categorized the behaviors into grinding mechanisms [8]. His conclusions, however, were rather qualitative.

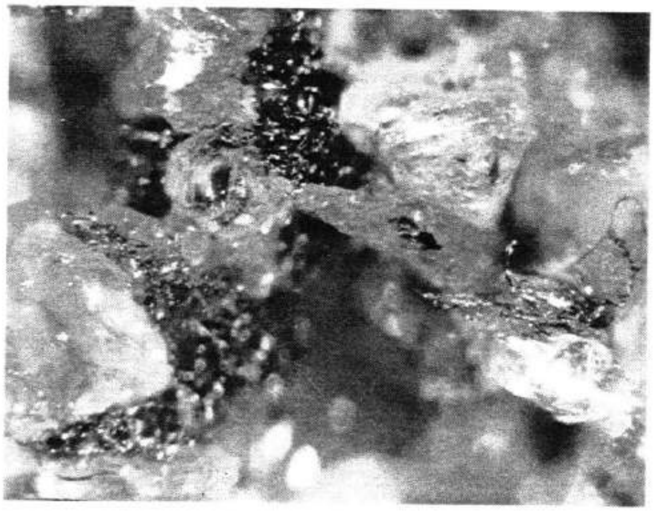

FIG. 4. Chips crammed into a wheel surface [13]

Methods of Analysis and Mechanisms of Cutting Ductile and Brittle Materials

The mechanism of chip formation has a significant effect on the surface integrity of the ground components. Four main methods have been used in the analysis of grain–workpiece interaction: experimental investigation, energy, slip–line, and upper bound. A number of studies have used these methods to examine grain workpiece interaction. Childs, while studying experiments on the sliding of conical indenters over ductile materials, analyzed theoretically the forces involved [9]. He used the principle of minimum energy in plastic works to predict the sliding forces and claimed that his force predictions were within 20 percent of the observed values. However, his shape predictions of the slide ridge were not satisfactory. Kida et al. conducted tests with conical tools simulating single abrasive grains [10]. They suggested five deformation regions, that is, the region removed as chip ahead of the tool: the stagnant region beneath and adjacent to the tool; the severely deformed region that followed down along the side of the stagnant one; and finally, an undeformed region in front of all the others. The stagnant region acted as a cutting edge, and the initial positions of such a region determined whether or not a chip could be formed. Kudo and Tsubouchi tested lubricated carbon steel ploughing and concluded that the relationships between the forces and the depth of penetration of the tool were almost parabolic, while the ratio of tangential to normal force was approximately constant with the change in depth of cut [6]. Challen and Oxley used slip-line field theory to explain the deformation of soft asperity by a hard asperity [11]. De Vathaire et al. proposed an upper bound method to study the ploughing action of a rigid pyramid indenter [12]. The model predicted the geometric shape of track made by the indenter, the normal and tangential forces, the strain, and the rate of strain of the ploughed materials. Simply put, in grinding ductile materials, chips are

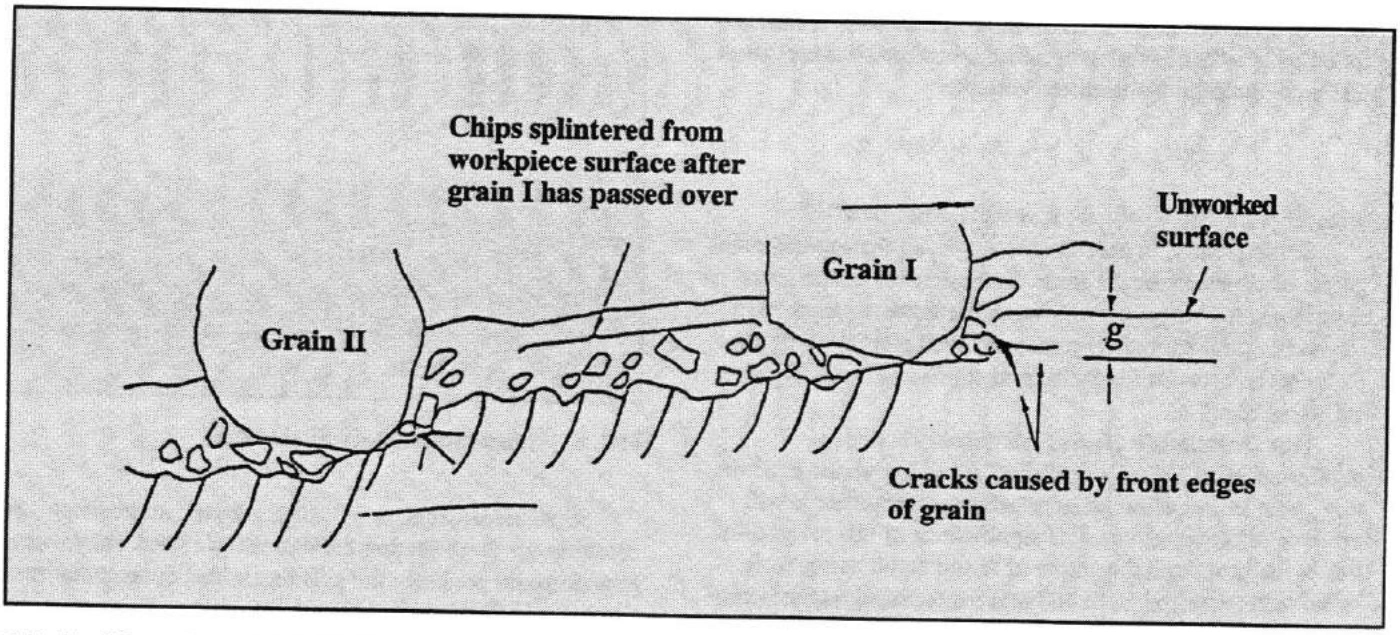

FIG. 5. Schematic model of chip formation process in grinding brittle materials [14]

formed by plastic shear deformation so that the processes of cutting, ploughing, and rubbing are quite clear. Chips usually like to cram and load, in an unpredictable way, into the pores or grain gaps on the wheel surface as shown in Fig. 4 [13]. Surface roughness is mainly characterized by the micro-structure of ploughed grooves.

In grinding brittle materials, however, chips are mainly produced through the mechanism of *micro-brittle fracture* [14]. The chips are fragments produced through micro-cracking the surface materials by grain indentation, as shown in Fig. 5 [14]. Plastic deformation becomes very slight. Unlike in grinding ductile materials, ploughing brittle materials may also lead predominantly to the creation of chips. The materials adjacent to the grain subjected to ploughing may undergo a process of compression, crack formation, crack development, unloading, and chip splitting [13]. The existence of surface micro-cracks is then a major problem among the factors determining surface integrity [13–17].

A new technology called *ductile-regime grinding* is being developed to avoid the damage of micro-cracking in grinding brittle materials [74]. It was found that ductile chip formation is also possible when a grinding unit becomes very small, on the order of nanometers. The transition from brittle chip to ductile formation was thought of as a transition process of favorable material removal energy. In fact, the ratio of material removal energies, plastic flow energy to fracture energy, is approximately proportional to the depth of cut, d_c. As d_c decreases to a specific value, plastic flow will become an energetically more favorable material removal mechanism. It is the transition phenomenon between cracking and plastic flow and should be independent of the materials under grinding [75]. In principle, a successful application of the ductile-regime grinding technique is to make full use of the brittle-ductile transition. However, further research is necessary to explore characteristic transition parameters for different materials.

Elastic Modulus of Grinding Wheels

It is well-known that a macroscopically measured, elastic modulus of a grinding wheel, E, is a physically well-defined wheel criterion because it reflects most of the effects of the wheel's microscopic components. It also significantly influences the interface condition between the wheel and the surface under grinding. In addition, the elastic modulus could meet the needs of both manufacturers and end-users.

Researchers have found that the elastic modulus of a grinding wheel is an extremely complex function of numerous factors: temperature, θ; specific weight, ρ; hardness grade, h_g, concentration, c; grain grade, G_g; total apparent volume, V; volume of grain, V_g; volume of bond material, V_b; volume of pores, V_p; type of grain, t_g; type of bond material, t_b; and the mean diameter of grains, d. It seems to be rather difficult to reveal clearly the dependence of E upon these factors. Typical investigations into this problem in the early stages included those published in [8, 18–25]. The first study looked at the relationship between E and h_g while the latter group discussed the variation of E with c, d, h_g, t_g, V, V_g, V_b, and V_p in a series of eight papers, which expressed their results with hundreds of curves.

Progress has recently been achieved by Zhang et al. in [26]. They dug out the nature of E with the aid of dimensional analysis. They found that h_g, c, V_p and G_g are not governing parameters, so that for a class of grinding wheels with specific types of grain and bond material, the nondimensional elastic modulus is only a function of non-dimensional temperature τ and a governing dimensionless variable:

$$\overline{E} = \Phi(X_1, X_2),\ X_1 = (v_g)^3(v_b)(D)^{-3/2},\ X_2 = \tau \qquad (1)$$

where $\overline{E} = E/(d\rho)$, $v_g = V_g/V$, $v_b = V_b/V$, and $D = d/V^{1/3}$.

Consequently, in coordinates $\overline{E} - X_1$ all the experimental points obtained under the same dimensionless temperature, τ, should lie on a single curve, if no measurement errors have occurred. Their formula is extremely well confirmed by the experimental results from different sources [21–23, 27], as shown in Fig. 6.

This formula is a general relationship between nondimensional Young's modulus, $\overline{E}$, and governing factors v_g, v_b, and D. For different measuring temperatures, it will produce different curves. The significance of this revelation lies in that it reveals the nature of E and that it can greatly reduce experimental work and make theoretical analysis convenient.

The nondimensional elastic modulus, $\overline{E}$, implies certain physical meanings. E/ρ corresponds to the square of the longitudinal wave speed of the material, v (under the condition of isotropy). Obviously, grain diameter, d, relates to the anisotropy of the wheel and, in turn, influences v. On the other hand, E/ρ is also a measure of specific stiffness, and appears in the formula for the bending of beams under their own weight. As luck would have it, people are using the methods of *sonic test* and *bending test* [18] to determine the modulus of elasticity, although the latter presently does not involve ρ.

The *bending test* method produces the so-called static modulus, E_{stat}, and the *sonic test* method gives a dynamic modulus, E_{dyn}. Comparisons have shown that these two methods lead to almost the same values of elastic modulus for a specific wheel [18]. It is therefore not valuable to distinguish E_{dyn} and E_{stat} in studying related problems.

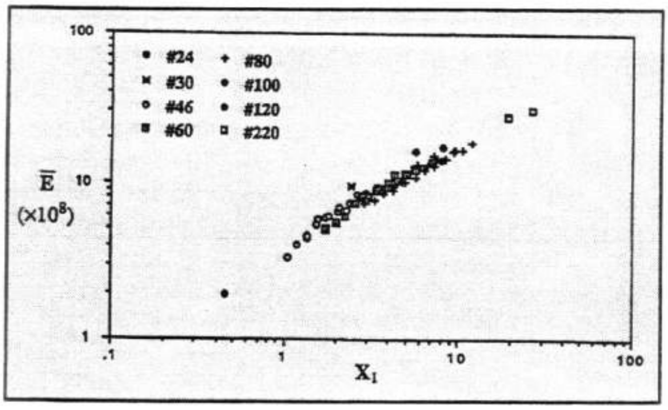

FIG. 6. Nondimensional elastic modulus

Some researchers, (e.g., [30]), adopted microscopic approaches for investigating the deflection effect. They wanted to understand precisely the grinding wheel contact deformation by studying the local elastic deflection of a single grain or set of grains. Although there is no doubt that the nature of the work material should have a huge effect on the behavior of grains, these researchers did not consider such interaction. Actually, their qualitative conclusions were only a repeat of existing solutions in the theory of elasticity — the solutions of a half space subjected to boundary tractions. Therefore, they are not useful to a real grinding process. To carry out investigations of practical interest on a microscopic level, in the authors' opinion, researchers should try to generate an extremely detailed description of the grain's topography and then determine how much of the grain cuts the work material, how much ploughs it, and how much rubs it.

Usually, it seems that because the shapes of grains are irregular and the depths of grain cut are different from each other, the distributions of interface forces could be very irregular and discontinuous. However, Zhang et al. argued that it is quite reasonable to assume that the wheel and the workpiece are in continuous contact for the sake of macroscopic analysis [26]. To a great extent, except for randomly distributed active and inactive grains, bond material and loaded chips can also be in contact with the work material, as shown, for example, in Figs. 2b and 4. This type of grinding force can not be distinguished from that of the cutting, ploughing, or rubbing force of active grains, because they always come together in the chip formation process. Based on this viewpoint, they proposed a macroscopic model to investigate interface forces that considered the cutting processes of grains comprehensively and where contact deformation of both the workpiece surface and the wheel were stressed. Their analysis showed that actual pressure distribution over the grinding bite deviates greatly from a Hertzian profile, as shown in Fig. 7. This conclusion was strongly confirmed by experimental measurements [31]. Snoeys and Wang also tried to apply continuum mechanics to grinding force analysis [32]. Unfortunately, they did not take micro-

Interface Forces and Contact Length

Investigations into the deformation of wheel-workpiece systems have been performed in different ways, including experimental and theoretical as well as microscopic and macroscopic approaches. Microscopically, an active grain will be deflected because of the forces exerted during grinding; macroscopically, the wheel might be considered as a thick circular disc pressed against the curved surface of a workpiece. Studies done before 1980 in this field were summarized individually in [28, 29]. They concluded that observations concerning the influence of various parameters on the magnitude of contact deflections were diverse and conflicted with each other, producing a paradox. Thus their results are still open to questions and further research.

effects properly into account and assumed in advance that the pressure distribution over the contact arc to be Hertzian. This assumption violated the actual circumstance [31].

The contact length between a grinding wheel and a workpiece during operation is one of the principal factors contributing to thermal and mechanical deformation, because it specifies the bottom length of the interface force distributions and the surface heat source. The abovementioned theoretical model can yield accurate predictions, but is not convenient or efficient from the standpoint of research engineers [26]. It is necessary to find a practical formula to compute the contact length approximately. At least fourteen formulas have been proposed to calculate the contact length empirically, theoretically, or semi-analytically. These have been carefully discussed and compared [33]. Various researchers have emphasized different parameters, such as roughness, heat expansion, and so on. However, a general expression for contact length calculation, valid over a wide range of grinding conditions, wheel types and structures, and workpiece materials has not yet been developed. It has been found that the macro-deformation of the grinding wheel is an elementary factor, and a compensatory parameter should be introduced to reflect the comprehensive effect of those variables that have been neglected in formulation [33]. From the available information and comparison, the following formula

$$L_c = R_d \arccos\left[1 - (d_c/R_d)\right] \qquad (2)$$

where

$$R_d = R_0 \{1 + z\,[(1 - \nu^2)\,F'_n]/Ed_c\}$$

is a more general example that can cover most cases in the range of conventional grinding and creep-feed grinding [33]. Here L_c is the calculated contact length, ζ is the grinding condition coefficient, d_c is the depth of wheel cut, F'_n the normal grinding force per unit width, ν is Poisson's ratio, and R_0 and R_d are the radii of the wheel before and after deformation, respectively. A validity criterion,

$$1 \le (L_c/L_g) < N, \qquad (3)$$

with L_g being the geometrical contact length and N a finite constant, was also proposed to judge the applicability of an approximate formula. Any formula that violates the criterion must not be used in practice. Zhang et al. pointed out, according to Eq. 3 [33], that the formulas proposed in [34–36] are acceptable in principle only in extremely narrow ranges.

Controlling Ground Component Surface Integrity

Main Problems

The concept of surface integrity has been widely accepted by researchers and industry experts in evaluating the quality of machined surfaces. Typical problems of ground component

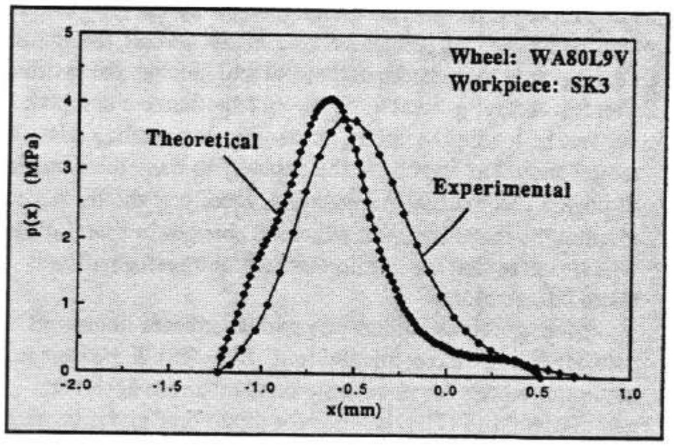

FIG. 7. Pressure distributions [26]

surface integrity include, as in the first discussion by Field and Kahles in [37]:

- plastic deformation;
- grinding burn;
- phase transformation;
- micro- and macro-cracking;
- residual stress distributions;
- surface topology; and
- distortion of ground components.

In order to insure a high degree of surface integrity, an active control or an on-line optimization process must be a goal of technical research. It is therefore evident that clarifying the inherent relationships between various grinding conditions and the above integrity problems will be of most importance.

Many research groups worldwide are carrying out extensive research on surface integrity. For example, the International Institution for Production Engineering Research (CIRP) has established an international network of researchers. Their research contributions are periodically published or summarized (e.g., [16, 17, 38–41]).

The following section will focus on residual stress analysis because it is an important measurement of surface integrity: undesired residual stress distribution will result in deformation of a ground component, lowering its dynamic strength, fatigue life, chemical resistance, magnetic properties, and so forth.

Residual Stresses

It is clear experimentally that mechanical deformation usually produces compressive residual stresses, but thermal deformation often results in tensile residual stresses and is the most undesirable form of deformation. With the aid of the force model [26], the real contact length model [33], and the thermal model [63] (discussed later in this article), the authors are now able to investigate thermal and mechanical residual stresses. Actual ground workpieces experience a complex process of loading, heating, unloading, and cooling. Hence, a model should at least have the capacity to trace the histories of plastic and thermal deformation. Ideally, it should also monitor the metallographic structural changes in a workpiece, which is essential when microstructural transformation is taken into account.

Most previous studies on residual stresses in ground components are experimental (e.g., [42–46]). For example, general methods for measuring residual stress have been summarized in [47]. Demands for theoretical and numerical studies have risen because purely experimental investigation is too expensive and sometimes very difficult to perform. For example, engineers in industry feel that it is diffiuclt to trace the working behavior of ground components with various residual stress fields, but this data is important in gathering feedback for improving grinding technology. A theoretical method could take many principal factors into account at the same time, like those from mechanical, thermal, microstructural, and chemical effects, so that it is strict in terms of physics and mathematics (e.g., [48, 49]). However, this method then faces being coupled with large-scale differential equations making it both expensive and time consuming. Users of the model may not get a reasonable solution in even a few days' time, even if they engage a powerful computer in determining the solution. It should be pointed out here that the modeling of boundary conditions plays an extremely important role in this approach. For example, if only a geometric contact length is used as the width of the heat source, it is not meaningful to get a so-called more accurate result by increasing the number of finite elements. As another approach, the semi-analytical model is a reasonable method that pays much attention to the modeling of working conditions with the aid of necessary experiments, but simplifies computational processes for stresses (e.g., [50]). This simplification makes it possible to involve various principal factors and to complete a whole circle of analysis in a short time.

Mechanical Residual Stresses

Mechanical stresses in a workpiece are directly produced by interface forces. Previously, researchers applied a moving Hertzian pressure to simulate grinding interface pressure. It is now clear that such an application can not fit a real case well, as discussed in [26]. It follows from this investigation that even a triangular pressure distribution would be much better than a Hertzian pressure, as shown in Fig. 7.

Thermal Residual Stresses

Three steps are necessary for thermal residual stress analysis: 1) determining the temperature field, which depends on the density and distribution of heat sources, the conductive nature of the medium, and the initial and boundary conditions; 2) calculating the stress field; and 3) determining the residual stress field if the thermal stress in the workpiece under material removal heating exceeded its yield point. Steps 2 and 3 should be carried out under the theory of thermoelasticity and thermoplasticity, which have been studied systematically [51, 52]. Step 1, however, is the base of thermal stress analysis, and successful stress prediction requires realistic modeling of heat sources for grinding. Therefore, it should be discussed in some detail.

Heat generated in grinding results mainly from plastic deformation of workpiece material. The portion that enters the workpiece determines the level of thermal stress. Mechanisms of heat transfer across the grinding interface are theoretically not very clear, but the conclusions drawn in [8, 53-55] are worth noting here. (It should be kept in mind that they are only qualitative and will vary from case to case):

- ❑ Total energy in grinding can be separated into energy due to chip formation (cutting), ploughing, and rubbing.
- ❑ Almost all of the ploughing and rubbing energy is conducted as heat into the workpiece, whereas about 55 percent of the chip formation energy is conducted into the workpiece.
- ❑ The chip formation energy is about two orders of magnitude higher than the other energy inputs. and
- ❑ The shearing energy generated during chip formation is limited by the energy required for melting.

Jaeger presented a two-dimensional solution to the moving heat source problem: a perfect insulator with a band heat source at its lower surface was considered to move at a constant velocity, V, across a semi-infinite stationary body [56]. It has been widely accepted that Jaeger's model is extremely suitable in connection with grinding heat transfer problems. Many studies have been conducted to analyze the temperature distribution and thermal deformation of workpieces during grinding (e.g., [57–59]), and to some extent the relationships between thermal deformation and machining accuracy have been investigated [8]. In these works the assumption of a constant heat transfer coefficient has been employed. Its use indicates that the effects of grinding fluid flow around a grinding wheel, and the porosity and geometric shape of a grinding wheel were neglected. Quantitatively, the accuracy of the results are reduced by such an assumption. Unfortunately, it is very difficult to involve all of these factors in theoretical analyses. As Snoeys et al. stated in their work, investigations of aspects concerning thermally induced damage are often hampered by a lack of characterization of basic physical parameters. Results obtained in one particular laboratory are, therefore, not always applicable in other laboratories or workshops because a number of work conditions have not been understood correctly, or they have been ill-defined.

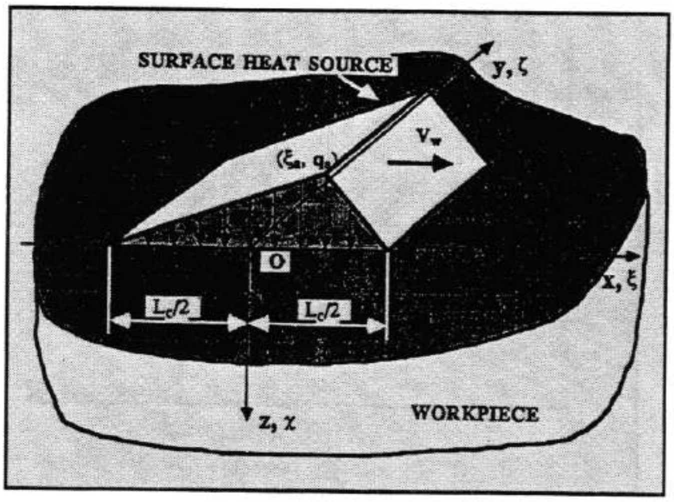

FIG. 8. A refined model of a surface heat source

It was found that the profile of the surface heat source has a large effect on the temperature distribution in a workpiece. Rectangular and parabolic heat sources can not simulate real cases well. A right triangle source, however, produces more reasonable results [60–62]. It is not difficult to understand the principle if one notices that surface heat generation should have a close relationship to the local deformation of workpiece material in contact with the wheel. High local temperature corresponds to large local plastic deformation and, hence, corresponds to high local intensity of interface forces and generated heat. Zhang et al. have shown that the profiles of interface forces between a grinding wheel and a workpiece surface are neither rectangular nor parabolic [26]. In fact, they could quite reasonably be approximated by a triangle, as shown in Fig. 7. The apex, however, should be located at a point between the inlet and outlet of the contact bite. This leads to a new model of a surface heat source with a general triangular intensity, as shown in Fig. 8. Equation 2 can be applied to determine the bottom width of the surface heat source.

By using a similar method to that in [56, 58], the distribution of steady-state temperature rise in the workpiece can be expressed in a nondimensional form as [63]:

$$\begin{aligned}\bar{T}(X,Z) = {} & 2\varphi\int_{X-L}^{X-X_a}\left\{1-\frac{(X-X_a)-m}{L-X_a}\right\}e^{-m}\cdot \\ & \cdot K_0\left(\sqrt{Z^2+m^2}\right)dm \\ & +2\varphi\int_{X-X_a}^{X+L}\left\{1+\frac{(X-X_a)-m}{L+X_a}\right\}e^{-m}\cdot \\ & \cdot K_0\left(\sqrt{Z^2+m^2}\right)dm \\ & -\pi He^{HZ}\int_0^\infty \tau e^{H^2\tau^2}\mathbf{erfc}\left(\frac{Z}{2\tau}+H\tau\right)\cdot \\ & \cdot\left\{\mathbf{erf}\left(\frac{X+L}{2\tau}+\tau\right)-\mathbf{erf}\left(\frac{X-L}{2\tau}+\tau\right)\right\}d\tau\end{aligned} \tag{4}$$

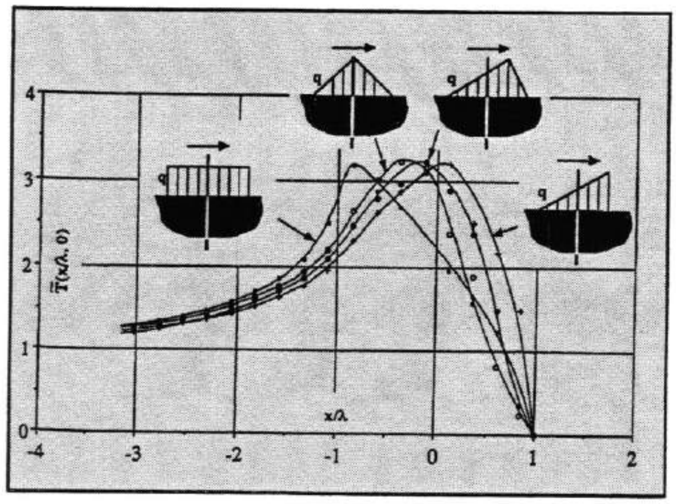

FIG. 9. Variation of surface temperature profiles with the change of heat source models [63]

where

$$\bar{T}(X,Z)=\frac{\pi\kappa V_w}{2\alpha\bar{q}}T(X,Z),\quad H=\frac{2\alpha h}{\kappa V_w},\quad X=\frac{V_w x}{2\alpha},\quad Z=\frac{V_w z}{2\alpha},$$

$$\tau=\frac{V_w t^{1/2}}{2\alpha^{1/2}},\quad X_a=\frac{V_w\xi_a}{2\alpha}\quad\text{and}\quad L=\frac{V_w L_c}{4\alpha}$$

have been introduced. Note that **erf** and **erfc** are error and complementary error functions, respectively. Equation 4 has assumed that the convective heat transfer coefficient, h, is a constant over the workpiece surface and that $0<X_a<L$ which is coincident with the real deformation mechanism of workpiece material in the grinding zone. Equation 4 implies that three physical points are of importance to temperature distribution: the profile effect of total heat strength, q (related to apex coordinate, ξ_a); the fraction of heat that enters into workpiece φ; and the convective effect of h. As mentioned above, it is not known at this stage how these parameters vary with grinding conditions, and therefore, it is meaningless to make any unpractical assumption before careful identification. These factors are presently determined through the trial and error method [63].

Figure 9 shows how the profile of the surface temperature changes with the change of apex position in the present heat source model. It is obvious that ξ_a is a judiciously chosen variable, and for different wheel structures, as shown in Fig. 10, and grinding operations one can not imagine that the heat source distribution should be the same. In surface grinding with the same grinding conditions, for instance, up- and down-grinding will bring about different temperature profiles over the contact arc as shown in Fig. 11 [64]. Details of previous investigations into heat generation models can be found in [53, 60, 63, 65–69].

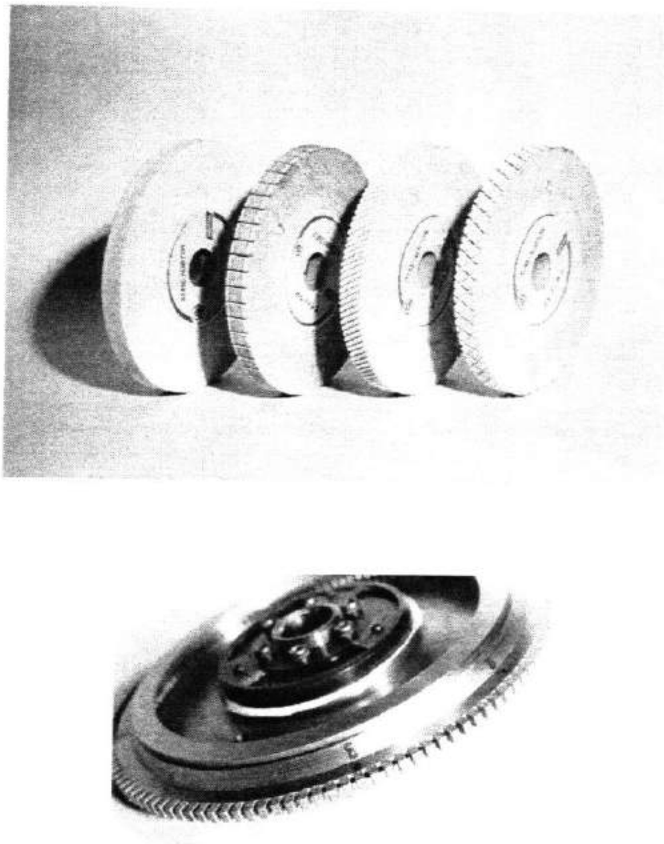

FIG. 10. **Wheels with different slot arrangements**

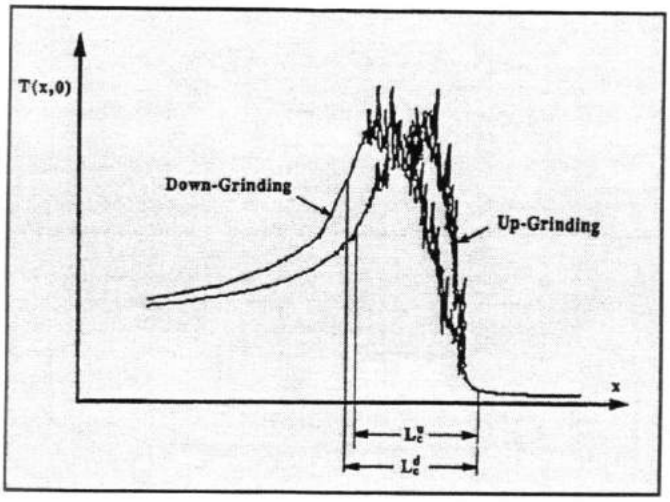

FIG. 11. **Graph of temperature distributions of up- and down-grinding [64]**

On Grinding Research Methodology

The demands made on grinding in modern design are increasingly stringent, and require the designer to know about the mechanics of grinding. This article has carefully discussed the details of the investigations toward a full understanding of grinding mechanisms. However, a summary of this work from the angle of research methodology is preferable for determining what kind of research methods should be used in future research.

The methods previously discussed and adopted have fallen into two categories: macroscopic and microscopic approaches. Materials for workpieces and grinding wheels obey certain laws: mechanics of thermodynamics, rate theory, and so on. These have generated the continuum theories of elasticity, plasticity, and heat flow (or even fluid flow), that can be thought of as a sort of rational empiricism that can be manipulated by mathematical methods. Continuum design is a very powerful tool when applied to obtain interface pressure and contact length [26, 33]. However, it is important to realize its limitations. It provides a description of material response to certain external conditions (like plastic behavior of a workpiece at fine grinding temperature). However, it gives no help in predicting the response of a material to a new condition (like plastic behavior of the workpiece at high grinding temperature), because a description of the material response to the new condition requires a completely new set of experiments from which new continuum rules must be distilled.

The microscopic approach investigates the interaction between a single grain and a workpiece. There are good reasons for this. Grain models contain microscopic parameters: rubbing, ploughing, cutting, wear of grain tip, local elastic deflection, ratio of normal to tangential forces, mechanisms of chip formation, and groove and ridge shapes on the remaining surface. Studies conducted with macroscopic models can not produce these details. In any real grinding process, these details are not known and it is not practical to measure them in routine manufacture. Microscopic models for a single grain are usually not used by engineers who design grinding machines and wheels, because they only need to develop procedures that depend on macroscopically measurable properties.

It is therefore important to construct a bridge between macro- and microscopic approaches. To move ahead, researchers must seek to identify the broad rules governing a grinding process, and the rules governing the magnitudes of interference properties contained in the microscopic models. The models proposed by Zhang et. al for the interface forces and elastic modulus of wheels are good examples of this approach [26, 33, 63].

SUGGESTIONS FOR FURTHER WORK

There are many problems remaining to be solved in grinding. Here, the authors suggest some topics for further research that they believe are compelling.

Dominant Variables and Approximate Formulas

In spite of a vast number of investigations, it is still not possible for researchers to predict general relationships between the real depth of cut, work condition, operational stability, and surface integrity for any process that has not been specifically investigated. However, research has now reached such a stage that for a given grinding operation one can obtain the relationships between various parameters with the aid of different methods, such as the experimental method, the analytical method, the numerical method, or a combination of these. In other words, researchers are now able to establish a certain kind of data base no matter how little information it will include and how difficult the procedure is to model. On the other hand, it is unrealistic to study every kind of engineering product in a laboratory setting because the work conditions in different shops are usually varied and grinding techniques are evolving. For example, a function of one variable may be plotted as a single curve. A function of two variables is represented by a family of curves, or chart, with one curve for each value of the second variable. A function of three variables is represented by a set of charts, with one chart for each value of the third variable. A function of four variables is represented by a set of sets of charts, and so on. If, for instance, five experimental points are required to plot a curve, 25 points are required to plot a chart of five curves, 125 points are required to plot a set of five charts, etc. This situation quickly gets out of hand, particularly if each experimental point entails much expense, which is not unusual in grinding operations [70]. Evidently, the question should be asked: *Is it possible to predict with desired accuracy the behavior of a group or a class of ground components by studying fewer particular cases?* The answer is affirmative although a great effort is required. The researcher's task is to find dominating parameters for various grinding operations and to predict the results. Dimensional analysis makes it possible to answer the question partially (The question should also partly be answered in the *Optimization Map* section below). It is a fact that dimensional analysis has saved a lot of unnecessary work in a variety of research fields, especially in the areas dominated by means of experiments [71]. The main idea of this method was clearly described by J. Clerk Maxwell:

> *The success of any physical investigation depends on the judicious selection of what is to be observed as of primary importance, combined with a voluntary abstraction of the mind from those features which, however attractive they may appear, we are not yet sufficiently advanced in science to investigate with profit.*

The successful selection of governing parameters for elastic modulus of grinding wheels is a good example [26].

An Optimization Map for Various Grinding Processes

The selection of grinding wheels and work conditions for individual grinding applications has been a process of trial and error. The dimensional analysis method just discussed can help in selecting approximate formulas and dominant grinding parameters with relatively fewer experimentations. However, it is not very helpful for the optimal selection of grinding wheels, type of coolants, or depth of cut for obtaining ground components with a desired surface integrity. To reach this end, an *optimization map* for various grinding processes must be developed. Collecting useful data and defining proper criteria will be the two important steps for the map construction. The authors believe that it is necessary to establish a set of standard grinding operations such that researchers can make full use of all obtained results and data transfer may become practical [72]. Various monitoring techniques (e.g., [73]) will serve as useful tools for the development of optimization maps.

Other Considerations

In conjunction with the above recommendations, the points listed below are of equal importance:

- the three-dimensional configuration of wheel–workpiece interaction,
- dynamic effects on surface integrity,
- the law of heat transfer during grinding,
- methods for grinding brittle materials,
- more realistic constitutive laws for work materials, and
- modeling of complicated wheel structures, for example, those wheels with complex slot arrangements as shown in Fig. 10.

CONCLUDING REMARKS

New concepts, such as a grinding condition coefficient for contact length prediction, an optimization map for grinding process selection, standard grinding operations for grinding data accumulation, and so on, have been introduced and discussed. Investigations suggest that mechanics problems in grinding should generally be solved with a combination of experimental, theoretical, and numerical analyses. Owing to extremely complex interface conditions, particular attention should be paid to the modeling of wheel–workpiece interaction and to a deeper understanding of grinding mechanisms. Microscopic study is necessary but should not be the aim of research efforts. Macroscopic models to bridge academic investigation with engineering application will be the most important goal.

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